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Research article

Exploring the nexus link of environmental technology innovation, urbanization, financial development, and energy consumption on environmental pollution: Evidence from 27 emerging economies

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ABSTRACT

The core intent of the present study seeks to probe the connection linking environmental technology innovation (ENVTI), economic growth (ECG), financial development (FID), trade openness (TROP), urbanization (URB) and energy consumption (ENC) on environmental pollution (ENVP) by employing 27 chosen African economies panel data. These variables merit critical attention when implementing decarbonization policies and significantly safeguarding a country's well-being in pursuit of massive industrialization and economic expansion. The fully modified ordinary least squares (FMOLS), the dynamic ordinary least square (DOLS), and the pooled mean group (PMG) estimation techniques were utilized to analyze the series from 2000 through 2020. This research used the FMOLS for long-run connections interaction of the variables, while the DOLS and PMG were used for robustness checks. Further, the Pedroni, Kao, and Westerlund cointegration approaches were employed to determine cointegration in the series. Also, the cross-sectional Im, Pesaran, and Shin (CIPS) and the cross-sectional augmented Dickey-Fuller (CADF) unit root testing approaches were utilized to check the stationarity of the series. Again, the stochastic impact on regression, population, affluence, and technology (STIRPAT) model, and the environmental Kuznets curve (EKC) was used as the theoretical framework supporting this research. The findings of the long-run analysis give credence to the EKC assumption demonstrating that a significant long-term ECG will support the decrease in ENVP when nations experience increases in the level of income. Further, this study found that ENVTI and URB are conducive to reducing ENVP in the long run. The current research finding is sensitive to the

Abbreviations: environmental technology innovation (ENVTI), economic growth (ECG),; financial development (FID), trade openness (TROP); urbanization (URB), energy consumption (ENC); dynamic ordinary least square (DOLS), fully modified ordinary least squares (FMOLS); pooled mean group (PMG), cross-sectional Im, Pesaran, and Shin (CIPS); cross-sectional augmented Dickey-Fuller (CADF), environmental Kuznets curve (EKC); environmental pollution (ENVP), stochastic impact on regression, population, affluence, and technology (STIRPAT).

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respective nations' income levels. This empirical research furnishes prudent policies tailored for the respective countries' pursuit of ECG and reducing ENVP.

1. Introduction

Environmental technology innovation (ENVTI) is focused on a challenged-oriented strategy to solutions that bring together a rich and efficient natural resource that underpins the application and development of environmentally friendly technologies to comprehend and pursue sustainable future development goals [1–3]. ENVTI could also be defined as 'clean technology' or 'green' and denotes the growth of modern technologies which seek to monitor, conserve or decrease the negative effect of some technologies on resource consumption and the environment [2,4,5]. Additionally, technological innovation can help to recover energy [2,6]. Through ENVTI, energy can be reused to enhance energy consumption efficiency, as a result helping to achieve the influence of carbon dioxide emission reduction [7–10]. This study considers the homogeneous need for development, environmental quality, and technology adoption in 27 selected African countries, including Angola, Botswana, Congo Democratic Republic, Egypt, Ghana, Gabon, Ethiopia, Gambia, Malawi, Kenya, Mauritania, Mozambique, Mauritius, Mali, Morocco, Cameroon, Nigeria, Rwanda, Namibia, Seychelles, Senegal, Tanzania, Sierra Leone, Tunisia, Togo, Zimbabwe, and South Africa. The purpose of selecting these African nations is based on their pursuit of faster economic growth and interconnected trade openness, which invariably contributes to the higher demand for energy consumption, hence its accompanying environmental pollution issues [10,11]. Thus, it suggests that nations' economic, cultural, and social expansion dramatically relies on a constant energy supply for industrial and domestic purposes [11]. Therefore, adopting novel approaches and models, including the stochastic impact by regression, population, affluence, and technology (STIRPAT), fully modified ordinary least squares (FMOLS), dynamic ordinary least squares (DOLS), and pooled mean group (PMG) in assessing ENVTI, economic growth (ECG), energy consumption (ENC), trade openness (TROP), urbanization (URB), and financial development (FID) influence on ENVP in emerging nations is critical [7,8,10,12–14]. It is argued that sustainable development would be achieved if individuals accept and implement environmentally friendly policies through economic and socially compatible avenues and determine the influence of energy consumption patterns in achieving environmental quality [10,12]. These challenges demand holistic and systematic environmentally friendly technologies and innovations incorporating the sustainable supply of available renewable energy resources, developing high and efficient technological countermeasures, adapting conducive energy supply systems to benefit the economy, and complementing governmental decisions to enhance citizens' welfare [10,12].

Furthermore, studies have examined the influence of economic growth, energy consumption, tourism, financial development, and trade openness on environmental pollution in diverse regions [10,14–18]. Besides the exciting outcomes of this research, varying and incongruent findings characterized the novelty of the investigations. Also, these studies failed to explore the importance of ENVTI and URB in mitigating the impact of ENVP [10,14–18]. Hence, this research seeks to bridge this gap by incorporating ENVTI and URB for analysis. Therefore, the motivation of this research aims to explore the merit of ENVTI and URB in reducing ENVP in the selected African nations. This exploration is crucial and timely because ENVTI and URB influence energy ENC, ECG, FID, and TROP [2]. This research is founded on the STIRPAT model and environmental Kuznets curve (EKC) assumptions to explore the nexus link between ENVTI, URB, TROP, FID, ENC, and ECG on ENVP [3,10,19]. Thus, adopting the STIRPAT model and EKC in this research is critical because technological change and income growth are vital to comprehend the explanatory variables behind environmental impacts [13,20,21]. Moreover, the EKC theory helps to understand the influence of income level expansion on the respective countries to environmental pollution control [9,10]. This study is unique because of its comprehensive analysis, including ENVTI, URB, ECG, ENC, FID, and TROP on ENVP, which is crucial in analyzing a nation's development trajectory and policies on economic expansion and pollution control. Also, many countries such as Morocco, Egypt, Tunisia, and Algeria achieve sustainable ECG through effective and efficient FID strategies and trade openness [17,22,23].

Moreover, financial development comprises a collection of markets, instruments, and institutions backed by regulatory and legal systems which facilitate economic transactions and growth via credit extension [24–26]. A regulated and enhanced FID is critical for long-lasting economic expansion [27,28]. Studies have revealed that FID is directly associated with ECG and ENC, which may adversely influence the environment's quality [24–26]. Although the causal connection linking ENVTI, FID, ENC, and ECG, on ENVP has been analyzed in diverse jurisdictions, there have been varying outcomes [2,3,8]. This research aims to amalgamate these critical variables for analysis to furnish novel findings in the context of the selected African economies. Africa is a continent that needs massive financial development and technological advancement to enhance its economic structure [29,30]. This study bridges the gap created by focusing on the influence of ENVTI, URB, and the other independent variables on ENVP. The findings of this research are critical for the selected African nations' conditions to ensure a varying and dynamic policy response. Thus, research on ENVP in Africa is gradually developing into an important issue for governments and institutions to ensure citizens' well-being and attain a quality environment [10]. This research put forward that the recent paradigm of ENVP would be significantly controlled through ENVTI and a streamlined urban development, which includes creating and consuming green products to improve the populace's living standards and attain ECG [31–33]. Furthermore, the gradual expansion of industrial sectors and technological advancement continues to impact nations' policies to control ENVP [34]. Thus, the current variations in the consumption and trading of products for industrial and domestic purposes may be enhanced through the continual adoption of technologies to control the devastating environmental effect [2]. Hence, the harmful gases emanating from industries in our environment are a significant source of ENVP and must be controlled [7,8]. In addition, environmental hazards in Africa are extensively experienced through waste materials disposed into the environment and other water bodies [2,19].

Again, agricultural activities, including deforestation, burning forests, fertilizer application, and other chemicals exposed to our environment, contribute immensely to ENVP [7,8,10]. This phenomenon has contributed to adopting several approaches, such as the PMG, DOLS, FMOLS, and Driscoll-Kraay panel regression, in determining varied outcomes for analyzing the ENVP impact [8,10,35]. Most studies following these analyses reveal a significant positive connection linking ECG and ENVP [3,36,37]. Notwithstanding, the negative influence of squared economic growth (ECG^2) gives credence to the EKC assumption [3,19]. Furthermore, extant studies have examined the causal link between ECG and ENVP and found a bidirectional causation between ECG and ENVP [3,14]. Thus, the trajectory of ECG influences ENVP, but the impact change with long-term economic growth as an inverted U shape connection is formed, crediting the EKC hypothesis [10]. Therefore, it suggests that at the preliminary stages of economic expansion, there is a tendency for high ENC within an economy; hence, ENVP issues increase due to natural resource exploitation [8,10,14]. As a result, securing environmental quality is ignored in the preliminary phase of pursuing ECG [38]. Simultaneously, the environmental conditions improve when income expands in the long run in the economies [10,19,24,39–41].

Based on the above exposition, this study projects that ENVTI and enhanced urban development may significantly support the control of ENVP when ECG, FID, TROP, and ENC policies are adequately managed and implemented [8,10,14]. The importance governments attach to ENVP control has increased the application of dynamic methodologies across diverse jurisdictions to determine varying outcomes but failed to consider the role of ENVTI and URB in controlling environmental degradation [14,38]. It, therefore, suggests that employing social phenomenon indicators with technology innovation and other critical economic variables for analysis enhances the determination of appropriate findings for various economic conditions to strengthen policy implementation [15]. For instance, Cherp et al. (2018) ascertained dynamic and significant results by examining different variables with technology innovation [42]. Furthermore, the increase in ENC and integration of the economy to achieve quality living may increase the demand for energy resources for production and consumption [43]. Therefore, this research suggests ENVTI and URB may be critical indicators for controlling ENVP in the chosen African nations [36,44].

Additionally, this research is essential and furnishes insights into sustainable environmental policies and bridges the gap in exploring the influence of ENVTI and URB on ENVP in the context of Africa based on judicious environmental technology resources to attain economic development and environmental quality [8,10,14]. Furthermore, the variables employed for analysis are critical in providing accurate findings and policy suggestions to support the economies to control non-renewable energies and adopt advanced and sustainable energy-friendly technologies. Moreover, this study offers policy measures to enhance the implementation of low-carbon, efficient, and clean energy use in the respective nations. Thus, as economies advance with income and renewable resources, using clean energy becomes vital in improving the quality of the environment and living conditions of the urban populace [8,38,43,45]. Therefore, urban areas' growth trajectory determines the regulatory or policy support for inclusive development and socially sustainable policies to complement the planning systems [8,38,43,45]. Hence, analyzing the chosen variables within the selected African economies is critical because of their interconnection and joint effort to control ENVP through environmentally friendly technology innovations in promoting long-term ECG and urban areas development [10,11,43,46–48].

This research contributes to the existing literature threefold: in estimating the research variables to furnish accurate statistical findings and long-run interconnection, this study employed the FMOLS for analysis. At the same time, PMG and the DOLS estimators were used for robustness checks [8,10,14]. This research also employed the second-generation cross-sectional dependence (CSD) testing approaches for analysis [49,50]. Furthermore, the Westerlund, Pedroni, and Kao cointegration testing approaches were used for cointegration testing. Thus, this comprehensive analysis trend within the selected African countries is lacking. Therefore, this research deems it appropriate to examine the merits of ENVTI and a streamlined URB to attain a long-term ECG in reducing the surge of ENVP in the chosen economies. Also, inconclusive findings in the context of Africa reveal that most research on African economies tries to find a response to the continual increase in climatic conditions but neglects the exploration of the role of ENVTI and URB as critical factors in decreasing ENVP [10,39,51,52].

This research also makes another exciting and novel contribution by analyzing the causal connections [53]. Thus, panel causality analysis support rendering effective and efficient policies to overcome the overwhelming trend of ENVP in economies. This research seeks to answer the following research questions: First, what is the influence of ENVTI, FID, ENC, ECG, TROP, and URB on ENVP in the chosen African nations? Secondly, are ENVTI and URB critical elements to control ENVP in the chosen African nations? Thirdly, is the EKC theory and STIRPAT model valid in the selected African countries? This research, therefore, investigates the connection linking these variables in respect of the framework of the STIRPAT model and EKC theory.

