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RESEARCH ARTICLE

Long-run equilibrium relationship between energy consumption and CO_2 emissions: a dynamic heterogeneous analysis on North Africa

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Abstract

Environmental protection and sustainable development are inextricably linked. This linkage is particularly crucial for North Africa, where the use of carbon-intensive energies has created environmental and economic challenges. Amazingly, limited studies on the connection between energy consumption and environmental quality has been conducted to help with policy options to minimize the above menace in the region. Inspired by the Sustainable Development Goals (SDGs) of the United Nations, this study contributed to filling this gap by examining the energy consumption–CO_2 emission nexus in North Africa for the period 1990 to 2018. In order to account for cross-sectional dependence, endogeneity, and slope heterogeneity that are mostly ignored by some conventional econometric techniques, this exploration adopted second generation econometric methods that are robust to the aforestated issues in its analysis. From the results, the studied panel was heterogeneous and cross-sectionally correlated. Also, the investigated series were first differenced stationary and cointegrated in the long-run. The cross-sectional augmented autoregressive distributed lag (CS-ARDL) and the dynamic common correlated effects mean group (DCCEMG) estimators were adopted to explore the elasticities of the explanatory variables and from the results, energy consumption worsened environmental quality in the region due to its positive influence on CO_2 emissions. Also, urbanization and economic growth increased the rate of CO_2 emissions in the countries. On the causal connections amid the series, bidirectional causalities between energy consumption and CO_2 emissions, between urbanization and CO_2 emission, between economic growth and CO_2 emissions, and between urbanization and energy consumption were unraveled. Finally, unidirectional causalities from economic growth to energy consumption, and from economic growth to urbanization were confirmed. It is recommended that countries in North Africa should shift to the consumption of clean energies to help them attain low-carbon economy. Unavailability of data for some periods was the major limitation of the study. Therefore, in future when such data become available, similar explorations could be conducted to confirm the robustness of the study's results.

Keywords Long-run equilibrium relationship · Energy consumption · Urbanization · Economic growth · CO_2 emissions · North Africa

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Introduction

The standard of the world's climate has declined significantly due to the increasing level of CO_2 emissions (Jian et al. 2019). As a result, several countries have signed many agreements like that of the Paris (2015) and the Kyoto Protocol (2005). These agreements provide recommendations for countries to adopt in order to minimize CO_2 emissions. According to Hall et al. (2013), more than 190 countries signed to these agreements, promising to significantly reduce the emanation of CO_2 in their environments. Despite their commitments to the above agreements, global CO_2 emissions continue to rise, owing primarily to the high utilization of energy (Sulaiman and Abdul-Rahim 2017). As reported by the International Energy Agency (IEA), the world's energy consumption grew by 2.3% in 2018, which is almost twice the average growth rate since the year 2010. To the body, 70% of global energy is consumed by the USA, India, and China, and that 85% of the world's CO_2 emissions will be accounted for by emerging nations by the year 2030. Also, according to the World Bank (2015), energy consumption particularly, fossil fuel outpaced alternative energy sources including clean and renewable energy, accounting for 79.67% of the world's total figure. This persistent increase in the utilization of energy aggravates the world's CO_2 emissions further, collaborating those of Ozturk and Al-Mulali (2019), Murshed et al. (2021a), Khan and Ahmad (2021), Rahman et al. (2019), Musah et al. (2021a), and Sharif et al. (2019). Amidst such high energy demand and its associated emissions, energy planners often recommend the adoption of energy efficient technologies and the integration of renewable energy sources into the national energy mix (Murshed 2020; Kumar et al. 2010; Yang and Yu 2015). Thus, transiting to energy efficiency and the utilization of renewable energy are the credible means through which pollutant emissions connected to the consumption of dirty energies could be minimized (Sharif et al. 2020a; Ozturk and Acaravci 2010; Murshed et al. 2021b; Ozturk et al. 2016; Koondhar et al. 2021a).

North African countries cannot be left out when discussing issues relating to energy consumption and its adverse consequences on the environment. This is because, most countries in the region are undergoing economic transformations chiefly dominated by activities that are highly reliant on emission-intensive energy sources. Thus, as economic growth in the region increases, so does the rate of pollution due to the consumption of carbon-induced fossil fuels. According to the World Bank (2021), almost two thirds of the CO_2 emissions of North Africa emanates from the consumption of gaseous fossil fuels. This portrays the region's predominant dependence on dirty energies for its economic activities. Shifting to the consumption of renewables is one of the best alternatives to attain low-carbon economy as enshrined in the Paris Agreement (2015) and other international treaties (Ozturk 2015; Murshed et al. 2021c; Ma et al. 2021; Le and Ozturk 2020; Qin et al. 2021), however, North Africa is yet to achieve a higher proportion of renewables in its overall energy mix (World Bank 2021). Thus, if the region is to witness environmental sustainability alongside economic viability, then countries in the bloc should phase-out their monotonic reliance on fossil fuels and should factor the consumption of renewable energies into their energy decisions.

Numerous studies have been conducted on the nexus between energy consumption and CO_2 emissions. The findings are however conflicting due to regional variations, sample characteristics, choice of variables, time frame, and econometric techniques among others. For instance, Ali et al.'s (2018) research on Nigeria, Jian et al.'s (2019) investigation on China, Rahman et al.'s (2019) study on BRIC and NAFTA countries, Nkengfack and Fotio's (2019) exploration on three African nations, and Sulaiman and Abdul-Rahim's (2017) research on Malaysia, all affirmed energy consumption as a significantly positive predictor of CO_2 emissions, while Liu et al.'s (2017) investigation on Asian nations, Solarin et al.'s (2017) study on India, Dong et al.'s (2018) exploration on China, Zoundi's (2017) research on some African countries, and Sinha and Shahbaz's (2018) investigation on India, all confirmed energy consumption as a substantially adverse predictor of CO_2 emissions. Notwithstanding the plentiful studies conducted to examine the connection between energy consumption and CO_2 emissions, studies of such types are limited in North Africa. This exploration was therefore performed to help fill that gap.

The key motivation behind this paper is sourced from the fact that, North African countries are among the largest economies in Africa. Apart from Sudan and Libya that are suffering of late, the other countries are growing faster and have been anticipated to grow faster than some other African economies due to their high volume of economic activities. Accompanying these growths are however worsened environmental quality, labeling North Africa as one of the most polluted regions in the continent. The region's lion share with regard to pollutant emissions could be attributed to their extensive reliance on the consumption of non-renewable energies. Therefore, since North African economies depend traditionally on non-renewable energy sources to back their development activities which end up worsening their environments, it is pertinent for the nations to shift from the conventional energy sources to more renewable sources that could make them sustainable. Hence, taken into consideration the CO_2 mitigation agenda of North Africa and the attainment of the sustainable development goals (SDGs) of the United Nations, particularly, SDG 7 (clean and affordable energy), SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production), and SDG 13 (climate action), it was worthwhile to explore the equilibrium association between energy consumption and CO_2 emissions in the region, so that policy recommendations could be raised to help boost environmental quality in the bloc. Against this backdrop, the study sought answers to the following research questions: (1) How does energy consumption influence CO_2 emissions in North Africa?

(2) What is the causal relationship between energy consumption and CO_2 emissions in North Africa?

Deductions from these questions will propel the nations to invest in green and energy-saving technologies that could help them to achieve low-carbon economy. Also, environmental regulatory bodies and other authorities in the nations can make use of the study's deductions to improve upon their regulatory structures. Discoveries from this exploration will finally serve as a guide for researchers who may conduct similar studies in the future.

