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Unravelling the impact of fossil fuel consumption and urbanisation on black carbon emissions in Africa

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Abstract

Black carbon (BC) is a leading short-lived climate pollutant (SLCP) with profound health and climate impacts. This research investigates the impact of fossil fuel energy consumption (FFEC) and Urbanisation (URB) on black carbon emissions (BCE) in 34 African countries over the period 2005–2022. Data were analysed using a panel regression with fixed effects ($x^2 = 97.26$, $p < 0.001$) to estimate the effects of each variable. Cross-country heterogeneity is further examined using country-level multiple linear regression (MLR) models. The fixed-effects model with clustered standard errors finds that fossil fuel energy consumption is weakly and negatively associated with Black carbon emissions. The average effect of countries in URB is not considered strong. In contrast, URB shows a positive and significant association with BCE in Eritrea, Ghana, Madagascar, Mauritius, Morocco, Niger, and Zimbabwewhile FFEC shows a positive and significant impact on BCE in Ghana and Zimbabwe. These results indicate that poorly planned urban sprawl overlaps with energy poverty, as it dramatically increases BCE. Policymakers should focus more on implementing cleaner cooking facilities, reliable low-carbon electricity generation, and eco-friendly transportation modes to achieve BCE neutrality.

Keywords Black carbon emissions, Fossil fuel energy consumption, Urbanisation, Africa, Sustainable development goals

1 Introduction

The worldwide community continues to place a high priority on achieving the Sustainable Development Goals (SDGs) and mitigating global warming. The Paris Agreement was adopted in 2015 in response to growing concerns about climate change. Black carbon emissions (BCE) are the second-largest contributor to human-caused global warming and lead to significant environmental impacts [1, 2]. Black Carbon Emissions are the strongly light-absorbing component of fine particulate matter (PM 2.5) released during the incomplete combustion of biomass, biofuels, and fossil fuels, and they are key drivers of both health damage and near-term climate warming [1, 3]. In empirical studies, "Black Carbon Emissions" usually denote the mass of black carbon (BC) released to the atmosphere from sectors such as households, transport, industry, and open burning, and are used to analyse links between African energy practices, air quality, and climate forcing [1, 4].

Fossil fuel energy consumption refers to the amount of primary energy derived from burning coal, oil, and natural gas in an economy, typically measured in tons of oil equivalent, joules, or as a percentage of total energy use [5]. This variable identifies fossil fuel energy consumption, which is widely used as an indicator of a country's carbon intensity [6, 7]. Perrin [8] estimated that the share was 94.5% of Africa's total energy consumption in 2024. Common fossil fuel uses such as diesel generators, kerosene lighting, and high-emitting vehicles tend to contribute more BCE than CO_2 emissions.

Cities in most African nations are growing faster than infrastructure, housing, and workplaces, resulting in overpopulated informal sectors, crowding, and pressure on the environment [9]. Urbanisation is the tendency for the proportion of the national population residing in urban zones to grow, and for towns and city districts to expand and concentrate, and is most frequently measured as the percentage of urban population or the urban population growth rate [10, 11]. African studies indicate that Urbanisation without growth, in which the increase in Urbanisation is not accompanied by structural change or productivity, Urbanisation is one of the primary demographic and structural predictors of poverty, infrastructure demand, and environmental pressures [10, 12].

Therefore, the purpose of this study is to investigate the impact of fossil fuel energy consumption (FFEC) and Urbanisation (URB) on black carbon emissions (BCE) in Africa for the years 2005–2022 and in 34 countries on the continent. The contribution of this study stands out from past research in four different ways. Firstly, it addresses the critical knowledge gap by delving into the simultaneous influence of fossil fuel energy consumption and Urbanisation as independent variables, providing a nuanced understanding of their collective impact on BCE in the African context, as many past studies have focused mainly on carbon emissions. Secondly, the research employs both panel regression and multiple linear regression, offering a robust methodological contribution and conducting a rigorous statistical analysis across the entire continent and selected African countries, which significantly contributes to the increase in BCE. Thirdly, graphical representations are included to elucidate how each of the three variables individually influences selected African countries. Lastly, the study furnishes a range of policy implications, guiding countries towards emission-reduction strategies with the overarching goal of achieving carbon neutrality by 2050, focusing on SDG 13 (Climate Action).