Aside from the introduction above, the other segment of this research is organized as follows: segment two reveals the hypothesis development and literary works, the third segment presents the methodology and theoretical underpinning of the study, and segment four offers the research result and discussion, whereas segment five elaborates the research conclusion, policy implication and limitations of the study.

2. Literary works and hypothesis development

Environmental technology innovation aims to monitor, control and conserve the environment from deterioration [54]. ENVTI provides avenues to utilize energy that eliminates or reduces pollution in a sustainable path [3,30,54]. These processes of ENVTI include water desalination, solar and wind energy, pyrolysis, and electric vehicles, which are vital in controlling ENVP [3,30,54]. Thus, the level of ENVP is streamlined and regulated by technological advancement and governance policies to attain a quality environment [9,55]. Hence, in ensuring environmental quality, policymakers need to re-echo the adoption of ENVTI strategies that enhance green growth practices to be incorporated into green consumption and production [55,56]. ENVTI is highly connected with green growth to achieve maximum utilization of green products to reduce ENVP [56]. Therefore ENVTI has been described as an eco-friendly technology used to churn goods and services that facilitate ECG and decreases ENVP, which are critical for developing emerging economies [9,39]. As a result, these vital variables significantly influence urbanization, technology, and ENVP in diverse regions [7,10,39,55].

Furthermore, studies have examined how ENVTI, FID, URB, and ENC affect the productivity of economies, including Brazil, China, Russia, South Africa, and India [57]. The empirical findings support a longitudinal cointegration association between ENVTI and ENVP [57]. The study outcome further revealed that URB and ENVTI potentially reduce ENVP and ensure long-term environmental quality within the five developing countries [57]. This finding demonstrates that moving to the path of ENVTI demands a robust and sustainable policy that may help comprehend the economic growth trajectory. Hence, implementing decarbonization measures within the chosen economies may require eco-friendly technology that may play a pivotal role. Also, ENVTI is critical in addressing ENVP issues by enhancing management strategies and efficiency [58,59]. Moreover, ENVTI is examined to have a more significant effect on curbing ENVP [3,30,54]. This study suggests that government policies must encourage heavy investment in ENVTI through subsidies to boost the enterprises' adoption of eco-friendly technologies [3,30,54]. It is, therefore, apparent that governments that massively support ENVTI adoption and usage motivate private businesses that adopt green, environmentally friendly technologies, which is critical for ECG and the reduction of ENVP [55,56]. Hence, the current study examines whether eco-friendly technology innovation would help mitigate the enormous increase of ENVP in selected African nations. Thus, studies have demonstrated that ENVTI significantly influences the reduction of ENVP [3,54,60]. ENVTI has also been outlined as an effective tool in decreasing ENVP in two stringent avenues. Initially, ENVTI enhances energy efficiency by limiting the embodied energy per unit of output; also, ENVTI reduces carbon dioxide emission due to per energy reduction in the unit [8,61]. Thus, ENVTI is an efficient and effective action in achieving energy conservation and decline in ENVP [3,8]. As a result, the role of ENVTI has been examined by adopting different methods, including PMG, FMOLS, DOLS, and the autoregressive distributive lag approach [8,61,62]. The findings revealed an inverse relationship linking ENVTI with ENVP [8,61,62]. Based on the above viewpoints, this study hypothesizes an inverse relationship between ENVTI and ENVP.

Recently, enormous attention has been geared toward addressing the environmental issues linking economic growth and ENVP issues in attaining sustainable global economic development [63–65]. Addressing the development of an economy with environmental issues could be achieved by guaranteeing minimal consumption of non-renewable resources that affect the environment and hinders the maximization of ECG benefits [66,67]. Economic growth has contributed to the search for technology and green innovation, which is crucial in decoupling ENVP [68,69]. With the continual exploitation of natural resources to expand economies, extreme hazards are posed by pursuing these activities, which requires an in-depth analysis and policy intervention [65]. Thus, pursuing ECG in an economy is highly linked with energy consumption which invariably causes ENVP [8,45,61,62]. Therefore, in ensuring a balanced and significant ECG, prudent policies with technology innovation should be implemented to improve and assist nations in carrying out clean production activities to promote the reduction of ENVP and energy conservation [3,10]. Hence, this research projects that effective and efficient energy usage policies would reduce ENVP and help achieve significant positive ECG [3,10]. This study hypothesized that economic growth is statistically significant and positively influences environmental pollution.

Also, energy consumption describes the quantity of energy utilized via buildings, transportation, and other domestic and industrial purposes [70–72]. The assessment of the aggregate ENC by nations comprising crude oil, coal, and their related products, including electricity and natural gas, are critical factors contributing to ENVP [70,71]. Notwithstanding the consumption of low calorific value, solar energy and bio-energy are mostly encouraged. Thus, energy conservation policies yield higher economic progress and improve inhabitants' living standards [16]. Furthermore, reducing emissions through less consumption of non-renewable energy contributes to cleaner air quality, creates a healthier environment, and assists in sustaining the available resources [72]. ENC elements, such as fossil fuel, coal, and electricity, are critical elements that support ECG in several nations due to their propensity to influence socioeconomic and environmental stability [14,73]. However, the increasing supply of fossil energies has its corresponding environmental impact and merits exploring the decoupling connection existing between ENVP, ECG, and ENC [74,75]. Hence, effective and efficient ENC policies would assist ecological protection policies, help to achieve gainful economic development, and decrease ENVP [76]. Studies conducted in most African nations established that ENC is statistically significant and dramatically contributes to ENVP [77,78]. Based on the above analysis, this research hypothesizes that energy consumption is statistically significant and positively impacts environmental pollution.

Financial development (FID) comprises a group of markets, instruments, and institutions backed by regulatory and legal systems that facilitate economic transactions via credit extension [58,79]. A standardized and enhanced FID is crucial for prolonged economic prosperity and technological progress [28,80]. Research has revealed that FID is directly associated with economic expansion and energy utilization, which may invariably influence environmental quality [24–26]. FID is relevant to developing economies, enhancing private sector expansion, stimulating economic prosperity, and poverty alleviation [41]. Studies have proven that FID significantly and positively influences economic growth [28]. Notwithstanding, the urge to increase income through the continual pursuit of FID contributes to the exploitation of resources, exchange of goods and services through automobiles, and other forms of energy usage to achieve a set target, which creates ENVP [24,28,41,81,82]. FID has been revealed as a critical element that influences the standard of ENVP [8]. Findings suggest that financial institutions that issue and lend monies to diverse organizations as an avenue to exploit non-renewable resources contribute to ENVP. An attempt for enterprises to expand income, production, and consumption of non-renewable resources increases, which invariably contributes to ENVP in the long term [28,80]. Simultaneously, as citizens and industries acquire financial support from banking institutions, it is anticipated that ENC may increase and contribute to ENVP [24,41,81,82]. Besides the findings of these earlier studies, other scholars have portrayed different results, which indicated that FID might promote environment-friendly technology innovations for enterprises and contribute to the reduction of ENC and ENVP [25,26]. Studies have revealed a two-way causal connection between FID and ENVP [28,57]. Therefore, some studies have shown that FID, ENVTI, and urban population expansion may boost environmental quality, lead to the decline of ENVP within emerging nations, and further support income expansion in the long run [28]. Hence, this research put forward that policymakers and governments of the selected countries implement prudent policies in enhancing FID through the effective and efficient adoption of eco-friendly ENVTI [28,80]. Based on the afore analysis, the authors of this research propose that a positive and significant connection linking FID and ENVP may follow the trajectory of the EKC assumption in the long run. Thus, financial development is projected to be statistically significant and positively influences environmental pollution.

From an economic perspective, trade openness is the propensity through which exports and imports are conducted and influence the magnitude and expansion of a country's economic growth [83,84]. It protects developing nations against shock and reduces volatility. TROP helps measure the extent governments are open to global trade with their exports and imports in aggregate gross domestic products [17,85,86]. Also, the extent of economic openness in trading, known as the Impex rate, describes the magnitude of accredited importations and exportations in an economy [87]. TROP helps analyze trade's consequences and influence on nations' economic and social conditions [86]. TROP may inherently support the growth of an economy by providing access to services and goods, attaining efficiency in the distribution of resources, and enhancing the total factor productivity via technological diffusion and dissemination of knowledge [17,86,87]. Trade through global interconnectedness and economic engagement seeks to satisfy the needs of citizens in diverse ways but has an inherent impact on the environment [52]. Through TROP, countries have become heavily dependent on importing and exporting electrical appliances and gadgets that may not be environmentally friendly, including automobiles, air conditioners, and fuel generators, contributing to ENVP through extensive ENC [17,86,87]. Thus, consuming high-energy products may influence the environment by aggravating the proportion of ENVP [17,86].

Furthermore, extant research has demonstrated the statistical significance and positive influence of TROP on ENVP in diverse ways [52,85]. Therefore, this research put forward that industrialized and advanced nations with a high volume of trade may adopt modern technologies and eco-friendly procedures of production to curtail the increasing trend of ENVP. Thus, non-eco-friendly technologies used for trading significantly impact the environment [17,86,87]. Moreover, studies have established a positive and statistically significant connection linking TROP and ENVP [17,18,86,87]. Hence, this study projects a positive relationship linking TROP and ENVP.

Urbanization denotes the gradual shift of population from rural areas to urban places, the respective decline in the percentage of the populace dwelling in rural areas, and the modalities in which the communities adapt to changes [88–91]. Studies have shown that population growth within urban vicinities impacts environmental quality through increased tension on limited resources through energy consumption [92]. Further, URB has been demonstrated to damage the quality of the environment through the increasing demand for automobile transportation and competition for non-renewable energy for domestic and industrial use [45,93]. Therefore, the trend of urban transformation merits in-depth research to evaluate the dynamics of URB and its impact on ENVP in the selected emerging nations through diverse models, including STIRPAT and EKC theory [45,92,93]. Thus, studies have demonstrated that streamlined URB could be achieved with ENVTI and renewable energy consumption to attain modern civilization [65,94–96]. Based on the significant impact of streamlined urban development in Africa, equitable distribution, and diversification of resources, coupled with long-term ECG and improvement in ENVTI, it is emphasized that URB will enhance the control of ENVP in Africa [88–91]. Thus, when countries' citizens' income expands, and policies for sensitization of environmental quality are improved, research demonstrates that URB leads to an asymmetric influence and may help to control ENVP [88–91]. This research is theorized on the STIRPAT model and EKC hypothesis to investigate the long-term effect of streamlined URB on ENVP. Hence, this research emphasized that in most regions in Africa, regulating URB issues with modernized structures will support the reduction of ENVP when citizens are sensitized to the use of energy-efficient technologies with less pollution and distribute resources equitably to the indigenes to desist from the traditional modes of ENC [88–91]. Drawing on the diverse results of the studies above, the authors of this present study propose that urbanization is statistically significant and inversely influences environmental pollution control in Africa.

3. The theoretical underpinning, model specification, data, and methodology

3.1. Theoretical underpinning

The discussion of ecological stakeholders in the contemporary periods has motivated scholars to investigate the factors influencing environmental pollution and provide solutions to ecological issues [10,19,40,41,62]. Several of these investigations were conducted in the context of the environmental Kuznets curve (EKC) theory [97]. This research is premised on the EKC theory [97]. The EKC theory is connected with ENVP and ECG. The EKC theorized that the tendency of environmental pollution to increase at the preliminary phases of ECG is high, and after it reaches a specific threshold, ECG reduces ENVP [7,89,97]. When it increasingly becomes apparent the extent to which man's activities have influenced the environment demands critical attention geared towards ENVTI adoption and education to address the ENVP issue [3,98,99]. Therefore, the EKC theory suggests that the quality of the environment improves as income increases in the respective nations [10]. Aside from the EKC theory, this study incorporates the Integrated Population, Affluence and Technology (IPAT), and STIRPAT models to bring more insight into the link between urban population impact on the environment because of income disparities and technological application to achieve ECG [12,21,54].