Contributively, this paper added to extant literature in three diverse ways. First, countless explorations on the linkage between energy consumption and CO_2 emissions have been conducted on different geographical environments (e.g., Asongu et al. 2020; Pata and Aydin 2020; Danish and Khan 2020; Sharif et al. 2020b; Yang et al. 2020), however, apart from Musah et al. (2021a) who employed the EKC framework to model the connection between energy consumption and CO_2 emissions in North Africa, there has been no other studies on energy consumption–CO_2 emission nexus in the region to the best of our knowledge. Contributing to filling this void, an exploration to examine the nexus between the variables in a dynamic form this time was conducted. Second, our exploration made a methodological contribution by examining the elastic effects of the covariates on the explained variable through the cross-sectional augmented autoregressive distributed lag (CS-ARDL) estimator of Chudik et al. (2016) and the dynamic common correlated effects mean group (DCCEMG) estimator of Chudik and Pesaran (2015). These econometric methods were considered because they are robust to a lot of factors which lead to biased estimates if neglected. Indeed, via trade and other economic activities, it is highly expected that any shock or effect on a member state of North Africa, is likely to have an influence on the other member countries. Also, there is a great variation among the nations with regard to environmental pollution and other macroeconomic factors. It was therefore pertinent to adopt econometric methods that could account for heterogeneity as well as any potential cross-sectional correlations among the countries. This approach is rare to come by after thorough review of available literature on North Africa.

The study finally controlled for urbanization and economic growth in the energy consumption–CO_2 emission linkage because of some special features of North African countries. From the data base of the World Bank, North Africa occupies a substantial position in the globe with respect to urban population. For the past three decades too, majority of countries in the region have been enjoying higher economic growth by transforming their economies from primary agricultural sector to energy-led industrial sector. Therefore, incorporating both variables into the analysis was worthwhile because, according to Ali et al. (2019) and Munir et al. (2020), urbanization and economic growth are correspondingly vital determinants of CO_2 emissions. To the best of our knowledge, there has been no study on the energy consumption–CO_2 emission connection in North Africa that controlled for the above variables except Musah et al. (2021a) which was even not a dynamic study like this present one.

A well outlined roadmap was followed in the study's empirical analysis. First, tests to examine the presence or absence of cross-sectional dependence in the residual terms were conducted. This was then followed by the homogeneity test to assess whether the slope coefficients were homogeneous or not. At the third stage, unit root tests were conducted to determine the integration order of the series. Afterwards, cointegration tests were performed to examine whether the variables were significantly cointegrated in the long-run or not. At the fifth stage, the elasticities of the covariates were explored, while the final stage examined the causal connections amidst the series. Aside the introduction, the other parts of the exploration are arranged as follows. Section 2 presents the literature review, while the third part presents the study's methodology. The fourth section displays the exploration's results and discussions, while the final stage outlines the conclusions and policy recommendations of the report.

Literature review

Energy consumption is the amount of energy consumed by residents or organizations, or to the process or system of such consumption. It also involves all energies related to the industrial and technological sectors of every economy (Lund and Boyd 2016; Nakićenović et al. 1998; Tuominen et al. 2015). The connection between energy consumption and CO_2 emissions have been thoroughly investigated with contradictory discoveries. For example, Murshed and Dao (2020) revisited the CO_2 emission-induced EKC hypothesis in South Asia for the period 1972 to 2014. From the results, energy consumption had a significantly positive influence on CO_2 emissions in the region. Also, the EKC hypothesis was validated only for Bangladesh and India while in the context of Pakistan, the economic growth–carbon dioxide emission nexus demonstrated a U-shaped association. Contrarily, economic growth monotonically decreased CO_2 emissions in Sri Lanka and Nepal. Rauf et al. (2018) investigated the EKC hypothesis in Belt and Road Initiative economies from 1981 to 2016. From MG, CCEMG, AMG, and PMG estimates of the study, energy consumption had a detrimental influence on environmental quality. The EKC conjuncture was also validated in the region supporting that of Koondhar et al. (2021b).

Al-Mulali et al. (2015) conducted a study on Kenya from 1980 to 2012. From the results, fossil fuel energy consumption added to environmental degradation in the country both in the long and the short-run. However, renewable energy consumption improved environmental quality over the same period. Over the period 1980 to 2016, Murshed et al. (2020b) investigated the authenticity of the EKC hypothesis for aggregate and disaggregated greenhouse emissions in the context of six South Asian economies, namely, Bangladesh, India, Pakistan, Sri Lanka, Nepal, and Bhutan. Econometric methods that are robust to structural breaks and cross-sectional dependence were employed in the study's analysis. From the results, LPG consumption homogenously reduced greenhouse emissions in all the studied panels. The EKC hypothesis was also validated for both the aggregate and the disaggregated greenhouse emission figures. Moreover, the country-specific EKC analysis revealed heterogeneity of the EKC findings across the concerned nations. The study recommended that the nations should promote the use of LPG to help them minimize energy crises and simultaneously attain environmental sustainability. Alama et al. (2016) examined the impact of income, energy consumption, and population growth on CO_2 emissions on India, Indonesia, China, and Brazil for the period 1970–2012. From the study's ARDL estimates, CO_2 emissions increased significantly with an increase in energy consumption. Murshed et al. (2020c) researched on 12 members of OPEC from 1992 to 2015. The study suggested that the concerned countries should reduce their monotonic dependency on the consumption of fossil fuels, particularly oil, and should gradually incorporate renewable energy resources into their energy-mix, particularly within their respective service sectors. Li et al. (2020a) analyzed the roles of green investments and other key macroeconomic aggregates in reducing carbon emissions in 30 Chinese provinces from 1995 to 2017. From the CS-ARDL estimates of the study, energy investments increased carbon emissions both in the short and the long-term. On a sample of 47 Emerging Market and Developing Economies (EMDEs), Le and Ozturk (2020) examined the effects of globalization, financial development, government expenditures, and institutional quality on CO_2 emissions, incorporating energy consumption, and GDP per capita in an EKC framework from 1990 to 2014. From the CCEMG, AMG, and DCCE estimates, energy consumption increased CO_2 emissions. Also, the EKC hypothesis was affirmed in the EMDEs. Murshed et al. (2021d) reinvigorated the role of clean energy transition for achieving a low-carbon economy in Bangladesh for the period 1975–2016. From the study's findings, aggregate energy consumption, fossil fuel consumption, and natural gas consumption boosted carbon footprint in the country. However, nonfossil fuel consumption and hydroelectricity consumption were environmentally friendly to the nation. This implies, transitioning to clean energy within the Bangladesh economy could be the panacea to the nation's persistently aggravating environmental hardships. Rehman et al. (2021) studied carbonization and atmospheric pollution in China for the period 1970 and 2017. From the discoveries, CO_2 emissions demonstrated a strong progressive association with the positive shocks to energy resources utilized within the Chinese economy. In order to attain the carbon-neutrality agenda of China, the study recommended that, the country should prioritize the use of renewable energy resources to help boost its environmental quality. Ma et al. (2021) analyzed the impacts of emission taxes, energy investments, research and development expenditure, technological innovation, and tertiary sector development on Chinese provincial CO_2 emissions for the period 1995 to 2019. From the overall findings, provincial growth and tertiary sector development were responsible for CO_2 emission aggravation in China. Contrarily, energy investments, renewable energy use, technological innovation, expenditure on research and development, and carbon emission taxes boosted environmental quality in the provinces. Liu et al. (2021) examined household consumption-induced carbon emissions in China for the period 1995 to 2017. From the results, household consumption raised the level of CO_2 emissions in the country. However, renewable energy consumption and technological innovation reduced the emanation of CO_2 in China. It was therefore recommended among others that household consumption of direct and indirect energy should ideally be sourced from renewable resources whereby their adverse environmental impacts in the country could be minimized. Thus, investments in renewable energy production could be a key energy policy for China.