2 Literature review

Black Carbon in Africa comes from both open fires and human activities, and these sources interact in complex ways. Long-term measurements in eastern Sub-Saharan Africa show that the regional background of BC levels exhibits a strong seasonal cycle, peaking mainly during the savannah fire season, and no clear long-term trend has been observed yet [13, 14]. At the same time, Keita et al. [15] shows that anthropogenic BC emissions almost doubled, with western Africa now the largest source due to residential fuel use, traffic, and waste burning, followed by eastern and northern Africa. Some studies indicate that BC from southern African biomass burning is still underestimated in global models, due to very high BC-to-organic aerosol ratios and strong light absorption

[16]. Moreover, large-eddy simulations over southern West Africa show that realistic BC Levels can strongly heat cloud layers, change droplet size and cloud-top height, alter low-level stratified cloud cover, and alter regional radiation [17]. Thus, even though fires dominate the regional background, studying the rapidly growing anthropogenic BC and its climate effects is becoming increasingly important.

Previous studies have used other methods to analyse black carbon emissions. Many have used specific source-attribution techniques, such as Aethalometer models and Positive Matrix Factorisation, to determine the sources of fossil fuel combustion, biomass combustion, and traffic emissions. Other emission inventories take a bottom-up approach and activity information to estimate BC emissions across sectors [18, 19]. BC emissions have varied strongly by region, with cleaner fuel and vehicle standards decreasing in Europe and North America since 2000, while energy equipment and transportation have increased in some regions. From 2010 to 2015, trends became mixed, with China peaking in the early 2010s and declining after 2013. Recent studies (2025–2026) highlight emerging BC sources, such as gas flaring, shipping, and municipal waste incineration [20–22]. Most of these studies agree that transportation, residential fuel consumption, biomass combustion, and industrial activities are the main contributors to black carbon emissions.

Urban and Household energy use are key contributors to BC. $PM_{2.5}$ levels are higher near busy roads and in dense neighbourhoods [23, 24]. A traffic inventory in estimates about 1.09 tons per day of BC from vehicles, with diesel cars accounting for the majority of emissions [25]. In South Africa, BC concentration rose quickly after 1994, mainly because low-income households still depend on domestic burning for cooking and heating, and increased transport activities, although levels appear to stabilize after 2014 [26]. The rural household energy also contributes significantly to the total burden. Biomass stoves in sub-Saharan Africa account for 6% of global BC, which can be reduced through simple renewable cooking [27, 28]. When combined, the specific actions on cooking, lighting, diesel-powered transport, and waste burning in African urban and rural areas can produce significant BCE, leading to rapid impacts on climate, clouds, air quality, and human health [29, 30].

The use of fossil fuels is a major cause of BC in Africa. It is not just from burning things. Across the continent, the fossil fuel share of the energy mix has increased from about 49% in 1990 to roughly 52% by the mid-2000s and has remained at that level, with most countries still relying heavily on coal, oil, and gas due to the slow uptake of solar and wind [31, 32]. Detailed inventories for 47 sectors show that most African countries experienced an average annual increase of 5.5% in fossil fuel-related emissions, driven primarily by production, electricity supply, and transport [33]. Moghayedi et al. [34] highlighted that about 90% of the primary electricity supply is based on fossil fuels. Broader regional work similarly finds that fossil fuel domination in energy production is at the core of the continent's greenhouse gas trajectory [35, 36]. Similarly, in urban locations such as Kenitra, Morocco, in North Africa, fossil fuel sources are found to contribute 6.2–90.1% of total BC pollution per season, with source rates of 93.8% in autumn and 90.1% in winter [37].