The IPAT model is an analytical tool for assessing the impact of certain variables on an environment [96]. IPAT was purposely designed to identify the forces motivating environmental effects and suggests that population, affluence, and technology significantly influence the environment [93,100]. Studies have indicated that the IPAT model could be employed to determine variables that harm the environment [100,101]. Therefore, this study used the selected variables to depict the impact trend when measuring ECG and its associated ENVP. Furthermore, research has revealed that the population has a more harmful environmental impact via agricultural, manufacturing, and tourism activities [10,87].

3.2. Model specification

This research seeks to quantify the effect of ENVTI, FID, ENC, ECG, URB, and TROP on ENVP in selected African nations to determine the impact of the chosen variables on environmental sustainability goals and the dynamics of causal connection. This research employs carbon dioxide emissions (CO_2) as a surrogate of ENVP and per capita GDP as a surrogate of ECG [10,87]. This research is crucial to the selected African economies because of their high pursuit of ECG and ENVTI to meet the decarbonization policies of the Paris agreement on ENVP [102]. Thus, it is suggested that as non-renewable energy consumption increases, the quality of the environment is affected; hence, the well-being of indigenes would be enhanced through enhanced ENVTI and streamlined urbanization [102]. Moreover, the critical nature of assessing the trajectory of these variables depicts the extant analysis conducted in diverse jurisdictions in justifying the credence of the EKC assumption and ENVP nexus [9,73,103,104]. The present research utilizes the yearly panel data sets spanning 2000 through 2020 for 27 economies in Africa. This study is premised on the EKC theory as specified in the subsequent econometric modeling approach below:

$$\mathrm{ENVP_{it}} = \alpha_1 + \alpha_2 \mathrm{ECG_{it}} + \alpha_3 (\mathrm{ECG_{it}})^2 + \alpha_4 \mathrm{W_{it}} + \mu_{it} \tag{1}$$

Where, $ENVP_{it}$ depicts the environmental pollution (CO_2 emission per capita), ECG_{it} denotes economic growth (GDP per capita), $(\mathrm{ECG_{it}})^2$ represents the income of the respective countries, and W_{it} denotes the respective macroeconomic elements that influence the dependent variable ENVP. To ensure the efficiency and consistency of the model with an understandable interpretation, the authors applied the strategies of natural logarithm in equation (1) for the variables as shown in equation (2).

$$\mathrm{lnENVP_{it}} = \alpha_0 + \alpha_1 \ln \mathrm{ECG_{it}} + \alpha_2 \ln(\mathrm{ECG_{it}})^2 + \alpha_3 \mathrm{lnW_{it}} + \varepsilon_{it} \tag{2}$$

Furthermore, equation (3) demonstrates the model estimation of the variables, including ECG, ECG^2, ENC, ENVTI, TROP, URB, and FID on ENVP spanning 2000 through 2020.

$$\mathrm{lnENVP_{2it}} = \alpha_1 + \alpha_2 \ln \mathrm{ECG_{it}} + \alpha_3 \ln(\mathrm{ECG_{it}})^2 + \alpha_4 \mathrm{lnENC_{it}} + \alpha_5 \mathrm{lnENVTI_{it}} + \alpha_6 \mathrm{lnTROP_{it}} + \alpha_7 \mathrm{lnURB_{it}} + \alpha_8 \mathrm{lnFID_{it}} + \varepsilon_{it} \tag{3}$$

Therefore, investigating the nexus link and effect of ECG, ENC, FID, TROP, URB, and ENVTI on ENVP is projected to furnish an innovative finding to aid policy implementation in the selected nations based on the IPAT and STIRPAT models. Furthermore, the trajectory of development and income levels of the economies will help to determine the longitudinal connection of the variables and their impact on the environment. Thus, the critical nature of examining the IPAT and STIRPAT model in relationship with the environment has been determined with varying and exciting findings [95,96,105,106]. The IPAT formula is shown in equation (4).

$$I = P \times A \times T \tag{4}$$

where the alphabet (I) symbolizes the integrated effect of environmental pollution, (P) describes the population, (A) denotes affluence level, and (T) indicates technology. This approach is widely acknowledged, consistent, and robust, and only a few studies have employed it for analysis. Due to the inherent concerns and limitations researchers raised on the IPAT model. Therefore, Dietz & Rosa, (1997) proposed the STIRPAT model as a stochastic approach to broaden the framework of the IPAT model, as shown in equation (5).

$$I = a \times P^b \times A^c \times T^d \times e \tag{5}$$

The parameters are denoted as $a, b, c, and\ d$, with e representing the error term. This empirical method is determined by taking the logarithm of equation (5) to evaluate operational capability. The estimated model of IPAT to STIRPAT extensions conducted by Refs. [106,107] serves as the premise of this study, as shown in equation (6). Also, this study introduced the research model for estimating the causal link of the variables and forecasting their repercussion on the environment [13] as follows:

$$lnENVP_{it} = \beta_0 + \beta_1 \ ln\ ECG_{it} + \beta_2 \ ln\ ENC_{it} + \beta_3 \ ln\ FID_{it} + \beta_4 \ ln\ TROP_{it} + \beta_5 \ ln\ ENVTI_{it} + \beta_6 \ ln\ URB_{it} + e_{it} \tag{6}$$

where $ENVP_{it}$ stands for environmental pollution surrogated and measured as metric tonnes per capita of carbon dioxide emissions at the time (t), ECG_{it} represent economic growth quantified as per capita GDP in prevailing (US$), FID_{it} stands for financial development measured as gross fixed capita to GDP at prevailing prices (US$), $TROP_{it}$ denotes trade openness measured as a percentage of imports and export of total GDP, ENC_{it} denotes energy consumption quantified as energies consumed, thus Kg of oil equivalent per capita, URB_{it} represent urbanization measured in respect of the percentage of the total populace living within an urban area, $ENVTI_{it}$ denotes technology measured on charges for using intellectual property receipts in US$, and e_{it} stands for the error term.

3.2.1. Study area

This present study is premised on 27 selected African nations, including Angola, Botswana, Congo Democratic Republic, Egypt, Ghana, Gabon, Ethiopia, Gambia, Malawi, Kenya, Mauritania, Mozambique, Mauritius, Mali, Morocco, Cameroon, Nigeria, Rwanda, Namibia, Seychelles, Senegal, Tanzania, Sierra Leone, Tunisia, Togo, Zimbabwe, and South Africa. The purpose of selecting these nations in Africa is based on their pursuit for faster economic growth, which contributes to higher demand for energy consumption with its accompanying environmental pollution. Therefore, investigating the connection of these variables in the economies to provide policies to enhance the pattern of the economies' environmental sustainability goals will support the climate change policies indicated in the Paris agreement for emission reduction and control [48]. Furthermore, environmental consciousness in Africa is integral to the respective economies' development. Also, the physical environment is indispensable and fragile, so ecological awareness will help address these threatening issues for posterity. In Africa, increasing mortality rates occur through the expansion of gas and oil industries in most countries like South Africa and Nigeria. In contrast, fire emissions and outdoor air pollution are the leading cause of death in Central and West Africa [108,109]. This study categorizes the purpose of choosing these countries and their respective data for analysis as twofold: (1) African nations' governments and individual stakeholders have extensively espoused environmental resilience and economic prosperity issues to be eco-friendly, which merits in-depth investigation because of its excessive use of non-renewable resources which leads to ENVP. Thus, the coherent coordination and interaction of the economy and environment culminated in the decline of the ENVP, which is critical to the aims of global environmental sustainability and development agenda [110–112]. (2) African nations are recently experiencing tremendous FID, ENC, ECG, and TROP growth, culminating in a higher ENVP [51,52,85]. Therefore, African countries need a massive expansion of ENVTI and streamlined urban development to decrease the continual surge of the ENVP.

3.2.2. Data sources and measurement units

Due to the availability of data issues, this research utilized the current data spanning 2000 through 2020 from the respective economies for analysis. Based on these two critical reasons furnished above for selecting the study areas, Table 1 reveals that the data employed for analyzing and normalizing the indicators in this study are sourced from reputable sources. The more significant percentage of the panel data was sourced from the world development indicators (WDI) database issued by World Bank [113]. Financial development data was sourced from the international monetary fund [114], and environmental technology innovation was collected from the organization for economic cooperation and development database [115]. Table 1 demonstrates the variables and symbols used, measurement descriptions, and data sources used for analysis. The measurement criteria for the variables used in this investigation are as follows: Environmental pollution (ENVP) was surrogated and measured as metric tonnes per capita of CO_2 emissions, and economic growth (ECG) was quantified as per capita GDP at the prevailing (constant rate of 2015 US$), ECG^2 describes per capita GDP squared which represents the threshold of the economies income, financial development (FID) is measured as the gross fixed capita to GDP at prevailing prices (US$), trade openness (TROP) measured as a proportion of total GDP to export and import, urbanization (URB) is quantified as the proportion of total populace living in urban areas, energy consumption (ENC) is quantified as energy usage (per capita equivalent of oil used in Kg), and environmental technology innovation (ENVTI) measured on the percentage of patent on environment-associated technologies or using intellectual property (patents) receipts in US$.

3.3. Methodologies

The approach to execute this research is a quantitative approach utilizing secondary data. This study investigates the nexus link amongst ECG, ENC, FID, ENVTI, TROP, and URB on ENVP by exploring panel data from 27 emerging economies. Examining the panel data of these countries renders the analysis comprehensive and in-depth to demonstrate their interconnectivity. This research amalgamates novel approaches and modeling procedures, including panel unit root testing and cointegration [116–119]. These approaches are crucial for analyzing the longitudinal connection between the selected study variables. Further, the following modeling estimation approaches are utilized to determine the robustness and short and long-term interconnection of the variables comprising: the FMOLS, DOLS, and PMG at different levels to ensure the accuracy and consistency of the study results. In obtaining accurate results for policymaking and further development of the respective countries, the panel granger causality approach was keenly adopted [120].

3.4. Econometric methodologies

The subsequent sections outline the specific econometric approaches and their respective analytical results using EViews 10 software for the estimations.

3.4.1. Unit root testing

Testing unit roots is one of the essential measurement tools widely used to investigate stationarity characteristics when analyzing data of econometric nature. Extant researchers have applied a series of unit root testing approaches for crucial analysis [121–124]. Notwithstanding, researchers have identified a series of statistical limitations in applying the unit root testing approaches based on sample size and the testing power [125–127]. This research was enhanced through the application of cross-sectional Im, Pesaran, and

Table 1
Selected variables and data sources for the research spanning 2000 through 2020.

Variables	Symbols	Description	Data Sources
Environmental pollution	ENVP	CO_2 emission metric tonne per capita	[113]
Economic growth	ECG	GDP per capita (constant 2015 $)	[113]
Energy consumption	ENC	Energy usage (Kilogram of oil equivalent per capita)	[113]
Financial development	FID	Gross fixed capita to GDP	[114]
Trade openness	TROP	Measured as a percentage of imports and export of total GDP	[113]
Urbanization	URB	Urbanized population (% of the total population)	[113]
Environmental technology innovation	ENVTI	Percentage of patents on environment-associated technologies	[115]

Shin (CIPS) and the cross-sectional augmented Dickey-Fuller (CADF) unit root testing strategies [128–131]. Further, scholars have proposed a unit root test that integrates the individual statistical probability values [127,132]. Thus, the panel unit root testing approach represents a systematic process of measuring panel data stationarity. Research findings demonstrate that panel-based diagnostic unit root tests outperform individual model unit root testing [122,125–127].

Although, some unit root testing approaches have been argued as not effective [131], as indicated in these studies [127,132]. This study foresees the need to apply Pesaran's unit root testing approach because of its inherent importance [131]; thus, it does not consider the assumption of every economy trending in an equilibrium direction. Hence it is characterized by minor interference. The unit root testing methodology of IPS performs better when it has a more extensive panel dataset. Accordingly, this research is conducted on the comprehensive panel dataset of 27 countries and justifies the suitability of applying the CADF and CIPS unit root testing methodologies [50,133]. Also, the CADF testing strategy is presupposed to be homogeneous in a group [134,135]. Equation (7) demonstrates the technique of CADF:

$$y_{it} = \rho_i y_{it-1} + z_{it} y + u_{it} i = 1, \ldots, N; = 1, \ldots, T \tag{7}$$

where z_{it} represent fixed effect, time dynamics, deterministic components, and u_{it} denotes the stationarity process. Further, the unit root testing, according to Levin, Lin, and Chu (LLC), states that the residuals need to be independently and identically distributed (iid) and must correspond with a zero mean of 0, σ_u^2 variance, and $\rho_i = \rho$ for the lag order of the autoregressive process of all i values.