Yusuf et al. (2020) studied oil producing African countries from 1970 to 2016 and confirmed energy consumption as an immaterial predictor of CO_2 emissions. The exploration is very relevant, however, it will be unfair to generalize its results for all nations in Africa and that of the globe, because it was limited to only oil producing African economies. If other non-oil producing African nations were to be considered in the analysis, the discoveries might have been different. Adebayo and Kirikkaleli (2021) undertook a research on South Africa from 1980 to 2017. From the discoveries, a percentage rise in coal consumption deteriorated the environment by 1.077%, when all other factors were held constant. The study recommended among others that, South Africa should embrace policies that encourage the consumption of renewable energy. This exploration is very vital, however, the interpretation of its outcomes warrants some caution, because it used only coal energy consumption as its variable of interests. If the other components of energy consumption or the aggregate energy consumption was to be considered for the study, the discoveries might not be the same. Osobajo et al. (2020) studied 70 countries for the period 1994 to 2013, and discovered a positive linkage between energy consumption and CO_2

emissions. This disclosure backs the need for a global shift to a low carbon economy, which will aid to boost large-scale investments in clean energy, a requirement to help abate the emissions of CO_2. The above investigation adopted the pooled OLS and the fixed effects regression techniques to examine the elasticities of the covariates. This signposts that, care should be taken when interpreting the study's results, because if other conventional econometric estimators like the FMOLS and the DOLS were to be employed for the study, the results might not be the same as above.

Nathaniel et al. (2020a) studied the MENA region from 1990 to 2016 and discovered that, energy from renewable sources did not add materially to environmental quality. Non-renewable energy on the other hand, escalated the rate of pollution in the region. Adebayo and Kirikkaleli (2021) performed a wavelet analysis on Japan, and confirmed renewable energy as friendly to the country's environment. This finding underscores the importance of instigating policies effectually coordinated by authorities to help abate the level of pollution in the nation. This study is very relevant, however, the interpretation of its findings needs caution, because it adopted the wavelet analytical approach. If other econometric approaches were to be engaged in the analysis, the results might not be the same. Also, only renewable energy was considered for the analysis. This signifies that, the outcome cannot be generalized for the other components of energy consumption. Peng and Wu (2019) conducted a study on 30 provincial regions of China from 2004 to 2016. From the exploration's FMOLS estimates, the long-run elasticity of transport carbon emissions (TCE) to transport energy consumption (TEN) was almost equal to the long-run elasticity of TEN to TCE. This research is very essential, however, its outcome does not represent the entire country, because it was confined to only 30 provinces. If all the provinces in China were to be used for the study, the finding might not be the same as above. Care should also be taken when interpreting the study's outcome, because it was limited to only TCE and TEN. If the other components of carbon emissivities and energy usage were to be considered for the investigation, different results could have been generated.

Nathaniel and Khan (2020) studied ASEAN countries for the period 1990 to 2016. From the AMG estimates of the study, non-renewable energy deteriorated the countries' environment significantly. This indicates that the region is developing to the detriment of its environment. The study recommended among others that, the countries need energy-efficient technologies. According to the authors, this will lead to the attainment of the SDGs by 2030. If the nations continue to consume non-renewable energy, without transiting to renewables, then their ambition of attaining clean environment, alongside economic viability cannot be materialized. The above exploration is very vital; however, it was confined to only the ASEAN region. This signifies that, care should be taken when interpreting the findings. The study also used the AMG estimator to explore the elasticities of the covariates. If other econometric estimators were to be considered for the analysis, the results might have been different. Therefore, in interpreting the study's outcomes, care should be taken. Yang et al. (2021) conducted a research on GCC countries and confirmed energy utilization as detrimental to environmental sustainability. This finding is not different from Osobajo et al. (2020), but varies with that of Danish and Khan (2020). The conflicting outcomes signify that, the argument on the linkage between energy consumption and CO_2 emissions is unceasing and needs more explorations like ours. Usman et al. (2020) investigated 33 upper middle income countries for the period 1994 and 2017. Discoveries of the study confirmed energy consumption as environmentally harmful. This study is very essential, however, it was confined to only 33 upper middle income countries. Therefore, care should be taken when interpreting the results, because if other countries in different income groups were to be included in the sample, the findings might not be the same.

Baz et al. (2020) studied the linkage between energy consumption and environmental quality, and established from the ARDL estimates that, energy consumption added to environmental pollution. It was recommended among others that, advanced and environmentally friendly production technologies, alongside the consumption of energy from renewable sources, should be considered by the investigated economies. The study employed the nonlinear ARDL approach for the analysis. This indicates that care should be taken when interpreting the study's results, because if the linear approach was to be used for the analysis, the results might be different. Yildirim and Yildirim (2021) examined the determinants of carbon effusions in Turkey from 1970 to 2015. From the disclosures, energy usage propagated CO_2 emissions in the country. The study recommended among others that, the government should take action against environmental pollution with efficient policies that save energy and abate the emanation of carbon. This exploration is very vital, however, its results cannot be generalized for all economies, because it was confined to only Turkey. If other countries were to form part of the sample, the findings might not be the same. Alharthi et al. (2021) researched on the MENA region from 1990 to 2015. From the disclosures, renewable energy consumption mitigated CO_2 emissions, while non-renewable energy consumption escalated the emissions of CO_2 in the region. This study is very essential, however, the fact that it was limited to only the MENA region implies, its results should be interpreted with caution.

For the period 1970 to 2016, Nathaniel et al. (2021) conducted a study on South Africa and affirmed energy consumption as harmful to the countries' environmental quality. This research is very relevant. However, it will be unfair to generalize its findings for all nations in the world, because it was limited to only South Africa. If other countries were to be incorporated into the sample, the findings might have been different. Asongu et al. (2020) examine the energy–environment nexus in Africa and confirmed energy utilization as an agent of environmental pollution. This finding collaborates those of Nathaniel et al. (2020b) and Pata and Aydin (2020) but contradicts that of Danish and Khan (2020). These contrasting findings signify that, the energy–CO_2 emission argument is ceaseless and demands for more investigations. Sharif et al. (2020a) conducted a study on Turkey from 1965Q1 to 2017Q4. Adopting the quantile ARDL approach, energy from renewable sources were friendly to the country's environment. This exploration is very vital, however, it will be unfair to generalize its findings for all nations, because it was limited to only Turkey. If other nations were to be included in the sample, the outcome might not be the same. Yang et al. (2020) undertook an exploration on 97 economies and affirmed energy utilization as hazardous to environmental quality. The study was conducted on only 97 countries. Therefore, it will be unfair to generalize its discovery for all nations in the world.

Adebayo et al. (2021a) explored the predictors of consumption-based carbon emissions in Chile from 1990 to 2018. From the study's non-linear ARDL estimates, positive variations in renewable energy consumption enhanced environmental quality in the country. This implies, Chile can improve its environment through the use of energy from renewable sources. The exploration covered the period 1990 to 2018. Therefore, care should be taken when interpreting the study's results, because if a different study period was to be considered for the analysis, the outcome might be different. Also, the fact that the investigation was done on only Chile implies, the outcome cannot be assumed same for all countries in the globe. Further, the non-linear ARDL estimation approach was adopted for the study. If the linear approach was to be engaged for the analysis, the outcome might not be the same. Therefore, in interpreting the study's outcome, serious care should be taken. Appiah et al. (2021) researched on 25 Sub-Saharan African (SSA) countries for the period 1990 to 2016. Employing modern econometric techniques, energy utilization positively predicted the emanation of carbon in the countries. This exploration is very relevant, however, generalizing its findings for the entire SSA region will be unfair, in that, it was confined to only 25 countries. If other nations in the region were to form part of the sample, the outcome might not be the same. Therefore, care should be taken when interpreting the study's finding.