In Africa and globally, the extant literature shows that fossil fuel combustion is the primary source of black carbon emissions. At the continental level, total emissions in African BC have almost doubled, with fossil-fuel-powered road transport and gas flaring increasingly contributing. At the same time, domestic biofuels remain the largest overall contributor [15, 38]. However, measurements at receptors across eastern sub-Saharan Africa indicate that very large amounts of BC have been emitted, particularly in the Niger Delta of Nigeria, due to long-term fossil-fuel gas flaring. These local results suggest that fossil fuel combustion, especially from transportation and low-tech residential and small industrial sources such as kerosene lamps and diesel, is rapidly increasing BC levels in developing countries such as Africa [39, 40]. Similarly, in Sub-Saharan Africa, international trade is associated with, particularly in oil- and gas-exporting countries, limiting the development of renewable energy [31, 35]. Hussain et al. [41] Evidence from African countries shows that urban growth and non-renewable energy consumption jointly degrade environmental quality. Charcoal which generated from the biomass emission function as a "Forgotten Coal" in urban Africa. It is a major cooking fuel for city households and drives forest degradation through poorly regulated production [42]. Multiple studies conclude that expanding renewable energy and substituting it for fossil fuels in electricity, industry, agriculture, and buildings is critical for long-term emissions reduction and health improvement [34, 35, 43, 44]. However, this highlights the need to formulate stringent energy policies in Africa. Environmental taxation has so far been relatively ineffective, as the population and manufacturing sectors are highly dependent on fossil fuels [36].

Urbanisation in Africa is accelerating rapidly, and the literature consistently shows that this transformation is closely tied to the continent's energy consumption patterns and environmental outcomes. As countries become more urbanized, overall energy demand, BC, and carbon emissions often rise along a biomass-dependent pathway rather than through cleaner energy transitions [27, 45–47]. At the household level, urban expansion typically shifts fuel use from firewood to charcoal because charcoal is easier to transport and store in urban environments. These dynamics reinforce a rural-urban divide in biomass use and deepen associated emissions [27].

Beyond the fuel switching, panel evidence across West Africa and the broader continent demonstrates that urbanisation has a significant long-run positive effect on CO_2 emissions. Especially when combined with non-renewable energy consumption and high energy intensity [41, 46, 48]. Ren et al. [49] shows that Urbanisation is associated with increases in aerosol optical depth and that air pollution exhibits spatial variability in individual cities. Urbanisation in Sub-Saharan Africa does not consistently increase electricity access or renewable energy use. In fact, some studies find that urbanisation and trade openness may reduce the share of renewable energy in the energy mix [35, 45]. Duan et al. [50] shows that a few countries, such as Angola and Eswatini, have managed to urbanize while slowing emissions growth, and most African nations experience weak or no decoupling between urbanisation and carbon emissions. In South Africa, Urbanisation appears to increase exclusion, suggesting that governance and the quality of urban development are crucial determinants of social outcomes [51]. Ngounou et al. [52] mention that Urbanisation is associated with higher life expectancy and lower mortality tuberculosis rates. It is simultaneously linked to undernutrition and higher birth rates.

Finally, policy-oriented studies emphasize that African countries, particularly in East Africa, should increasingly integrate climate and urban development strategies, focusing on infrastructure, water access, informal settlements, and green urban planning [53, 54]. However, these studies emphasize that it is essential to consider Africa's urban transition in an environmentally inclusive manner. This suggests that fossil fuel burning and urban deforestation in Africa have increased but are not yet quantified over long-term scales. Ren et al. [55] points out that while BC emissions in the Global South are generally underestimated, Africa is the most prominent.

3 Data and methodology

3.1 Data

To complete a comprehensive examination, this study employed a panel data set comprising 34 African countries for the period 2005–2022. The selection of this timeframe solely depends on the data availability constraints for the considered variables. The data used for the analysis were sourced from Our World in Data and the World Bank (see Table 1). Per capita is used as the unit of measure for BCE. For FFEC, this study used the percentage of the total energy consumption. This study also used the percentage of the total population for the URB. The researchers used Stata software for the statistical analysis.