The lagged dependent variable's coefficient is considered homogeneous across all units of the panel's cross-sections. $H_O : \rho = 1$ is the null hypothesis, which states the variables within the panel dataset possess a unit root while $H_1 : \rho < 1$ represents the alternative hypothesis, stating the stationarity of the series. The CIPS testing approach refines the LLC testing that relaxes the homogeneity assumptions by permitting heterogeneity in the panel dataset and autoregressive coefficients. Hence, the CIPS unit root tests are revealed in equation (8):

$$\Delta y_{it} = \alpha_i + \rho_i y_{it-1} + \sum_{j=1}^{P} \varphi_{ij} \Delta y_{it-j} + \varepsilon_{it} i 1, 2\ldots, N; t 1, 2, \ldots, T \tag{8}$$

Where y_{it} denotes individual variables in the study's model, α_i is the coefficient of the variables, fixed effect, and ε_{it} denotes the independent and identically distributed random variables for the values of i *and* t with a mean of zero and a finite heterogeneous variance σ_i^2. P is chosen to ensure that the residuals are uncorrelated throughout the period. Thus, the null hypothesis states that $\rho_i = 0$ for the value of i, whereas the alternative hypothesis states that $\rho_i < 0$ for specific values of $i = 1, \ldots N_1$ while $\rho_i = 0$ for $i = N_1 + 1 \ldots N$. The Im, Pesaran, and Shin statistic is calculated by averaging individual ADF statistics as shown in equation (9):

$$\bar{t} = \frac{1}{N} \sum_{i=1}^{N} t_{iT} \tag{9}$$

where t_{iT} represent the ADF $t - statistics$ for individual i depending on the type of ADF regression, as shown in equation (8). The IPS proves that the $\bar{t}$ statistics asymptotically succeed in a standardized normal distribution premised on the assumption of non-stationarity of the null hypothesis in the panel data framework. Equation (10) expresses the standardized statistic t_{IPS} as:

$$t_{IPS} = \frac{\sqrt{n} \left(\bar{t} - \frac{1}{N} \sum_{i=1}^{N} E I t_{iT} I \rho_i = 0 \right)}{\sqrt{\frac{1}{N} \sum_{i=1}^{N} Var\, [t_{iT} I \rho_i = 0]}} \tag{10}$$

3.4.2. Panel cross-section dependence testing

Income level disparities among nations are important in predicting the cross-sectional dependency of countries concerning culture, economic system, new technology, industry, economic expansion, carbon dioxide emissions, energy consumption, and overseas investment. This study examines data from different countries on varying sample size (N) and time (T) correlated observations; thus, the results of panel experiments are frequently misrepresented [136]. The current research applies the CSD testing to affirm the authenticity of this study's outcome [137,138]. The cross-sectional dependence is expressed in equation (11) as follows:

$$CSD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{\rho}_{ij} \right) \Longrightarrow N(0, 1) \tag{11}$$

Thus, the null hypothesis states that: $H_0 : u_{it} = \sigma_i \varepsilon_{it}, with\, \varepsilon_{it} \sim IID(0, 1)$ for all i and t. The disturbance of the ε_{it} are normally distributed around 0. Also, the N and T denote the sample size and time of this study accordingly. The presence of correlations between the errors of the various cross-section of country i and j are represented by $\widehat{\rho}_{ij}$.

3.4.3. Panel cointegration testing

Long-term correlations between different variables are pretty prevalent. A linear combination followed by two or more non-stationarity series can be stationary [139]. Thus, the non-stationarity series is assumed to be cointegrated when a static linear combination occurs. Therefore, a longitudinal equilibrium association between the variables can be understood as a stationary linear combination [140,141]. When using panel data, co-integration testing is employed to assess whether a cluster of non-stationarity series is cointegrated or otherwise [129,130,141]. In an econometric analysis, the evaluation of longitudinal connections has usually been the subject meriting substantial investigation. Also, cointegration approaches have been proposed and utilized to investigate the presence and form of longitudinal relations on solitary cross-sectional units [139,142–145]. Additionally, because the maximum likelihood process possesses substantial and quantifiable sample properties, Maddala [127] argued that the Fisher-kind panel co-integration testing utilizing the Johansen [144] cointegration assessment approach is much more effective than the Engle and Granger measurement technique. This research employed the advanced cointegration panel approaches for analysis [116–119]. The cointegration methodology of Westerlund [116] was used to investigate the study variables' heterogeneity and CSD. According to this approach, the null hypothesis (H_o) demonstrates the non-existence of cointegration within the series error correction terms. The Westerlund [116] cointegration methodology is revealed in mathematical terms within equation (12).

$$\Delta Y_{it} = \psi_{,i} d_t + \alpha_i (Y_{it-1} - \beta_{,i} X_{it-1}) + \sum_{j=1}^{p_i} \alpha_{ij} \Delta y_{it-j} + \sum_{j=1}^{p_i} \varphi_{ij} \Delta X_{i,t-j} + \mu_{it} \tag{12}$$

hence, $d_t = (1, t)'$ indicate the trend of the series, $\psi_{,i} = \psi_{,i}$ *and* ψ_{2i} represent the elasticity estimates and the constant terms of the respective nation series, while t and i represent the study time and the CSD.

The mathematical expression of the two categories of the Westerlund test statistics are indicated in equations (13) and (14) below:

$$G_\tau = \frac{1}{N} \sum_{i=1}^{N} \frac{\eta_i}{SE(\widehat{\eta}_i)} \tag{13}$$

$$G_a = \frac{1}{N} \sum_{i=1}^{N} \frac{T\eta_i}{1 - \sum_{j=1}^{k} \widehat{\eta}_{ij}} \tag{14}$$

The approach of panel cointegration statistics are estimated in equations (15) and (16) as follows:

$$P_\tau = \frac{\widehat{\eta}_i}{SE(\widehat{\eta}_i)} \tag{15}$$

$$P_a = T\eta_i \tag{16}$$

Therefore, G_τ and G_a demonstrate the group mean statistics, P_τ and P_a reveal the panel statistics, η_i represents transitioning from short and long-term equilibrium and the efficiency in transition. Also, $SE(\widehat{\eta}_i)$ represent the conventional standard error of $\widehat{\eta}_i$.

Furthermore, premised on the novel investigation of Pedroni [117,118], cointegration testing is necessary for time series and panel data explorations since it directly impacts spurious regression, especially when the variables are non-stationary. The assumption is that regression findings with non-stationary or non-cointegrated variables are likely to be biased. Hence, this study's analysis aims to examine ENVTI, ECG, ENC, FID, TROP, and URB's impact on ENVP from the assumption of panel co-integration tests, contributing to a far more effective measure [117,118]. Hence, this research adopts Pedroni's cointegration testing to verify the longitudinal connection within the panel dataset analyzed. Evaluating the assumption of the null hypothesis of no-cointegration based on Pedroni's cointegration [117,118] reveals a series of multiple testing approaches suitable for achieving robust results. The testing approach of Pedroni [117,118] allows for significant variability. Thus, this co-integration criterion is divided into two categories [117]. The first group uses averaging test statistics for the non-existence of co-integration in cross-section panel data. In contrast, the second category uses component averages established on piecewise denominator and numerator term limits. The succeeding types of regression are considered by Pedroni, as shown in equation (17):

$$y_{it} = \alpha_i + \delta_{it} + \beta_i X_{it} + \varepsilon_{it} \tag{17}$$

Considering the time series panel observables y_{it} and X_{it} represent the values $i = 1, .., N$ for the time $t = 1, .., T$. The variables y_{it} and X_{it} are expected to indicate an integration order of 1, denoted as 1 (I), and the corresponding parameters α_i and δ_i permit the observation of specific impacts and linear dynamics sequentially. Since the individual slope coefficients can differ, the co-integration vectors among the panel members may be heterogeneous in principle. Considering heterogeneous panels, Pedroni presents seven (7) statistics in testing the null hypothesis of the non-existence of co-integration. These categories are of two kinds.

The initial is the panel co-integration tests (within-dimension). The four statistics used for within − dimension testing are panel v − statistic, panel ρ − statistic, panel PP − statistic, and panel ADF − statistic. These statistics pool the autoregressive coefficients through multiple groups based on the estimated residuals for the unit root testing. The final 3 test statistics depend on the "between" dimensions of "the Group." They are group ρ, group PP, and group ADF − statistic. The evaluated residuals from the model emphasized that the regressors are subjected to all seven tests in equation (17). By following the steps of Pedroni [117], heterogeneous distribution and heterogeneous group mean panels are measured based on the cointegration test statistics. The measurement criteria for the co-integration statistics are outlined in equations (18)–(24) as follows:

$$\text{Panel v} - \text{statistic} \quad Z_{ç} \equiv T^2 N^{\frac{3}{2}} \left(\sum_{i=1}^{N} \sum_{t=1}^{T} \widehat{L}_{11i}^{-2} \widehat{e}_{i,t-1}^{2} \right)^{-1} \tag{18}$$

$$\text{Panel } \rho - \text{statistic} \quad Z_{\varsigma} = \left(\sum_{i=1}^{N} \sum_{t=1}^{T} \widehat{L}_{11i}^{-2} \widehat{e}_{i,t-1}^{2} \right) \tag{19}$$

$$\text{panel PP} - \text{statistic } Z_t = \left(\overline{\sigma}_{N,T}^{2} \sum_{i=1}^{N} \sum_{t=1}^{T} \widehat{L}_{11i}^{-2} \widehat{e}_{i,t-1}^{2} \right)^{-\frac{1}{2}} \sum_{i=1}^{N} \sum_{t=1}^{T} \widehat{L}_{11i}^{-2} \left(\widehat{e}_{i,t-1} \Delta \widehat{e}_{i,t} - \widehat{\lambda}_i \right) \tag{20}$$

$$\text{Panel ADF} - \text{statistic } Z_t^{-} \equiv \left(\widehat{S}_{N,T}^{*2} \sum_{i=2}^{N} \sum_{t=2}^{T} \widehat{L}_{11i}^{-2} \widehat{e}_{i,t-2}^{*2} \right)^{-\frac{1}{2}} \sum_{i=2}^{N} \sum_{t=2}^{T} \widehat{L}_{11i}^{-2} \widehat{e}_{i,t-1}^{*} \Delta \tag{21}$$

$$\text{Group } \rho \quad \widetilde{Z}_{\varsigma} \equiv TN^{-\frac{1}{2}} \sum_{i=2}^{N} \left(\sum_{t=2}^{T} \widehat{e}_{i,t-2}^{2} \right)^{-2} \tag{22}$$

$$\text{group PP } \widetilde{Z}_t \equiv N^{-} \frac{2}{2} \sum_{i=1}^{N} \left(\widehat{\sigma}_i^{2} \sum_{t=2}^{T} \widehat{e}_{i,t-2}^{2} \right)^{-\frac{2}{2}} \sum_{i=1}^{T} \left(\widehat{e}_{i,t-1}^{*} \Delta \widehat{e}_{i,t}^{*} - \widehat{\lambda}_i \right) \tag{23}$$

$$\text{group ADF} - \text{statistic} \quad \widetilde{Z}_t^{*} \equiv N^{-} \frac{2}{2} \sum_{i=1}^{N} \left(\sum_{t=2}^{T} \widehat{s}_i^{*2} \widehat{e}_{i,t-1}^{*2} \right)^{-\frac{2}{2}} \sum_{i=1}^{T} \widehat{e}_{i,t-1}^{*} \Delta \widehat{e}_{i,t}^{*} \tag{24}$$

where:

$$\widehat{\lambda}_i = \frac{1}{T} \sum_{s=1}^{k_i} \left(1 - \frac{s}{k_i + 1} \right) \sum_{t=s+1}^{T} \widehat{\mu}_{i,t} \widehat{\mu}_{i,t-s}, \widehat{s}_i^{2} = \frac{1}{T} \sum_{t=s+1}^{T} \widehat{\mu}_{i,t}^{2}, \overline{\sigma}_i^{2} = \widehat{s}_i^{2} + 2\widehat{\lambda}_i, \overline{\sigma}_{N,T}^{2} = \frac{1}{N} \sum_{i=1}^{N} \widehat{L}_{11i}^{-2} \widehat{\sigma}_i^{2},$$

$$\widehat{s}_i^{*2} = \frac{1}{T} \sum_{t=s+1}^{T} \widehat{\mu}_{i,t}^{*2}, \widetilde{s}_{N,T}^{*2} = \frac{1}{N} \sum_{i=1}^{N} \widehat{s}_i^{*2}, \text{and } \widehat{L}_{11i}^{-2} = \frac{1}{T} \sum_{t=1}^{T} \widehat{\eta}_{i,t}^{2} + \frac{2}{T} \sum_{s=1}^{k_i} \left(1 - \frac{s}{k_i + 1} \right) \sum_{t=s+1}^{T} \widehat{\eta}_i \widehat{\eta}_{i,t-s}$$