Summarily, numerous explorations have affirmed energy consumption as harmful to environmental quality in different geographical environments (Yang et al. 2021; Adebayo and Kirikkaleli 2021; Appiah et al. 2021 among others), while others have also confirmed energy consumption as beneficial to the environment (Danish and Khan 2020; Adebayo et al. 2021b; Sharif et al. 2020b among others). These contrasting outcomes signpost that the energy consumption–CO_2 emission argument is endless and demands for more investigations. Therefore, an exploration in the context of North Africa was deemed appropriate.

Materials and methods

Theoretical foundation and model specification

To begin with, economic activities like industrialization and business expansion are impossible to accomplish without energy. However, the energies used to carry out the above operations are harmful to the environment since they escalate the emanation of carbon. Therefore, following Phong et al. (2018) and Chen and Lei (2018), energy consumption was considered a predictor of CO_2 emissions. Also, many citizens move to big towns to look for better jobs and better living conditions. This scenario raises the utilization of energy from dirty sources leading to more CO_2 emissions. Therefore, following the works of Ali et al. (2019) and Solarin et al. (2017), urbanization was considered a predictor of CO_2 emissions. Further, nations' primary factors of production improve as economic growth increases. However, the running of those economic activities is heavily reliant on unclean energy sources that escalate the emissions of CO_2. Therefore, following Akadiri et al. (2019) and Ali et al. (2018), economic growth was used as a predictor of CO_2 emissions. Finally, CO_2 emissions were considered a measure of environmental impacts because it efficaciously assesses the performance of the environment. This cites with the works of Rahman et al. (2019) and Sinha and Shahbaz (2018). Based on the above justifications, the following function was proposed for the study:

$$CO2_{i,t} = f\left(EC_{i,t}, URB_{i,t}, GDP_{i,t}\right) \quad (1)$$

Where CO_2 emissions and energy consumption (EC) are the output and input series correspondingly. To help minimize omitted variable bias issues, urbanization (URB) and economic growth (GDP) were introduced into the function as control variables. **Equation 1** was therefore specified in a panel data form as

$$CO2_{i,t} = \alpha_i + \beta_1 EC_{i,t} + \beta_2 URB_{i,t} + \beta_3 GDP_{i,t} + \mu_{i,t} \quad (2)$$

Where β_1, β_2,and β_3 are the parameters of energy consumption, urbanization, and economic growth correspondingly of country i in time t, while $u_{i,\ t}$ and α_i are the residual and constant terms respectively. According to Cook and Weisberg (1983) and Breusch and Pagan (1979), heteroscedasticity leads to invalid and unreliable estimates. To therefore lessen the demerits of heteroscedasticity, all the series in **Eq. 2** were log-transformed. The econometric specification after the log transformations became

$$lnCO2_{i,t} = \alpha_i + \beta_1 lnEC_{i,t} + \beta_2 lnURB_{i,t} + \beta_3 lnGDP_{i,t} + \mu_{i,t} \quad (3)$$

Where $lnCO_2$, lnEC, lnURB, and lnGDP are the log conversions of the explained and the explanatory variables correspondingly. Expectedly, the marginal impact of energy consumption on CO_2 emissions was expected to be positive $\left(\beta_1 = \frac{\partial lnCO2_{it}}{\partial lnEC_{it}} > 0\right)$ if the energy consumed in North Africa was from dirty sources that promoted CO_2 emissions (Bekun et al. 2019; Musah et al. 2021a). Otherwise, energy consumption was to have an adverse influence on CO_2 emissions $\left(\beta_1 = \frac{\partial lnCO2_{it}}{\partial lnEC_{it}} < 0\right)$ if the energy used was from clean sources that mitigated the emissions of CO_2 in the bloc (Zafar et al. 2019; Dong et al. 2018). Also, urbanization was projected to positively influence CO_2 emissions $\left(\beta_2 = \frac{\partial lnCO2_{it}}{\partial lnURB_{it}} > 0\right)$ if the movement of people to urban cities raised the level of residential and industrial usage of energy leading to more CO_2 emissions (Ali et al. 2019; Franco et al. 2017). Otherwise, β_2 was to have a negative sign $\left(\beta_2 = \frac{\partial lnCO2_{it}}{\partial lnURB_{it}} < 0\right)$ if urbanization was affiliated to the use of energies that are healthy to the environment (Lin et al. 2018; Rafiq et al. 2016). Finally, the marginal influence of economic growth on CO_2 emissions was to be positive $\left(\beta_3 = \frac{\partial lnCO2_{it}}{\partial lnGDP_{it}} > 0\right)$ if activities undertaken to help develop the economies of North Africa were linked to the consumption of high-polluting energies (Ali et al. 2018; Salahuddin et al. 2017). Otherwise, β_3 was to be negative $\left(\beta_3 = \frac{\partial lnCO2_{it}}{\partial lnGDP_{it}} < 0\right)$ if economic activities undertaken in the region were linked to green energy sources (Bekhet et al. 2017).

Econometric techniques

First, the Pesaran (2004) cross-sectional dependence (CD) test was engaged to test for dependencies or independencies in the residual terms. Afterwards, the Pesaran and Yamagata (2008) test was adopted to test for homogeneity or otherwise in the slope parameters. This was then followed by the Cross-sectionally Augmented Dickey–Fuller (CADF) test and the Cross-sectional Im, Pesaran, and Shin (CIPS) test to assess the stationarity properties of the variables. At the fourth phase, cointegration features of the series were assessed through the Westerlund and Edgerton (2007) test and the Durbin–Hausman test. Afterwards, the cross-sectional augmented autoregressive distributed lag (CS-ARDL) estimator of Chudik et al. (2016) and the dynamic common correlated effects mean group (DCCEMG) estimator of Chudik and Pesaran (2015) that control for endogeneity, slope heterogeneity, and residual cross-sectional dependence were employed to estimate the elastic effects of the explanatory variables on the explained variable. Following Chudik et al. (2016), the study's CS-ARDL model with added cross-sectional averages to control for cross-sectional correlations was specified as

$$\begin{aligned} lnCO2_{it} = {} & \alpha_i + \sum_{j=1}^{p_y} \lambda_{ij} lnCO2_{it-j} + \sum_{j=0}^{p_x} \beta_{1j} lnEC_{it-j} \\ & + \sum_{j=0}^{p_x} \beta_{2j} lnURB_{it-j} + \sum_{j=0}^{p_x} \beta_{3j} lnGDP_{it-j} \\ & + \sum_{j=0}^{p} \Theta_{1j} \overline{lnCO2}_{t-j} + \sum_{j=0}^{p} \Theta_{2j} \overline{lnEC}_{t-j} \\ & + \sum_{j=0}^{p} \Theta_{3j} \overline{lnURB}_{t-j} + \sum_{j=0}^{p} \Theta_{4j} \overline{lnGDP}_{t-j} + \varepsilon_{it} \end{aligned} \quad (4)$$