3.2 Methodology

In this study, the analysis focuses on 34 African countries over the period 2005–2022, selected based on data availability and completeness. While climate variables were not included in the analysis due to data limitations, we provide a detailed site description of the study context. The selected countries span diverse geographic regions across Africa, including Northern, Western, Eastern, Central, and Southern Africa, and capture variations in economic development, urbanisation patterns, and energy consumption. Each country's approximate geographical location and regional classification are provided to contextualize the analysis. By explicitly defining the study sites and their regional characteristics, this approach enhances the transparency and reproducibility of the methodology, while acknowledging that climate-related factors were beyond the scope of the current study and could be considered in future research.

For this study, panel regression analysis was chosen as the statistical analysis model. This helps the study capture both cross-country variations of effect and longitudinal shifts within each country. We built the following equation to assess the relationship between fossil fuel energy consumption and Urbanisation on Black carbon emissions. In this equation, i indexes the regions, t denotes the year under consideration, and εit is the error term.

$$BCE_{it} = \beta_0 + \beta_1 FFEC_{it} + \beta_2 URB_{it} + \epsilon_{it} \quad (1)$$

Before model estimation, we conducted several diagnostic checks, including unit root tests to assess the stationarity of the data, variance and stability tests to ensure our data were appropriate for analysis, and a multicollinearity test to confirm that the

Table 1 Data sources and variable definitions used in this panel study, along with their sources

Variable	Definition and measure	Source	Spatial coverage
BCE	Black carbon emissions (per capita)	Our World in Data	34 African countries
FFEC	Fossil fuel energy consumption Fossil fuel energy consumption (% of total)	World Bank	34 African countries
URB	Urbanisation Urban population (% of total population)	World Bank	34 African countries

independent variables did not exhibit high correlation. In addition, the FFEC variable was transformed into first differences(D_FFEC) to address non-stationarity. Therefore, the equations given below are given in terms of the first-difference FFEC variable. The complete dataset is available in Online Appendix 2.

$$BCE_{it} = \beta_0 + \beta_1 D.FFEC_{it} + \beta_2 URB_{it} + \epsilon_{it} \tag{2}$$

After verifying the data's reliability, we estimated a panel regression model using pooled ordinary least squares (POLS), fixed effects (FE), and random effects (RE). Statistical tests were used to select the model. The Breusch pagan LM test suggested the use of panel data models rather than simple pooled regression. Relatedly, the Hausman test results indicated that the fixed-effects model was appropriate, as it accounts for unobserved country-specific characteristics that do not change over time. Thus, the FE model is considered the primary model in this study.

Furthermore, in Eq. (3), a single-country analysis using a multiple linear regression (MLR) model is employed to provide an in-depth understanding of the relationships among variables for each country.

$$BCE_t = \propto_0 + \propto_1 FFEC_t + \propto_2 URB_t + \epsilon_t \tag{3}$$

In the equation, t shows the year taken into consideration. ε_t shows the standard error. This study analyses the significance levels for each African country regarding the considered variables using the MLR model.

As per Fig. 1, to assess the validity and reliability of the estimated fixed-effects model, several diagnostic tests were conducted. The Levin-Lin-Chu (LLC) unit root test was employed to examine the stationarity properties of the panel data, as stationarity is a key assumption in panel regression analysis and helps avoid spurious estimation results. The LLC test is particularly appropriate for panel datasets with a relatively large cross-sectional dimension, as it allows for heterogeneity across panels while testing for a common unit root process. The results indicated that BCE and URB were stationary at levels ($p < 0.001$), whereas FFEC was non-stationary at the level ($p = 0.612$). To address this issue and ensure the validity of the regression estimates, FFEC was first-differenced (DFFEC), which was found to be stationary ($p < 0.001$).