Additionally, $\widehat{\mu}_{i,t}$, $\widehat{\mu}_{i,t}^{*}$ and $\widehat{\eta}_{i,t}$ are quantified from $\widehat{\varepsilon}_{i,t} = \widehat{\gamma}_i \varepsilon_{i,t-1} + \widehat{\mu}_{i,t}, \widehat{\varepsilon}_{i,t} = \widehat{\gamma}_i \widehat{\varepsilon}_{i,t-1} + \sum_{k=1}^{k_i} \widehat{\gamma}_{i,k} \Delta \widehat{\varepsilon}_{i,t-k} + \widehat{\mu}_{i,t}^{*}$ and $\Delta y_{i,t} = \sum_{m=1}^{M} \widehat{b}_{mi} \Delta x_{mi,t} + \widehat{\eta}_{i,t}$, accordingly. $\widehat{L}_{11i}^{-2}$ represents the long-term conditional asymptotic covariance matrix for the residuals $(\Delta \widehat{\varepsilon}_{i,t})$ whereas $\widehat{\sigma}_i^2$ and $\widehat{s}_i^2$ denote the individual longitudinal variations that occur contemporaneously in the residuals $(\widehat{\varepsilon}_{it})$. Furthermore, Pedroni [117] realized that under appropriate mean and variance corrections, the standardized panel and group mean statistics for cointegration achieve the asymptotical normality distribution. Hence, the respective test statistic is adjusted to be evenly distributed $N(0,1)$ based on the null hypothesis. These adjustments hinge on the regressors' quantity and the test statistics' trend.

3.4.4. *Long-term estimation modeling*

This research adopted three econometric approaches for analysis to confirm the longitudinal correlation among the series. The subsequent three modeling estimation approaches are utilized to determine the longitudinal and short-term interconnection of the variables and robustness check. These models include FMOLS, DOLS, and PMG, used at different levels to ensure the study results are accurate, robust, and consistent [146–149]. The FMOLS estimation approach is adopted in this study to comprehensively eliminate endogeneity, heteroskedasticity, and serial correlation [117,118]. The core objective of adopting the FMOLS is its effectiveness in yielding accurate estimations, robustness, and unbiased findings. The mathematical procedure of quantifying FMOLS is demonstrated in equation (25).

$$\text{FMOLS}_{\text{Estimator}} = N^{-1} \sum_{i=1}^{N} \left[\left(\sum_{t=1}^{T} (Z_{i,t} - \overline{Z}_i)^2 \right)^{-1} \left(\sum_{t=1}^{T} (Z_{i,t} - \overline{Z}_i)^2 \widehat{ENVP}_{it} - T\widehat{\beta}_i \right) \right] \tag{25}$$

Where the coefficient of the series is denoted by β, $\widehat{ENVP}_{it}$ represent the dependent variable environmental pollution concerning time t, and i represents the series of the nations.

3.4.5. *Robustness testing adopting PMG and DOLS*

This study employs the PMG and DOLS estimation modeling for robustness check based on the maximum likelihood strategies, which is assumed as the disturbance error ε_i and considered normally distributed [146,147,149,150]. The maximum likelihood for the panel data is estimated as the product of every represented group [149]. Thus, it ensures that the targeted parameters have a long-term impact, and the coefficients can be adjusted based on the log-likelihood functioning mechanism. The mathematical structure of the PMG is expressed in equation (26)

$$PMG_{Estimator} = l_T(\varphi) = -\frac{T}{2}\sum_{i=1}^{N} ln\ 2\pi\sigma_i^2 - \frac{1}{2}\sum_{i=1}^{N}\frac{1}{\sigma_i^2}(\Delta y_i - \varphi_i\xi_i(\theta))' H_i(\Delta y_i - \varphi_i\xi_i(\theta)) \tag{26}$$

where

$$H_i = I_T - W_i\left(W_i' W_i\right)^{-1} W_i',\ \varphi = (\theta'\varphi'\sigma')',\ \varphi = (\varphi_1\varphi_2, \ldots, \varphi N)',\ and\ \sigma = \left(\sigma_1^2\sigma_2^2, \ldots, \sigma_N^2\right)'$$

Finally, the dynamic ordinary least squares (DOLS) panel approach was also employed for the estimation and robustness check of the series. Thus, when panel DOLS is employed, analyzing panel datasets with time series trends and cross-sectional dependence dimensions is vital. Hence, extant studies have adopted the standardized panel DOLS estimator methodology to measure the robustness of their variables accordingly [146,147,150]. Notwithstanding the asymptotic bias and dependence on non-confirming parameters connected with the distribution OLS, the DOLS panel data is targeted to correct the anomalies and yield robust findings [151]. This present study outlines the mathematical structure of the panel DOLS in equation (27) adapted from Ref. [151]:

$$\mathrm{DOLS_{Estimator}} = \mathrm{Q}_{\prime} = \mathrm{X}_{\prime}\mathrm{M}' + \sum_{i=-m}^{i=m}\varphi_i\Delta\mathrm{P}_{\prime-\prime} + \sum_{i=-n}^{i=n}\psi_i\Delta\mathrm{Y}_{\prime-\prime} + \sum_{i=-l}^{i=l}\theta_i\Delta\mathrm{A}_{\prime-\prime} + \varepsilon_{\prime} \tag{27}$$

where $M = [c, \alpha, \beta, \gamma], X = [1, P, Y, A]$ and m, n *and l are the lengths of leads and lags* of the regressors. Therefore, Q is assumed to be $\mathrm{I}(1)$, and with other study variables, $\mathrm{I}(1)$ or $\mathrm{I}(0)$; hence, the DOLS estimation in this study is obtained through regression analysis as expressed in equation (27). In this study, P represents ENVP, Y defines ENC, and A means ENVTI and the other independent variables accordingly.

3.4.6. Panel causality analysis

In analyzing the causality connection of the series, the novel granger causality test was employed to determine the association of one series to the other [53,120]. The novel strategy of analyzing causality interaction assists in addressing the tendency of CSD and detecting whether slope variation exists within the study model [120]. The novel Dumitrescu and Hurlin (DH) causality testing emphasizes the null hypothesis of the series to exhibit no causal interconnection [53,120,152]. Nevertheless, the alternative hypothesis emphasizes that there should be a causal connection within the model. The mathematical expression revealing the DH non-causality connection is shown in equation (28).

$$\mathrm{Y_{it}} = \alpha_i + \sum_{m=1}^{M}\psi_i^m, \mathrm{Y_{i(m-t)}} + \sum_{m=1}^{M}\lambda_i^m, \mathrm{Z_{i(m-t)}} \tag{28}$$

therefore, the symbol m denotes the lag length, while ψ_i^m demonstrate the series parameters of the autoregressive modeling.

4. The empirical results and discussions

The descriptive statistical results of the variables selected for the African countries for the period spanning 2000 through 2020 are presented in Table 2. The results from the series of the countries are furnished with diverse measurements, including the standard deviation, mean, median, skewness, kurtosis, minimum, maximum, and probability values, among others. The mean values of the series are lnENVP (32906.53), lnECG (2952.381), lnECG2 (2491.499), lnFID (47.84898), lnENC (836.7561), lnENVTI (133.3282), lnTROP (73.83528), and lnURB (32.47475). Additionally, the results reveal a high standard deviation for most of the variables analyzed. Thus, the average values of the standard deviation show lnENVP (82916.83), lnECG (3181.614), lnECG2 (1179.320), lnFID (12.79335), lnENC (777.1760), lnENVTI (243.4503), lnTROP (38.41193), and lnURB (11.61942). The minimum and maximum values of the dependent variable ENVP are (0.425820) and (447980.0). These exciting findings are in unison with these studies [10,19,89,108].

Table 2
Descriptive statistical results.

	lnENVP	lnECG	lnECG2	lnFID	lnENC	lnENVTI	lnTROP	lnURB
Mean	32906.53	2952.381	2491.499	47.84898	836.7561	133.3282	73.83528	32.47475
Median	5050.000	1419.120	2353.921	48.23323	493.1301	45.00000	62.88852	33.28027
Maximum	447980.0	15913.95	7523.409	86.73759	3203.971	1353.000	225.0231	66.60059
Minimum	0.425820	258.6288	585.8707	0.000000	69.95974	1.000000	20.72252	11.90475
Std. Dev.	82916.83	3181.614	1179.320	12.79335	777.1760	243.4503	38.41193	11.61942
Skewness	3.634741	1.643401	1.525733	−0.334911	1.816999	2.956594	1.570881	0.214247
Kurtosis	16.01100	5.491075	6.564363	5.894095	5.033339	11.18274	5.711756	2.715941
Jarque-Bera	5247.854	401.8262	520.1311	208.4776	409.6672	2407.933	406.9238	6.244009
Probability	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.044069
Sum	18658002	1674000.	1412680.0	27130.37	474440.7	75597.08	41864.60	18413.18
Sum Sq. Dev.	3.89E+12	5.73E+09	7.87E+08	92637.14	3.42E+08	33545710	835119.7	76416.25
Observations	567	567	567	567	567	567	567	567

Furthermore, the statistical testing results, including the probability value (p-value), kurtosis, and Jarque Bera for the series, revealed the normality of the data analyzed, as shown in Fig. 1. Thus, the panels (A-H) in Fig. 1 indicate the trend of normality distribution of the variables, including CO_2 emission surrogated as environmental pollution, economic growth, energy consumption, foreign direct investment, economic growth squared, environmental technology innovation, trade openness and urbanization accordingly, based on the quantile-to-quantile plot (Q-Q plot). The statistical findings in Table 2 show that the series is characterized by heterogeneity and non-normal distribution. Thus, the study results show heterogeneity in the data used for analysis due to the significant variations in the maximum and minimum values. Fig. 2 reveals the trend comparison for panels (A-H) of the respective nations, including CO_2 emission represented as environmental pollution, economic growth, energy consumption, foreign direct investment, economic growth squared, environmental technology innovation, trade openness, and urbanization respectively. Interestingly, the trend of CO_2 emission in Fig. 2 proxied as ENVP showed that four African countries, comprising South Africa, Egypt, Nigeria, and Morocco, are economies with higher ENVP. This result is in unison with this research [10,153,154]. Also, Fig. 2 further indicates