Where $\overline{lnCO2}$, $\overline{lnEC}$, $\overline{lnURB}$, and $\overline{lnGDP}$ denote the cross-sectional averages of the response and the input variables respectively; α_i represents the effect specifications of unobserved economies; λ_{ij} is coefficient of the lagged response variable; β_{1j}, …, β_{3j} are the parameters of the covariates; and Θ_{1j}, …, Θ_{4j} are the mean cross-sectional values of the lagged series. The DCCEMG estimator was engaged to assess the robustness of the CS-ARDL estimator. In line with Chudik and Pesaran (2015), the DCCEMG model developed for the study was expressed as

$$\begin{aligned} lnCO2_{i,t} = {} & \alpha_i + \lambda_i lnCO2_{i,t-1} + \beta_1 lnEC_{i,t} + \beta_2 lnURB_{i,t} \\ & + \beta_3 lnGDP_{i,t} + \sum_{r=0}^{K} \alpha_{1ir} \overline{lnCO2_{i,t-1}} \\ & + \sum_{r=0}^{K} \alpha_{2ir} \overline{lnEC_{i,t}} + \sum_{r=0}^{K} \alpha_{3ir} \overline{lnURB_{i,t}} \\ & + \sum_{r=0}^{K} \alpha_{4ir} \overline{lnGDP_{i,t}} + e_{i,t} \end{aligned} \quad (5)$$

Where $\overline{lnCO2_{i,t-1}}$, $\overline{lnEC_{i,t}}$, $\overline{lnURB_{i,t}}$, and $\overline{lnGDP_{i,t}}$ are the cross-sectional averages of the lagged criterion variable and the regressors correspondingly; while α_{1ir}, α_{2ir}, α_{3ir}, and α_{4ir} are their impacts on CO_2 effluents respectively. Finally, K denotes the cross-sections' mean lags. Lastly, the causality test of Dumitrescu and Hurlin (2012) expressed in **Eq. 6** was adopted to examine the causalities between the variables.

$$Y_{it} = \gamma_i + \sum_{m=1}^{M} \alpha_i^{(m)} Y_{it-m} + \sum_{m=1}^{M} \delta_i^{(m)} X_{it-m} + \varepsilon_{it} \quad (6)$$

Where the lag orders are represented by M and γ_i captures fixed effects. Also, $\alpha_i^{(m)}$ and $\delta_i^{(m)}$ are the lag and slope coefficients, respectively. Based on **Eq. 6**, the following models were developed for the causalities between the variables.

$$lnCO2_{it} = \gamma_1 + \sum_{m=1}^{M} \alpha_1^{(m)} lnCO2_{it-m} + \sum_{m=1}^{M} \delta_1^{(m)} lnEC_{it-m} + \sum_{m=1}^{M} \delta_2^{(m)} lnURB_{it-m} + \sum_{m=1}^{M} \delta_3^{(m)} lnGDP_{it-m} + \varepsilon_{it} \quad (7)$$

$$lnEC_{it} = \gamma_2 + \sum_{m=1}^{M} \alpha_2^{(m)} lnEC_{it-m} + \sum_{m=1}^{M} \delta_4^{(m)} lnURB_{it-m} + \sum_{m=1}^{M} \delta_5^{(m)} lnGDP_{it-m} + \sum_{m=1}^{M} \delta_6^{(m)} lnCO2_{it-m} + \varepsilon_{it} \quad (8)$$

$$lnURB_{it} = \gamma_3 + \sum_{m=1}^{M} \alpha_3^{(m)} lnURB_{it-m} + \sum_{m=1}^{M} \delta_7^{(m)} lnGDP_{it-m} + \sum_{m=1}^{M} \delta_8^{(m)} lnCO2_{it-m} + \sum_{m=1}^{M} \delta_9^{(m)} lnEC_{it-m} + \varepsilon_{it} \quad (9)$$

$$lnGDP_{it} = \gamma_4 + \sum_{m=1}^{M} \alpha_4^{(m)} lnGDP_{it-m} + \sum_{m=1}^{M} \delta_{10}^{(m)} lnCO2_{it-m} + \sum_{m=1}^{M} \delta_{11}^{(m)} lnEC_{it-m} + \sum_{m=1}^{M} \delta_{12}^{(m)} lnURB_{it-m} + \varepsilon_{it} \quad (10)$$

Where γ_1, …, γ_4 are constant parameters to be examined and α_1, …, α_4 symbolize autoregressive coefficients. Also, δ_1, …, δ_{12} denote the coefficient of the predictors. The D-H causality test tests the null hypothesis of no causality as against the alternative hypothesis of the existence of causality between variables. These two hypotheses are stated as

$$\begin{array}{lll} H_0 = \beta_i = 0 & \forall_i = 1, \dots, N_1 & \\ H_1 = \beta_i = 0 & \forall_i = 1, \dots, N & 0 \leq N_1/N < 1 \\ H_1 = \beta_i \neq 0 & \forall_i = 1, \dots, N+1, N+2, \dots, N & \end{array} \quad (11)$$

Data source and descriptive statistics

Panel data of Libya, Sudan, Morocco, Tunisia, Egypt, and Algeria from 1990 to 2018 was employed for the analysis. The period 1990 to 2018 was used for the analysis after taken into consideration the availability of data. Authors could not go beyond this duration since data for some of the studied variables were missing for most periods below 1990 and for some periods above 2018. The fact that some of the variables lacked data for some periods left us with no other option than to use the selected period for the exploration. All data used for the study were sourced from the database of the World Bank. Further details on the variables are displayed in Table 1. Summary statistics of the series are outlined in Table 2. From the table, economic growth had the uppermost mean value, while CO_2 emissions had the least mean value. Also, the distributions of all the series were positively skewed. With regard to the kurtosis, the entire series had distributions that were leptokurtic in shape. This implies, the variables had kurtosis values more than the standard 3. The skewness and kurtosis statistics vindicate the Jarque–Bera test outcomes that also underscored the non-normality of the variables' distributions. Further, variance inflation factor and tolerance tests found no collinearity amid the covariates. Lastly, economic growth, energy consumption, and urbanization had a materially favorable association with CO_2 emissions based on the matrix of correlation between the variables. This indicates that an upsurge in economic growth, energy consumption, and urbanization led to an upsurge in CO_2 emissions and vice versa.

Results and discussions

Cross-sectional dependence and heterogeneity test results

As a first step, the researchers examined dependencies or otherwise in the residual terms via the Pesaran (2004) CD test. From the test's results displayed in Table 3, the null hypothesis of no cross-sectional dependence amid the residuals of the model could not be accepted. This indicates that, an influence on one country could spill-over to the other member states. The revelation collaborates that of Musah et al. (2020a) for West Africa and Mensah et al. (2020) for African countries, but deviates from that of Zhao et al. (2016) for North China. It is proposed that non-observed heterogeneity is captured by individual specific coefficients in a classical panel data framework, whether they are surmised to be fixed or random (Mensah et al. 2020). Therefore, ignoring heterogeneity among slope coefficients could lead to biased estimations

Table 1 Data description and measurement units

Variable	Abbreviation	Measurement	Source
Carbon dioxide emissions	CO_2 emissions	Metric tons per capita	WDI (2021)
Energy consumption	EC	Kg of oil equivalent per capita	WDI (2021)
Urbanization	URB	Urban population growth (annual %)	WDI (2021)
Gross domestic product	GDP	GDP per capita (constant 2010 US$)	WDI (2021)

and extrapolations. Hence, following the works of Musah et al. (2020a), Musah et al. (2021b), Mensah et al. (2019), and Musah et al. (2020b), the heterogeneity assumption was tested through the Pesaran and Yamagata (2008) test at the second phase. From the test's discoveries also exhibited in Table 3, the null hypothesis of the slope coefficients being homogeneous was rejected. This implies that the slope parameters were heterogeneous in nature symbolizing variations in the studied countries. An empirical exploration by Mensah et al. (2019) for Africa lends support to the above outcome.