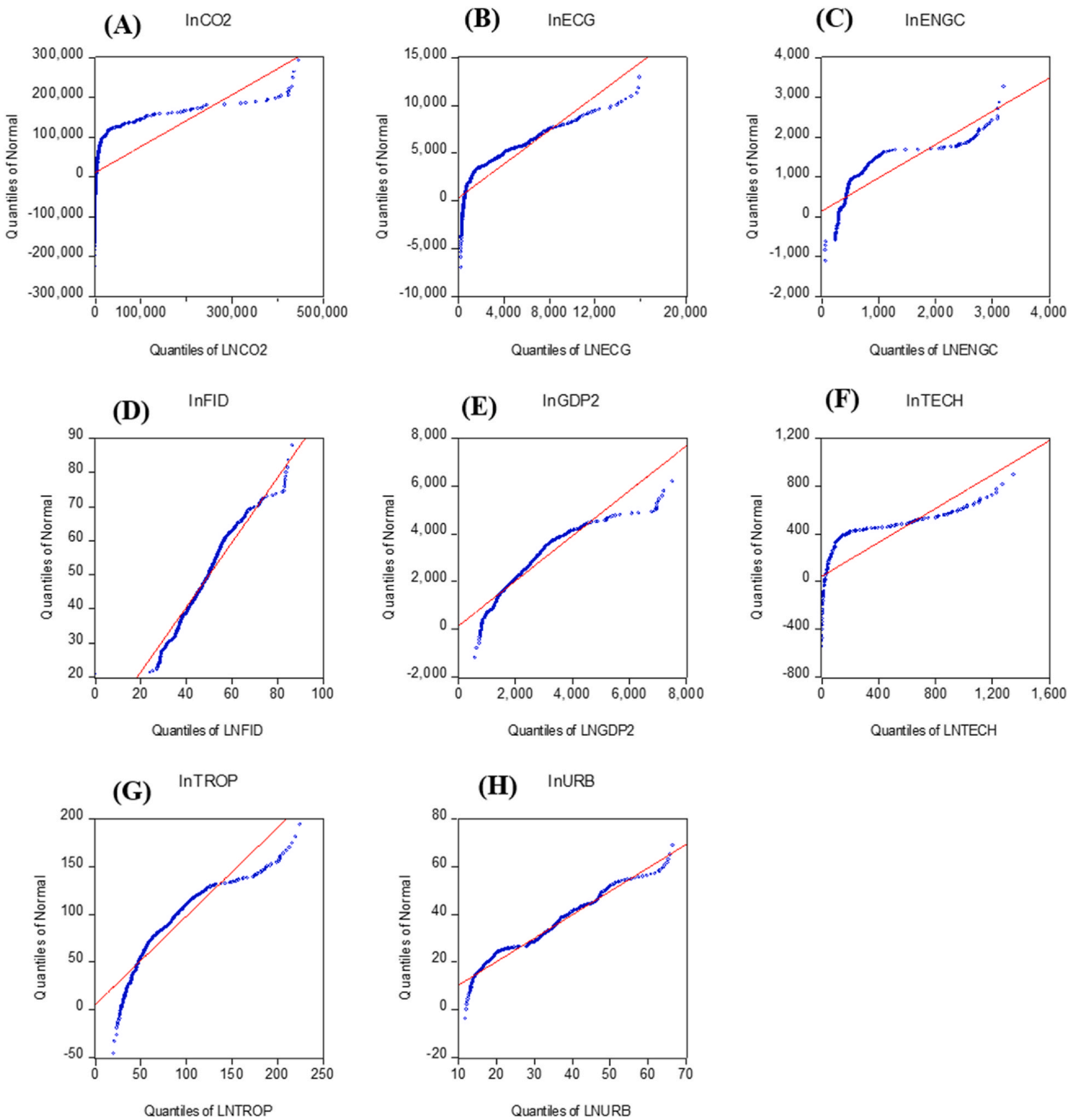

Fig. 1. Q–Q plot for the trend of normality distribution of the selected variables.

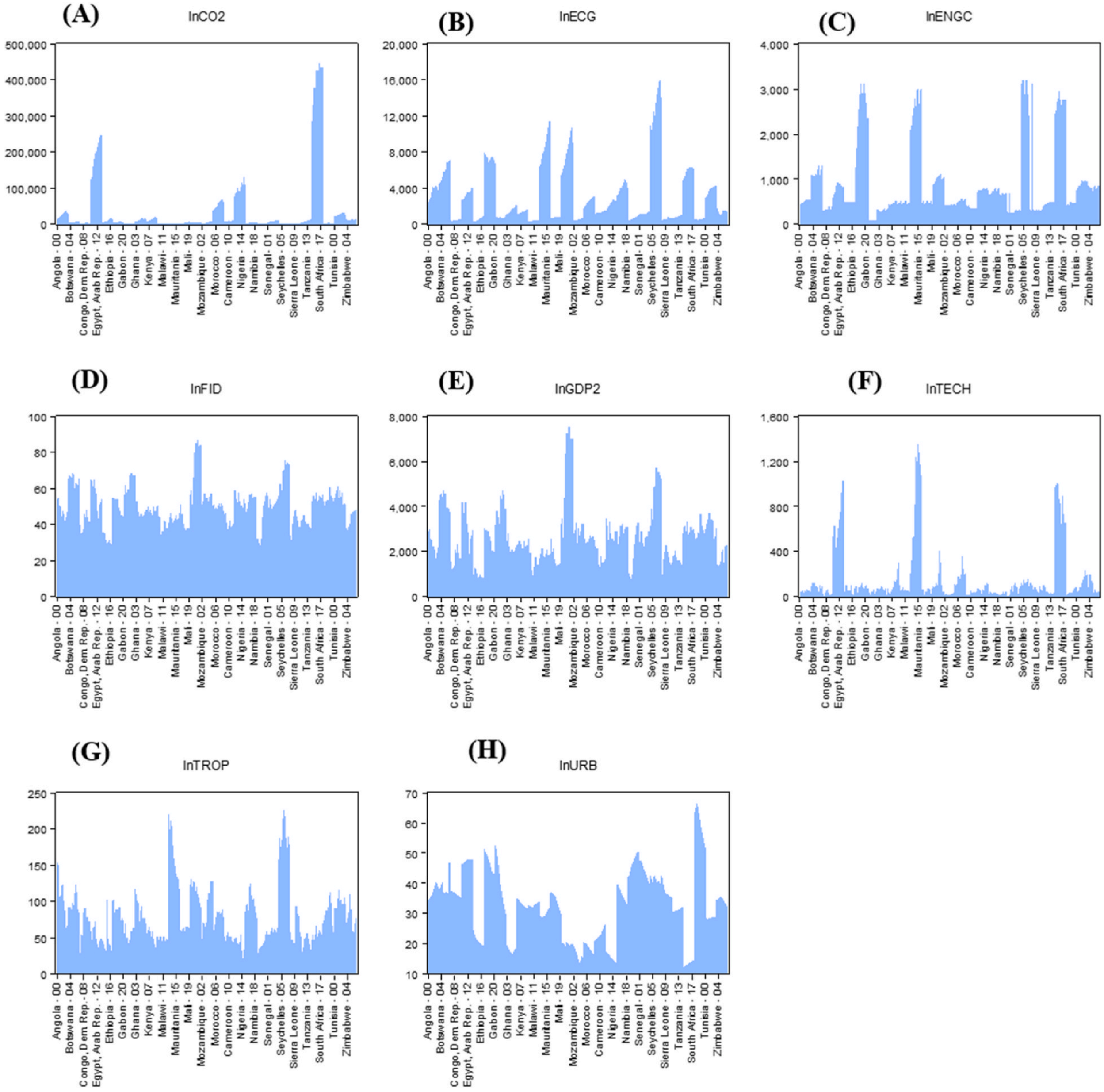

Fig. 2. Trend of development of the selected variables in the African countries.

Table 3
The cross-sectional dependence test findings.

Series	Breusch-Pagan LM	Pesaran scaled LM	Biased-corrected scaled LM	Pesaran CD
lnENVP	4158.584***	143.7080***	143.0330***	55.61576***
lnECG	4824.993***	168.8600***	168.1850***	52.45064***
$lnECG^2$	1577.270***	46.28259***	45.60759***	2.941127***
lnENC	2166.452***	68.51981***	67.84481***	16.04812***
lnFID	1654.812***	49.20920***	48.53420***	6.805024***
lnENVTI	819.5083***	17.68271***	17.00771***	0.936162***
lnTROP	1370.796***	38.48971***	37.81471***	9.358591***
lnURB	4524.367***	157.5136***	156.8386***	2.332315***

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

the exciting development concerning the growth pattern in the economies regarding ECG, ENC, FID, ECG^2, ENVTI, TROP, and URB. Therefore, the authors suggest that policymakers in the respective countries should strengthen the decarbonization policies to achieve zero emissions in their pursuit of economic prosperity [2,3,10,28].

Cross-sectional dependence testing results.

Extant research has demonstrated that an attempt to ignore CSD testing renders the study findings unreliable, biased, inconsistent, and inaccurate [8,155–157]. Hence, this research presents four critical CSD approaches for analysis to address the obstacles inherent in CSD. The empirical results of the CSD derived from Pesaran CD, Breusch Pagan, Pesaran scaled LM, and Bias-corrected scaled LM are revealed in Table 3. The assumptions of the CSD indicate that in estimating panel data based on CSD, a significant p-value found within the data signifies that the null hypothesis needs to be rejected, as shown in Table 3. Therefore, the findings of these four tests give credence to rejecting the null hypothesis indicating the existence of the CSD within the series of cross-sections at a 1% significance level. Hence, this study concludes that the selected African nations are interconnected regarding externalities, trade, technological innovation, economic prosperity, and financial development [10,46,158,159]. Additionally, the findings demonstrate the heterogeneity slope testing characteristics as indicated in Table 3. Therefore, the existence of CSD and the corresponding impact on slope heterogeneity coefficients is theoretically demonstrated as the first-generation unit root testing is not ideally appropriate for the modeling of this study [117]. Hence, the authors of this study applied the second generational unit root testing approach.

Panel stationarity checking

Following the examination and the existence of CSD with the study variables, the current study deems it appropriate to check the integration order and stationarity levels of every variable under investigation. Hence, this research analyzed two relevant second-generational panel unit roots: the CIPS and CADF [7–9]. Fascinatingly, it is worth noting that the series lnENVP, lnENVTI, lnECG, $\ln ECG^2$, lnENC, lnFID, lnTROP, and lnURB were non-stationary at the level. Notwithstanding, the subsequent tests based on the first differences became integrated at order one I(1), suggesting that all the variables were transformed to stationarity [7–10]. Premised on this fascinating result, it demonstrates that the approach employed in this research can facilitate examining the long-term cointegration connection. Table 4 reflects the panel stationarity testing approaches employed for analyzing the series and the respective order of integration.

4.1. *Pedroni and Kao cointegration testing results*

This study employed the panel cointegration approaches of Pedroni and Kao [118,119] for analysis. The findings of the Pedroni's panel v-statistics, panel rho-statistics, panel Phillips, panel ADF-statistics and Perron (PP) (within dimension) statistics and their corresponding (between dimensions) statistic including group rho-statistics, group PP-Statistic, and group ADF-statistic are indicated in Table 5. Based on the findings, seven of the 11 testing results refute the null hypothesis of no cointegration among the series. Therefore, based on the testing approaches, the researchers concluded that cointegration exists among the series lnENVP, lnENVTI, lnECG, $\ln ECG^2$, lnENC, lnFID, lnTROP, and lnURB [117–119]. Furthermore, the Kao panel cointegration test was employed as the robust approach. The findings of the Kao cointegration with t-statistic (−5.344159) and p-value (0.0000) also confirm cointegration among the series. This exciting finding demonstrates that the variables move in tandem in the long run, and their long-run interrelationship is estimated by employing the FMOLS. The exciting discovery in this research gives credence that the series analyzed exhibits cointegration [2,3,10,35].

The results of Westerlund panel cointegration testing.

This study further used the Westerlund [116] cointegration for analysis. The cointegration approach of Westerlund [116] is composed of two-group statistics and two-panel statistics with their corresponding probability values. Thus, the longitudinal connection of the series was estimated based on the Westerlund error correction mechanism cointegration approach, as depicted in Table 6 [116]. Hence, the two categories G_t and G_a and two panels P_t and P_a are revealed in Table 6 [116]. The results show that three out of the four p-values are statistically significant at 1%. Thus, the Westerlund cointegration affirms the long-term cointegration connection of the series lnENVP, lnENVTI, lnECG, $\ln ECG^2$, lnENC, lnFID, lnTROP, and lnURB in the selected African nations. Therefore, the findings give credence to the long-term relationship in the chosen African economies' variables analyzed in this research.

Table 4
The testing results of CIPS and CADF.

	CIPS		CADF		
Series	Level	First difference	Level	First difference	Order of integration
lnENVP	1.10035	−6.30228***	41.7478	134.791***	I(1)
lnECG	1.05229	−3.01100**	42.8879	105.180***	I(1)
LnECG2	−2.41688	−12.7746***	76.7081	258.643***	I(1)
lnENC	−3.42567	−10.7991***	90.7556	218.353***	I(1)
lnFID	0.33003	−6.67234***	47.8470	169.118***	I(1)
lnENVTI	−2.18797	−13.9582***	81.2401	287.767***	I(1)
lnTROP	−1.23465	−11.1800***	67.3667	225.470***	I(1)
lnURB	−5.83412	−5.05387***	159.828	314.100***	I(1)

Note: *** and ** represent 1% and 5%, accordingly.

Table 5
The Kao and Pedroni cointegration testing results.

[117,118] cointegration residual testing results		
within dimensions	**Statistics**	**P-value**
Panel v-Statistic	−0.444505	0.6717
Panel rho-Statistic	2.793162	0.9974
Panel PP-Statistic	−5.792253	0.0000***
Panel ADF-Statistic	−5.731402	0.0000***
weighted statistics	**Statistics**	**P-value**
Panel-v-Statistic	−2.370586	0.0911*
Panel rho-Statistic	4.262604	1.0000
Panel PP-Statistic	−1.277726	0.0107*
Panel ADF-Statistic	−1.707417	0.0439*
between dimensions	**Statistics**	**P-value**
Group rho-Statistic	6.188845	1.0000
Group PP-Statistic	−3.006569	0.0013**
Group ADF-Statistic	−1.682521	0.0462*
[119] **panel cointegration testing result**		
	t-statistic	**p-value**
ADF	−5.344159	0.0000***

Note: Lag length was chosen based on the SIC criterion. Therefore ***, **, and * signify 1%, 5%, and 10% statistical significance accordingly.

Table 6
The Westerlund panel cointegration results.

Statistics	G_t	G_a	P_t	P_a
Values	−4.0663	−10.0151	−9.4134	−12.7182
Z-values	−3.7892	−0.0173	−4.0133	−1.0523
P-values	0.0000***	0.2926	0.0000***	0.0000***
Robustness of P-values	0.0040	0.0006	0.0000	0.0002

Note: *** signifies the statistical significance of 1%.

4.2. Estimation of the long-run elasticities

The long-run interconnection of the series parameters was estimated by adopting the FMOLS, while the robustness checks were conducted using DOLS and PMG, as demonstrated in Table 7. The significance of employing these approaches is premised on their propensity to yield equal signs of their respective coefficients [8,10,149,160,161]. They also demonstrate the pooling and averaging effects of the series. Notwithstanding, the level of significance and magnitude may differ. Also, the variance inflation factor (VIF) was utilized to verify multicollinearity issues in the series, as shown in Table 7. The dependent variable is ENVP, and the independent variables are ECG, ECG^2, ENC, FID, TROP, ENVTI, and URB. The variables' results and their long-term connection are indicated in Table 7.

Based on the study hypothesis, ECG has a positive influence on ENVP. The FMOLS long-run estimation analysis supports the hypothesis that ECG is statistically significant and positively influences ENVP. Thus, a 1% change in ECG will lead to an increase in ENVP of about 0.792%. Contrarily, ECG^2 is statistically significant, albeit demonstrated a negative connection to ENVP. The fascinating finding reveals that as income increases in the respective countries, ENVP decreases. Thus, the exciting findings support the inverted U-

Table 7
Results of full panels of FMOLS long-run elasticity, PMG, and DOLS robustness, and VIF.

Dependent	variable:	ENVP	(CO_2)							
Variables		FMOLS			PMG			DOLS		VIF
	coefficient	t-Statistics	p-value	coefficient	t-Statistics	p-value	coefficient	t-Statistics	p-value	
lnECG	0.7921***	0.8378	0.0000	1.5278**	1.0294	0.0037	6.3323***	6.027389	0.0000	1.4536
lnECG2	−0.5447***	−0.4596	0.0000	−9.4370*	−2.3817	0.0076	−9.4237*	−1.9863	0.0479	1.8449
lnENC	0.5606***	2.6710	0.0000	3.6904***	7.0664	0.0000	5.3701**	3.1061	0.0021	1.1722
lnFID	0.6370***	0.1372	0.0000	5.6144*	2.1379	0.0330	4.3752	0.9757	0.3299	1.5939
lnENVTI	−0.7772***	−1.0669	0.0065	−5.1084***	1.3162	0.0000	−5.079*	2.4542	0.0147	1.1081
lnTROP	0.6009*	2.2268	0.0264	1041.007***	2.3536	0.0000	0.7546*	0.4515	0.0519	1.1703
lnURB	−0.5286***	−0.6128	0.0000	−1.6121***	−6.6552	0.0000	−7.9852	−0.2427	0.8083	1.0576
Turning point of EKC in US$	5753.599			7634.959			12,855.69			

Note: The significance level is represented by ***, **, and * for 1%, 5%, and 10%.

shape connection of EKC and the STIRPAT assumptions in the chosen economies [8,10,12,20,38]. Therefore, a 1% change in ECG^2 will support the decline of ENVP by about 0.545% in the selected countries. Thus, the evidence of EKC in the chosen countries demonstrates that preceding measures had determined the dependence of long-term ECG in curbing ENVP from TROP, FID, and ENC [8,17,52].

Furthermore, the present study examined the economies' income threshold turning points after ENVP started to dwindle. The down segment of Table 7 reveals the turning point values ranging from USD 5753.599 to USD 12,855.69. Premised on these fascinating findings, it demonstrates that some of the chosen economies have reached the threshold of the turning point [10]. Thus, these economies are trending toward implementing effective decarbonization measures due to income expansion [7,8,17,20,52]. Nevertheless, economies that have not adequately attained the income threshold must expedite actions to increase their income levels to intensify ENVP prevention mechanisms. This study found a high-income rise in Mauritius, Seychelles, Botswana, Namibia, and Gabon. Contrarily, the study found that economies, including Egypt, Nigeria, Tanzania, Ghana, Rwanda, Mozambique, Sierra Leone, Kenya, Congo, Mali, Gambia, Ethiopia, Togo, and others, are gradually progressing to the income threshold. Therefore, it is hopeful that these economies will combine effective mechanisms to harness ECG, ENVTI, TROP, and FID to decouple ENVP by sensitizing the populace's knowledge on the merit of living in a quality environment and attaining sustainable development goals [10,99].

Based on the research hypothesis, this study examined the connection linking ENC and ENVP. The empirical findings reveal that ENC is statistically significant and positive. Thus, a 1% variation in ENC may contribute about 0.561% in ENVP if all other things keep unchanged. Therefore, there is a need for effective government policies to control the trajectory of ENC in the respective countries. This finding agrees with these studies [8,87].

Also, this study explored the nexus link between FID and ENVP premised on the study's hypothesis. The findings support the research hypothesis demonstrating that the connection linking FID to ENVP is statistically significant and positive. Thus, a percentage change in FID will contribute to the trajectory of ENVP by about 0.637% within the long term. Based on this interesting finding, it is suggested that policymakers take the necessary precautionary measures to harness FID while curbing its influence on ENVP. This finding is in harmony with this study [39,41]. Thus, in ensuring a positive FID that culminates in reducing ENVP, the respective countries' governments must implement credit facilities and other funding network frameworks to boost citizens' access to financial support to expand their businesses while controlling the elements that increase ENVP.

Further, this study examined the long-term connection linking ENVTI to ENVP based on the research hypothesis and revealed a statistically significant but inverse link between ENVTI and ENVP. This finding indicates that ENVTI negatively influences ENVP and can potentially reduce aggregate emissions in the chosen economies. Therefore, it is apparent that a percentage change in ENVTI may decrease ENVP by 0.777% in the long run. The economic insight linking these exciting results is that efficient and eco-friendly technologies used in the respective nations will produce less pollution and vice versa [162]. Thus, studies have demonstrated that the influence of ENVTI help to streamline ENVP [3,28,55,85]. Hence, the ENVTI approaches used within an economy may depict the trajectory of ENVP control. Thus, environmental-related issues are significantly controlled through income expansion, eco-friendly technologies, and economic development. The current finding is in unison with previous studies analyzing ENVTI from the perspective of EKC assumption and STIRPAT on ENVP [8,10,12,20,38].

Again, this research investigated the longitudinal connection of TROP to ENVP based on the study's hypothesis. The findings reveal that TROP is statistically significant and positive and contributes to the increase in ENVP, which validates the research hypothesis [59,75,163]. This study finding is in unison with these studies emphasizing that the effect of trade as a result of import and export to and from diverse jurisdictions impacts the environment quality and leads to ENVP [24,77,82,93]. Besides, some earlier studies have revealed that when countries streamline their import and export activities connecting to trade, it may help to determine the direct influence of TROP on ENVP within an economy [24,77,82,93]. Therefore, this research proposes that policymakers institute vibrant and eco-friendly policies for manufacturers and trade partners in importing and exporting products with higher pollution to achieve environmental quality in the economies.

Moreover, the current study also analyzed the long-term connection of urbanization to the trajectory of ENVP in the chosen economies. Based on the study's hypothesis, it was found that URB has an inverse effect on ENVP. Therefore, the findings of this research give credence to the stated assumption. Thus, the outcome reveals that a 1% change in the trajectory of URB will lead to a decline of ENVP by 0.528%. Hence, this study put forward that policymakers should assist in streamlining urban population areas in the selected economies by upgrading renewable energy use to ensure a faster decline of ENVP and support the economies' long-term development [90,91].

Furthermore, the populace in both rural and urban areas must be encouraged to utilize eco-friendly energies and production technologies with zero emissions to enhance ECG and reduce ENVP [90,91]. Further, Africa is one of the continents experiencing a speedy ECG, attracting tourists and business engagement; therefore, implementing quality environmental policies would expand the growth of URB [10]. Also, the inverse connection of URB on ENVP suggests that a streamlined development of the urban centers alongside environmental awareness and educational policies may increase the judicious use of resources that will help reduce ENVP in the economies [10,20,88,99]. Therefore, this research proposes that intensifying formal and informal education programs in urban economies will ensure the reduction of ENVP. This exciting result is in harmony with this research [90,91].

4.3. Results for robustness testing adopting PMG and DOLS

In connection with the exciting findings from the FMOLS long-run connection analysis, the DOLS, and PMG robustness statistical findings indicated that the results of this research are more robust and reliable, and their values exhibit similar signs, as demonstrated in Table 7. Thus, applying these three models for analysis reveals their effectiveness in addressing heterogeneity and CSD issues [98,164]. Another exciting and novel validation of this research findings is estimating the variance inflation factor (VIF) to verify the existence of the problems relating to multicollinearity, as indicated in Table 7. Thus, the results show that all the VIF estimates are below the value of 10. Hence, the exciting results authenticate the robustness of the research findings and demonstrate the non-existence of multicollinearity. This research further presents the empirical results in graphical form, as shown in Fig. 3.

Panel causality analysis of Dumitrescu and Hurlin.

Fascinatingly, the analysis of the FMOLS, PMG, and DOLS approaches employed in this research was geared toward the longitudinal connection and robustness estimations linking the study variables for the economies. Therefore, research has demonstrated that these approaches do not indicate the causality connection linking these series in panel data analysis [10,39,98,99]. Hence, evaluating the causal relationship of the study variables is crucial for projecting efficient and effective policy measures for policymakers and other stakeholders to achieve economic prosperity and environmental sustainability. Therefore, in achieving this critical objective, the researchers employed a novel strategy efficient for addressing slope heterogeneity issues within cross-sectional variables [165]. Thus, the Dumitrescu and Hurlin (DH) approach is a novel and modernized rendition of the Granger causation testing, which incorporates and integrates slope heterogeneity and CSD factors. The approach of DH causality furnishes the probability values (p-values), W-Stat., and Zbar-Stat. for accurate and precise analysis. Hence, the findings of the DH causation testing are revealed in Table 8. The results indicate a bi-direction Granger causation connection linking ECG and ENVP, between ECG^2 and ENVP, between ENC and ENVP, between FID and ENVP, between URB and ENVP, between ENC and ECG, between URB and ECG, between FID and ENC, between ECG^2 and ENC, between TROP and ENC, between URB and ENC, between ECG^2 and FID, between TROP and FID, between URB and FID, between TROP and ECG^2, between URB and ECG^2, and between TROP and ENVTI.