Unit root and cointegration test results

At the third stage of the analysis, the integration properties of the variables were assessed through the CIPS and the CADF stationarity tests that control for dependencies and heterogeneity in residual terms. From the tests' revelations portrayed in Table 4, the null hypothesis of no stationarity could not be rejected at levels, but was rejected after the first difference. This implies, the variables gained stationarity after the first difference depicting homogeneous sequence of integration amidst the series. Studies by Li et al. (2020b) for China, Adamu et al. (2019) for India and Salehnia et al. (2020) for 14 countries of the MENA region offered support to the above discovery. Before the elasticities of the covariates could be explored, it was pertinent to assess the variables' cointegration features. Therefore, at the fourth stage, the Westerlund and Edgerton (2007), and the Durbin–Hausman tests portrayed in Table 4 were performed. From the tests' discoveries, the null hypothesis of no cointegration among the investigated variables could not be accepted. This suggests that, energy consumption, urbanization, economic growth, and CO_2 emissions were flanked by a long-term cointegration association. Explorations by Al Mamun et al. (2014) across the globe, Erdogan et al. (2020) for G20 countries, and Musah et al. (2020b) for NAFTA countries backed the above finding.

Table 2 Descriptive statistics and correlation matrix

Statistic	$\ln CO_2$	lnEC	lnURB	lnGDP
Mean	0.496	5.754	3.984	24.659
Std. Dev.	1.068	2.391	0.292	0.824
Minimum	−2.238	0.000	3.354	22.674
Maximum	2.302	8.118	4.383	26.531
Skewness	0.348	2.314	0.754	4.346
Kurtosis	2.297	8.065	3.752	37.728
Jacque-Bera (JB)	7.435	115.966	13.742	0.929
Probability (JB)	0.024**	0.000***	0.001***	0.061*
VIF	_	1.07	1.03	1.08
Tolerance	-	0.934	0.971	0.928
$\ln CO_2$	1.000			
lnEC	0.403 (0.000)***	1.000		
lnURB	0.791 (0.000)***	0.101 (0.185)	1.000	
lnGDP	0.292 (0.001)***	−0.231 (0.002)***	0.108 (0.153)	1.000

*Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels respectively*

Panel model estimation and causality results

At the fifth phase, the CS-ARDL estimator was first engaged to estimate the elastic effects of energy consumption, urbanization, and economic growth on CO_2 emissions. From the results displayed in Table 5, a 1% rise in energy consumption worsened environmental quality by 0.77% in North Africa. The above discovery has serious implications for the region since all the nations are predominantly reliant on the consumption of non-renewable energies for their economic activities. It can therefore be said that the nations undergoing renewable energy transition to ensure environmental sustainability is comparatively the most effective option they have to choose. In order words, countries in North Africa should phase-out their dependency on traditionally high-polluting energy sources and opt for clean sources like hydro, wind, solar, and biomass among others in order to attain environmental sustainability. The positive association between energy consumption and CO_2 emissions discovered by this study collaborates those of Phong et al. (2018) for Vietnam, Chen and Lei (2018) for 30 countries in the globe and Bekun et al. (2019) for 16 European Union countries, but conflicts those of Dogan and Seker (2016) for the European Union and Adebola Solarin et al. (2017) for India and China.

Also, urbanization weakened environmental quality in North Africa since it escalated CO_2 emissions by 3.211%. This implies, the urbanization policies of the countries are

Table 3 Cross-sectional dependence and heterogeneity test results

Pesaran (2004) CD test		
Variable	Statistic	Prob.
$\ln CO_2$	52.052	0.000***
lnEC	35.022	0.036**
lnURB	21.914	0.073*
lnGDP	33.359	0.003***
Heterogeneity test		
Test	Statistic	Prob.
Delta tilde ($\widetilde{\Delta}$)	12.901	0.036**
Adjusted delta tilde ($\widetilde{\Delta}_{adj}$)	10.302	0.000***

*Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels respectively*

Table 5 CS-ARDL and DCCEMG estimation results

Variable	CS-ARDL		DCCEMG	
	Coef.	Prob.	Coef.	Prob.
$\ln CO2_{t-1}$	−0.458	0.004***	−0.125	0.047**
lnEC	0.770	0.000***	1.769	0.051*
lnURB	3.211	0.071*	0.215	0.021**
lnGDP	0.296	0.023**	0.959	0.092*
F-statistic	120.231	0.054*	127.112	0.012**
R-squared	0.872		0.841	
RMSE	0.022		0.035	
CD-statistic	−2.34	0.911	−3.11	0.167

*Notes: Dependent variable is $\ln CO_2$; ***, **, and * denote significance at the 1%, 5%, and 10% levels respectively*

not facilitating their environmental welfare targets, which is a frequent occurrence in developing countries, where rapid population growth in urban and metropolitan areas presents severe environmental problems due to the lack of effective planning, traffic congestion, overcrowding, urban sprawl, and excessive utilization of dirty energy (Kaya and Koc 2019). This aligns that of Zhang et al. (2017) who postulated that emerging economies with over-agglomeration problems are more likely to pollute the atmosphere than advanced economies. In North Africa, urban cities are home to a higher proportion of economic activities and basic services, thereby influencing the citizenry to move there. However, most residents in these areas are unconcerned about environmental sustainability and spend more on items that degrade the environment. It has also been asserted by Kurniawan and Managi (2018) that, coal, which is pollution-intensive, serves as the main source of energy in urban areas. It is therefore not surprising that the rate of environmental degradation in North Africa is galloping of late. The positive relationship between urbanization and CO_2 emissions uncovered by this study supports that of Ali et al. (2019) for Pakistan and Solarin et al. (2017) for Ghana, but contrasts those of Azam and Khan (2016), for four SAARC countries encompassing Bangladesh, India, Pakistan, and Sri Lanka, Rafiq et al. (2016) for increasingly urbanized emerging economies, and O'Neill et al. (2012) for India and China.

Table 4 Unit root and cointegration test results

Unit root test results								
Variable	CIPS				CADF			
	Levels	Decision	1st Diff.	Decision	Levels	Decision	1st Diff.	Decision
$\ln CO_2$	−2.619	I(0)	−5.379***	I(1)	−2.654	I(0)	−3.692***	I(1)
lnEC	−2.623	I(0)	−6.059***	I(1)	−2.180	I(0)	−4.720***	I(1)
lnURB	−1.324	I(0)	−3.406***	I(1)	−2.061	I(0)	−1.979*	I(1)
lnGDP	−2.648	I(0)	−4.559***	I(1)	−2.456	I(0)	−3.948***	I(1)
Cointegration test results								
Westerlund and Edgerton test								
Statistic	Value	Z-value	Robust P-value	Statistic	Value	Z-value	Robust P-value	Statistic
Gt	−3.322	−2.830	0.000***	Gt	−3.322	−2.830	0.000***	Gt
Ga	−9.493	0.513	0.000***	Ga	−9.493	0.513	0.000***	Ga
Pt	−4.267	0.414	0.060*	Pt	−4.267	0.414	0.060*	Pt
Pa	−4.583	1.075	0.041**	Pa	−4.583	1.075	0.041**	Pa
Durbin–Hausman test								
	Statistic		Value			P-value		
	D_{Hg}		3.022			0.083*		
	D_{Hp}		2.493			0.013**		

*Notes: ***, **, and * denote significance at the 1%, 5%, and 10% levels respectively*