Nevertheless, there was the existence of a unidirectional causation connection from FID to ENVP, from ENVTI to ENVP, from TROP to ENVP, from FID to ECG, from ECG^2 to ECG, from ENVTI to ECG, from TROP to ECG, from ENVTI to ENC, from ENVTI to FID, from ENVTI to ECG^2, from URB to ENVTI, and from URB to TROP. These exciting results reveal that policies designed to identify and address ENVP, ECG, ENC, TROP, URB, FID, and ENVTI will require alternative strategies due to the bidirectional causation impact on the respective variables. The economic intuition suggests that any extreme variation in ECG, URB, ENC, ENVTI, TROP, and FID shall alter ENVP within the economies and contrariwise. The presence of bidirectional causation linking ENC and ENVP suggests that efficient energy conservation and usage programs may support the reduction of ENVP within the selected African nations [166,167]. Further, the findings of the unidirectional causation among the variables reveal that policy strategies premised on the chosen variables may influence policies aimed at addressing ENVP issues within the selected African economies.

5. Summary and conclusion

This research explored the nexus link of environmental technology innovation, financial development, trade openness, energy consumption, economic growth, and urbanization on environmental pollution in 27 emerging economies. This study theorized on the EKC and STIRPAT model in analyzing the impact of ENVTI, ECG, ECG^2, ENC, FID, TROP, and URB on ENVP. The long-run connection

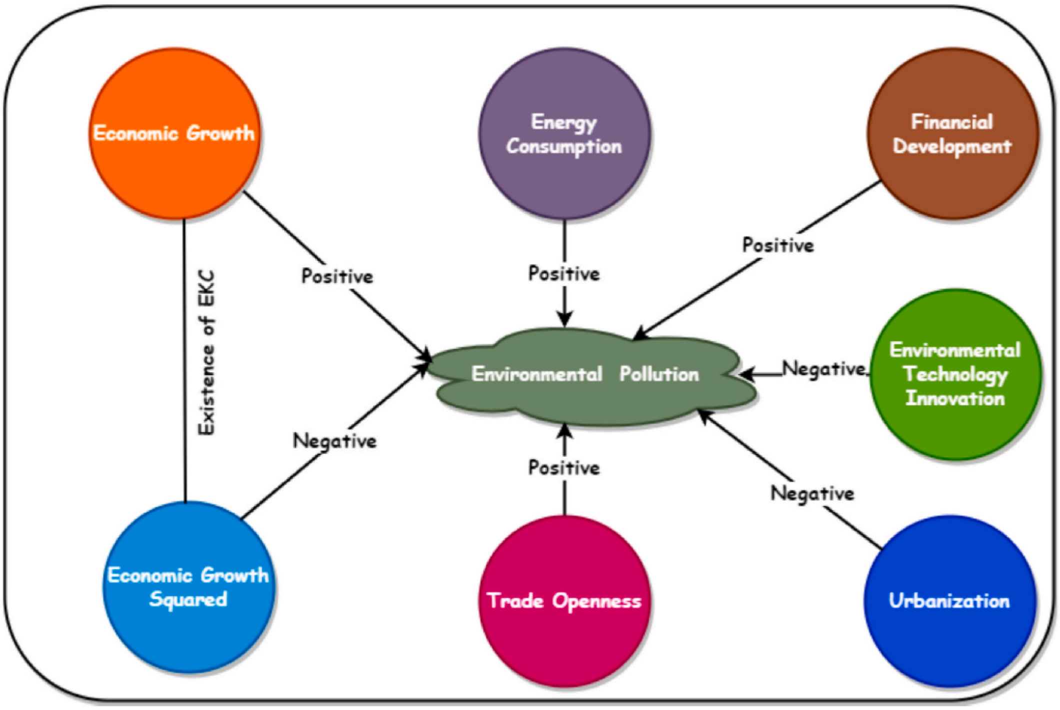

Fig. 3. Graphical representation of the study results.

Table 8
Testing results of Dumitrescu and Hurlin panel causation.

Null hypothesis:	W-Stat.	Zbar-Stat.	P-value	Conclusion
lnENVP ⇎ lnECG	4.77399***	4.59355	0.0000	ECG ↔ ENVP
lnECG ⇎ lnENVP	5.59439***	6.13761	0.0000	
lnENVP ⇎ lnECG^2	2.94166	1.14493	0.2522	ECG^2 ↔ ENVP
lnECG^2 ⇎ lnENVP	2.99458	1.24453	0.2133	
lnENVP ⇎ lnENC	2.23196	−0.19080	0.8487	ENC ↔ ENVP
lnENC ⇎ lnENVP	3.15531	1.54704	0.1219	
lnENVP ⇎ lnFID	7.10676***	8.98403	0.0000	FID → ENVP
lnFID ⇎ lnENVP	2.92816	1.11952	0.2629	
lnENVP ⇎ lnENVTI	6.75940***	8.33026	0.0000	ENVTI → ENVP
lnENVTI ⇎ lnENVP	2.95985	1.17916	0.2383	
lnENVP ⇎ lnTROP	3.42956	2.06319	0.0391	TROP → ENVP
lnTROP ⇎ lnENVP	2.78713	0.85409	0.3931	
lnENVP ⇎ lnURB	4.92546***	4.87862	0.0000	URB ↔ ENVP
lnURB ⇎ lnENVP	6.12272***	7.13197	0.0000	

Note: *, **, and *** demonstrate the significance level at 10%, 5%, and 1% accordingly. The symbol ⇎ represents (does not homogeneously cause), ↔ denotes (bi-directional), and → denotes (uni-directional).

of the series was examined using FMOLS, while the robustness was conducted by adopting the PMG and DOLS estimators. The empirical findings of the FMOLS indicate that ECG, ENC, TROP, and FID significantly increase the trajectory of ENVP. At the same time, ENVTI, ECG^{2,} and URB reduce ENVP within the chosen African economies. Moreover, the inverse connection linking ENVTI, URB, and ECG^2 on ENVP demonstrates that critical policies aimed at enhancing eco-friendly technologies, deurbanization or streamlined urban systems, and long-term economic growth are essential in reducing the trajectory of ENVP within the selected nations. Therefore, the authors project that an effective policy and eco-friendly ENVTI, regulating URB systems or deurbanization, and long-term ECG growth may help stimulate energy consumption, financial development, and trade openness to support environmental pollution control in the economies [10,19,28]. Thus, the debate between ENVTI, ENC, ECG, FID, TROP, URB, and ENVP may be harmonized through a standardized and sustainable development policy initiative by the respective nations [10,19,28]. Furthermore, the high dependence on non-renewable energy products may be substituted with renewable energies to sustain economic development.

5.1. Theoretical implication

The current study employed the EKC theory and the STIRPAT model to extend and build on the analysis of environmental pollution by including recent variables such as environmental technology innovation, trade openness, urbanization, economic growth, financial development, and energy consumption in achieving the objective of this research. The EKC theory and the STIRPAT model furnish an extensive comprehension of the mechanism through which the activities of humanity influence the environment. Applying the STIRPAT and the EKC theory aims to help identify the elements that impact the environment and the factors that may enhance its sustainability and quality in the long run. These theories also provide a statistical approach and conceptual framework in testing the link between the actions of individuals and their repercussions on the environment. The concept underlying this analysis trend is determining the key variables contributing to ENVP and how this impact may be controlled to help conserve the environment. Hence, it is believed that the STIRPAT and the EKC approaches will promote the fundamental understanding of the interplay linking the conservation of the ecosystem and the individuals in an economy.

5.2. Policy implication

The underlined critical policy implications are suggested for controlling ENVP in the selected African economies. Initially, the significant positive influence of energy consumption on ENVP through its higher contributing factor to ENVP demonstrates the need for governments and policymakers to implement pragmatic measures to curb these critical issues. Therefore, this research suggests that the respective governments in the selected African countries concentrate on adopting environmental technology innovation and reducing the consumption of traditional fossil fuels [9,10,158]. Furthermore, investment in advanced and innovative energy efficiency practices will help reduce ENVP. Also, focusing on energy conservation policies and investing in low-carbon areas in the selected regions are critical for controlling ENVP. Additionally, this research recommends patronizing green practices and policies would provide an enhanced alternative to improve the selected African economies' trajectory in controlling ENVP. Moreover, in offsetting the influence of economic growth contribution on ENVP. This study recommends that policymakers support industry-university collaboration to expand technological approaches that facilitate an effective and efficient way of harnessing ECG that contributes to income expansion which may invariably reduce ENVP in the long run, as emphasized in the EKC theory [168,169].

Also, empirical findings from this study revealed that trade openness increases ENVP. Therefore, this research recommends that policymakers institute appropriate measures that support trading activities and would invariably support the reduction of ENVP by adopting renewable energy resources in transporting goods and services [10,17,86]. Further, policymakers must institute stringent measures that support the control of the importation and exportation of high ENVP in the chosen African nation [10]. Policymakers must also implement global collaboration and international agreements policies that focus on controlling ENVP. Moreover, the connection linking financial development and ENVP was also statistically significant and positive in the selected African economies. This research reveals that FID increases ENVP; hence, this study recommends that policies be initiated to effectively harness FID that simultaneously focus on managing waste within and among firms. Therefore, governments must implement sustainable policies for FID that may support addressing ENVP issues in the selected economies.

Again, a statistically significant and inverse connection of urbanization on ENVP was observed for the selected African nations. This suggests that policymakers implement a streamlined urban development policy that supports the control of ENVP within the selected African economies. Thus, policymakers should pursue urban expansion without compromising the fight against ENVP. Moreover, policymakers should encourage smart city development, effective acquisition, and land utilization in addressing ENVP issues in the chosen nations. Furthermore, improving energy efficiency in the selected African countries' industrial and domestic sectors is critical to dissipating urban development from ENVP [7–9]. Further, urbanization improves foreign direct investment and economic openness; policymakers in the selected African economies should adopt advanced technologies and limit obsolete technologies. Moreover, policymakers must strengthen clean energy use policies, reduce costs and address technological disparities in the respective countries to lower the increasing pattern of ENVP.

Additionally, this research found that environmental technology innovation has an inverse connection with ENVP. Therefore, in controlling the influence of ENVTI on ENVP, policymakers in the respective countries may depend on ENVTI as the solid mechanism for controlling ENVP. Also, ENVTI has the benefit of ensuring a conducive and quality environment due to the high investment in green energy adoption and technology innovation to support industries in attaining a competitive standard. Additionally, ENVTI may also support the creation of a larger market due to the higher demand for green products and services; therefore, policymakers should focus on supporting ENVTIs in the various sectors of the selected economies [2,7,8,19]. The authors project that in overcoming the overwhelming trajectory of ENVP, policymakers should incorporate environmentally friendly technology innovation and adopt educational programs into the respective countries' educational systems and curricula. Thus, controlling ENVP in Africa will help ensure economic growth and a sustainable environment that supports environmental technology innovation in realizing the African dream of prosperity [48].

In summary, the selected African economies should pay crucial attention to harmonizing a balance linking economic growth and ENVP; they should firmly oppose unstructured and hasty development culminating in high-level ENVP; and there should be an extensive increase in investment in research and development, green innovation, growth in low carbon technologies as well as industry-university collaboration to help reduce ENVP [168,169].

5.3. Future scope of the research and limitation of the study

This study acknowledges limitations in approach, outcome, and period selected for analysis. As an illustration, the result of this research is focused on a limited panel dataset gathered for the chosen nations, spanning from 2000 through 2020. Future research will expand the period and incorporate other variables such as governance, green innovation, and agriculture. Furthermore, carbon dioxide emission surrogated as ENVP covers some aspects of pollution. Therefore, further research will cover the broader part of the ecological footprint, which covers the fundamental components of pollution for analysis. Also, the authors intend to choose all 54 African countries for research, but we only emphasized 27 of the 54 economies whose data were up to date. Further, studies would be conducted to expand the scope of the investigation to diverse regions and continents.

Author contribution statement

Fredrick Oteng Agyeman: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Emmanuel Adu Gyamfi Kedjanyi; Agyemang Akwasi Sampene; Malcom Frimpong Dapaah; Paul Buabeng: Performed the experiments; Wrote the paper.

Abdul Razak Monto; Guy Carlos Guimatsie Samekong: Performed the experiments; Analyzed the interpreted the data.

Data availability statement

Data included in article/supp. material/referenced in article.

Additional information

Supplementary content related to this article has been publish online at [URL].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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