Similarly, economic growth was harmful to environmental sustainability in North Africa via high CO_2 emissions. As depicted by the results, a 1% surge in economic growth escalated CO_2 emissions by 0.296% at the 5% level. This suggests that economic growth did not help to improve environmental welfare by curbing CO_2 emissions. Thus, the running of economic activities in the region was heavily dependent on unclean energy sources that propagated the emissions of carbon. Every economy needs growth to survive. However, if the environment continues to deteriorate, development would be difficult to attain. This is contrary to the tenets of the Sustainable Development Goals (SDGs) (Nathaniel and Khan 2020). If nations in North Africa only target increasing growth, their environments will be adversely affected in the long-run. Therefore, as a recommendation, policy makers should factor environmental quality into their economic development policies (Perkins et al. 2018; Martínez et al. 2018). The positive connection between economic growth and CO_2 emissions discovered by this study is in line with Munir et al. (2020) for ASEAN-5 countries, Ali et al. (2018) for Nigeria and Akadiri et al. (2019) for Saudi Arabia, but conflicts those of Mesagan and Nwachukwu (2018) for Nigeria and Bekhet et al. (2017) for GCC countries.

Further, the lagged criterion variable was negatively substantial indicating that, in absolute terms, any shock in the short-term was adjusted at a speed of 0.458% to restore the long-term equilibrium. The R-squared figure of 0.872 implies, the predictors explained 87.2% of variations in CO_2 emissions. Also, the F-statistic value was significant at the level of 10%. This depicts a good sign of model fitness. Additionally, the model had a very good predictive power, because the RMSE value was far less than 0.08 as per Hair et al. (2017). Finally, the post-estimation CD statistic was not statistically significant. Therefore, the null hypothesis of no CD in the residual terms was validated justifying the robustness of the CS-ARDL estimator to issues of dependencies. The DCCEMG estimates depicted in Table 5 were also explored to check the vigorousness of the CS-ARDL estimator. Though the parameter estimates varied in weight and significance, that of sign were the same for the two estimators symbolizing that the results were robust. Also, the post-estimation statistics of the two estimators followed the same trend. This further underscored the validity and reliability of the study's findings.

At the sixth phase of the analysis, the Dumitrescu and Hurlin (2012) panel causality test was engaged to explore the causal connections amid the series. From the results indicated in Table 6, a bilateral association between energy consumption and CO_2 emissions was discovered. This means the two variables were interlinked such that, a rise in one variable caused the other variable to also rise. Hence, it can be said that enhancing the utilization of renewable energies is one of the effective ways through which CO_2 emissions could be curbed.

Table 6 Pairwise Dumitrescu–Hurlin panel causality test results

Null hypothesis	W-Stat.	Zbar-Stat.	Prob.
lnEC ⇏ lnCO_2	2.039	3.419	0.056*
lnCO_2 ⇏ lnEC	4.623	2.796	0.024**
lnURB ⇏ lnCO_2	2.642	2.317	0.025**
lnCO_2 ⇏ lnURB	10.766	14.43	0.000***
lnGDP ⇏ lnCO_2	2.363	1.902	0.057*
lnCO_2 ⇏ lnGDP	2.248	1.733	0.083*
lnURB ⇏ lnEC	2.583	2.233	0.026**
lnEC ⇏ lnURB	9.018	11.821	0.000***
lnGDP ⇏ lnEC	2.467	2.057	0.037**
lnEC ⇏ lnGDP	1.997	1.356	0.175
lnGDP ⇏ lnURB	7.361	9.354	0.000***
lnURB ⇏ lnGDP	2.172	1.617	0.106

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

In other words, the aggravation of the CO_2 emission levels is likely to motivate the nations to undergo renewable energy transition, particularly thorough phasing-out of traditional energy sources like fossil fuels. The finding is consistent with Alper and Alper (2017) for Turkey, Sekrafi and Sghaier (2018) for Tunisia, and Asumadu-Sarkodie and Owusu (2016) for Ghana. However, those of Pata (2018) for Turkey and Lin and Moubarak (2014) for China are conflicting to the study's discovery. A two-way causal movement between urbanization and CO_2 emissions was also disclosed in the North African context. This signpost that urbanization and CO_2 emissions were inter-reliant, such that a surge in urbanization ended up increasing the level of CO_2 emissions in the nations. The bidirectional causality between the variables also implies future urban activities in the nations are conditional on CO_2 emission levels. Studies by Financeiro (2018) for Kyoto Annex countries and Al-Mulali et al. (2014) for MENA countries are consistent with the study's revelation, however, those of Liu et al. (2017) for four selected ASEAN countries, Hossain (2012) for Japan, and Ma et al. (2017) for China contrast the above discovery.

Similarly, a bilateral causality between economic growth and CO_2 emissions was affirmed. This implies that the two macroeconomic variables were interlinked such that economic development could not be sustained without ensuring environmental sustainability in tandem. It is therefore pertinent for the nations to integrate environmental protection policies within their respective economic development strategies. Empirical investigations by Saud et al. (2019) for Central and Eastern European Countries and Jamel and Maktouf (2017) for European countries were in alignment with the study's finding, but those of Ali et al. (2017) for Singapore, Shahbaz et al. (2016) for selected

African countries, and Cowan et al. (2014) for BRICS countries contrasted the above finding. Furthermore, a mutual connection amid urbanization and energy consumption was established. This implies, energy consumption was reliant on the rate of urbanization in the bloc. Likewise, urbanization also depended on the amount of energy consumed in the region. The revelation is consistent with Ma (2015) for China and Shahbaz et al. (2014) for United Arab Emirates, but contradicts those of Salim and Shafiei (2014) for OECD countries, Faisal et al. (2018) for Iceland, and Sadorsky (2014) for emerging economies.

Additionally, a causality from economic growth to energy consumption was established. This signposts that economic growth led to more energy utilization in the region supporting the exploration of Esen and Bayrak (2017) for net energy-importing countries, but conflicting to those of Comfort et al. (2018) for Nigeria and Zerbo (2017) for Sub-Saharan African countries. Finally, a single-directional causality running from economic growth to urbanization was revealed. This discovery suggests that a surge in economic growth raised the level of urban population in the region. However, economic growth was not dependent on the upsurge of urban population. Studies by Liddle (2013) and Liddle and Messinis (2015) support the study's discovery, but those of Kasman and Duman (2015) for new EU member and candidate countries, Zhao and Wang (2015) for China, and Ghosh and Kanjilal (2014) for India are contrasting to the above disclosure.

Conclusions and policy recommendations

Since a greater percentage of North African countries are developing, it is expected that their economies will expand in the years to come. Accompanying these economic expansions is a serious environmental challenge like high CO_2 emissions that arise from the consumption of dirty energies. Irrespective of the numerous explorations in the energy and environmental economics field, limited studies (if any) have been conducted to investigate the connection between energy consumption and CO_2 emissions in North Africa to the best of our knowledge. To help fill the above gap, a study to examine the energy consumption-CO_2 emissions nexus in the context of North Africa over the period 1990 to 2018 was conducted. In order to obtain valid and reliable findings, second generation econometric techniques that are robust to residual cross-sectional correlations, endogeneity, and slope heterogeneity were employed. From the Pesaran (2004) cross-sectional dependence test results, there were dependencies in the residuals of the investigated model. This implies, any shock on a member country could have a spillover effect on the other member countries. Also, the slope parameters were heterogeneous based on the homogeneity test of Pesaran and Yamagata (2008). This signifies that there were dissimilarities in the countries understudy. The CIPS and the CADF unit root tests were engaged to assess the integration order of the variables and from the results, all the variables were stationary after first difference. This suggests a homogeneous sequence of integration among the variables. At the fourth stage of the analysis, the cointegration attributes of the series were investigated via the Westerlund and Edgerton (2007), and the Durbin–Hausman tests. From the discoveries, the studied series were cointegrated in the long-run. This signifies that a long-run relationship existed between energy consumption, urbanization, economic growth, and CO_2 emissions.

The CS-ARDL estimator of Chudik et al. (2016) alongside the DCCEMG estimator of Chudik and Pesaran (2015) were employed to examine the elastic effects of energy consumption, urbanization, and economic growth on CO_2 emissions and from the results, energy consumption had an increasing effect on CO_2 emissions in North Africa. Also, urbanization and economic growth unanimously promoted CO_2 emissions in the region. Because regression estimates do not give details on the causal directions amid series, the Dumitrescu and Hurlin (2012) panel causality test was engaged to explore the causalities between the variables. Estimates from the causality tests provided support to the regression outcomes. Specifically, bidirectional causalities between energy consumption and CO_2 emissions; between urbanization and CO_2 emission, between economic growth and CO_2 emissions, and between urbanization and energy consumption were unraveled. Finally, unidirectional causalities from economic growth to energy consumption, and from economic growth to urbanization were confirmed. Based on the above mentioned findings, the following policy-level suggestions were put forward.

First, energy consumption escalated CO_2 emissions in North Africa. This result is not surprising because most North African countries have a large number of industries that use high-polluting energies to back their operations. As a recommendation, the consumption of non-renewable energies should be minimized in the region. Instead, clean energies like biomass, hydro, solar, and wind among others should be considered. According to Qin et al. (2021), enhancing financial inclusivity can play a major role by facilitating the financing of renewable energy development projects. Therefore, the nations should factor financial inclusion into their clean energy decisions. In line with Qin et al. (2021), the economies can also look forward to attracting foreign direct investments into their respective renewable energy sectors whereby technological spillover effects can be expected to enhance their renewable energy generation capacities further. Besides, improvements in environmental regulatory standards, particularly, the ones related to renewable energy and energy-saving technologies will be beneficial to the nations. In order to attain environmental sustainability, governments in the bloc should also raise environmental awareness of their people. Through this, the citizens will be well informed about the relevance of embracing renewable energy technologies that could help boost environmental quality. Strict adherence to the regulations set out in the Paris Agreement (2015) and the Kyoto Protocol (2005) among others, could further improve the countries' energy efficiency rates, thereby minimizing the emanation of CO_2. Additionally, industries with higher levels of carbon emissions should be charged higher taxes, while the tax burden of cleaner ones should be lessened. This will encourage the dirtier ones to move toward cleaner production. Finally, improving policy coordination in the energy and economic sectors may help advance the countries' energy efficiency and environmental quality.

Second, urbanization had an increasing influence on CO_2 emissions in North Africa. This finding means, as people migrate to cities, more economic activities that are harmful to the environment emerge, thereby escalating the level of emissions in the bloc. As a recommendation, job creation and improvement in the living conditions of people in remote areas should be factored into the plans of the nations. Furthermore, offering social amenities to rural communities would help to reduce the rate of urbanization, thus mitigating CO_2 emissions in the bloc. This point is in tandem with the assertion of Nathaniel and Khan (2020) that, in rural areas, sufficient infrastructure and basic facilities would not only help to reduce urbanization and its effects, but will also help to advance economic and environmental sustainability. The above recommendation is also in line with Hashmi et al. (2020) who postulated that existing infrastructure should be improved to make it more energy-efficient and environmentally friendly in order to help urban dwellers boost their living conditions, because the recent spread of many infectious diseases in developing countries is a bad sign. Also, the countries need to adopt a sustainable urbanization model rather than an erratic or an unsustainable urbanization model in their management of migration and its related environmental issues. This collaborates that of Behera and Dash (2017). According to Hashmi et al. (2020), Japan has a more efficient and compact city design with efficient public transportation systems. Countries in North Africa should therefore copy this strategy to help lessen the pollution levels of their transportation systems.

Lastly, economic growth worsened environmental quality in North Africa. This suggests that, the countries are after economic viability to the detriment of environmental quality. However, economic development and environmental quality can move together. If environmental quality improves, development in the economy could easily be sustained. Therefore, the nations should have a good balance between economic development and environmental quality, by engaging in activities that can boost economic growth at no cost to the environment. Also, countries in North Africa should expedite their respective economic growth rates to the level that they could gain environmental sustainability. Hence, following Nathaniel and Khan (2020) and Qin et al. (2021), the nations should adopt sustainable and environmentally-friendly consumption and production strategies that could stimulate their growth without any CO_2 emission-related consequences. The implementation of such macroeconomic development policies can aid the nations to attain the sustainable development goals (SDGs) of the United Nations by 2030. In line with Behera and Dash (2017), countries in the region should economically come to a cross-country agreement, so that the rate of environmental pollution in the region could be minimized. According to Saidi and Mbarek (2016), life expectancy and human health could help boost sustainable development due to the variables' adverse association with CO_2 emissions. Therefore, countries in North Africa should factor life expectancy and human health issues into their policy decisions. Summarily, energy consumption, urbanization, and economic advancement policies in North Africa should idyllically be made more environmentally friendly whereby greener initiatives could be undertaken to negate their adverse environmental impacts.

This study had a limitation in that it was confined to the period 1990 to 2018 because of data constraints. The authors could not go beyond this duration since data for some of the studied variables were missing for most periods below 1990 and for some periods above 2018. The fact that some of the variables lacked data for some periods left us with no other option than to use the selected period for the exploration. As lengthier data sets on the investigated variables become available, similar explorations could be conducted to establish whether the discoveries of this study are vigorous. For comparison purposes, the study finally suggests that, investigations on other parts of Africa like West, East, Central, and Southern Africa should be conducted to establish whether energy utilization has similar impacts on CO_2 emissions.

Abbreviations *EC,* energy consumption; *URB,* urbanization; *GDP,* economic growth; *CO_2,* carbon emissions; *CS-ARDL,* cross-sectional augmented autoregressive distributed lag; *DCCEMG,* dynamic common correlated effects mean group; *AMG,* augmented mean group; *MENA,* Middle East and North Africa; *WDI,* world development indicators; *CADF,* Cross-sectionally Augmented Dickey–Fuller; *CIPS,* Cross-sectional Im, Pesaran, and Shin; *IEA,* International Energy Agency; *BRIC,* Brazil, Russia, India, and China; *NAFTA,* North American Free Trade Agreement; *OLS,* ordinary least squares; *DOLS,* dynamic ordinary least squares; *FMOLS,* fully modified ordinary least squares; *TCE,* transport carbon emissions; *TEN,* transport energy consumption; *GCC,* Gulf Cooperation Council; *UMI,* Upper Middle Income; *ARDL,* autoregressive distributed lag; *SSA,* Sub-Saharan Africa; *ASEAN,* Association of Southeast Asian Nations; *SDGs,* Sustainable Development Goals; *LPG,* liquefied petroleum gas; *MG,* mean group; *CCEMG,* common correlated effects mean group; *PMG,* pooled mean group; *EKC,* Environmental Kuznets Curve

Authors contribution MM conceptualized and wrote the final manuscript. MO supervised the study. FB aided in drafting the original manuscript. FI helped in analysis and discussions. IAM analyzed the data and aided in discussions. SKA contributed data. JKA helped in editing the final manuscript. All authors read and approved the final manuscript.

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Declarations

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