Furthermore, to examine multicollinearity among the explanatory variables, the variance inflation factor (VIF) was calculated. The VIF test is widely used in regression analysis to detect potential collinearity among independent variables, which can bias coefficient estimates and inflate standard errors. The mean VIF was 1.01, well below the commonly accepted threshold, indicating that multicollinearity is not a concern in the model. In addition, country-clustered robust standard errors were applied to account for potential heterogeneity and within-country correlation in the panel dataset. This approach is appropriate for panel data analyses, as it corrects the standard errors for possible cross-sectional dependence and heteroskedasticity within clusters, thereby improving the robustness of the statistical inference. Overall, these diagnostic procedures provide methodological justification for the selected estimation approach and confirm the validity and robustness of the estimates obtained from the fixed-effects model.

All the steps followed in the statistical analysis of this study are systematically illustrated in Fig. 1 below, which presents the overall analytical framework adopted in the research.

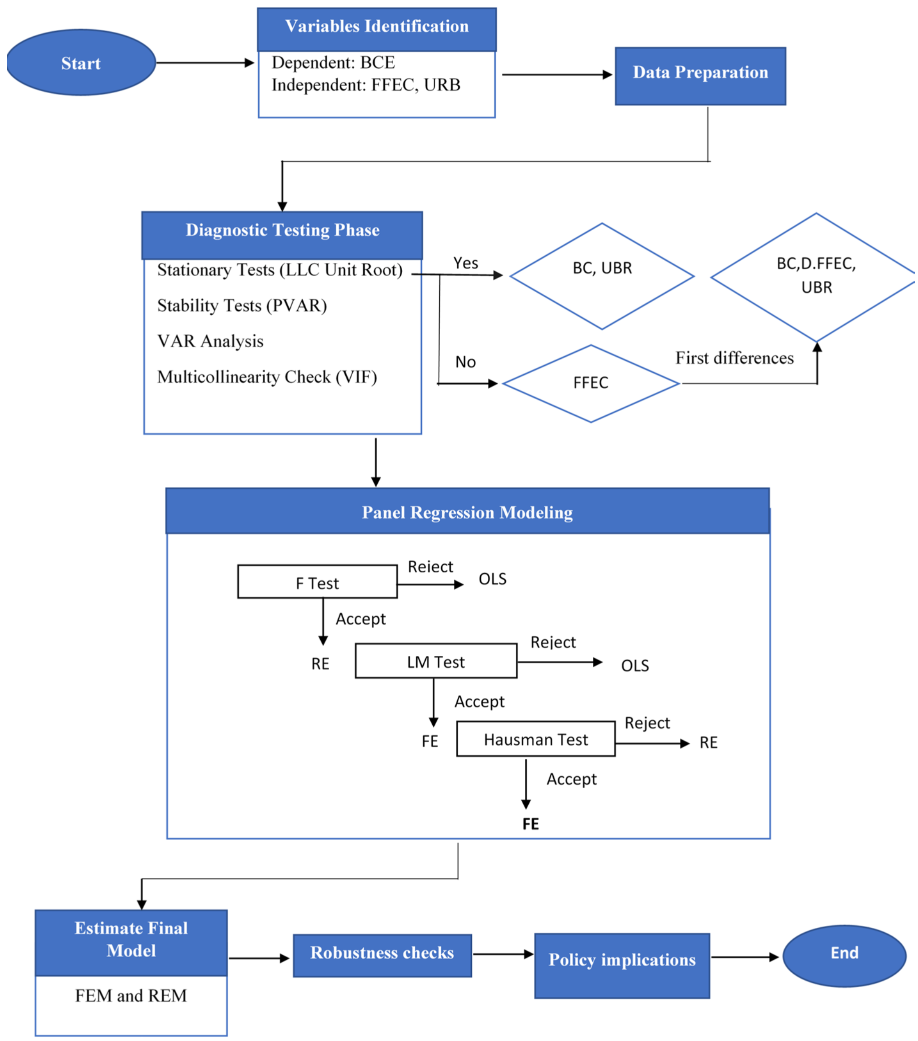

Fig. 1 WLEorkflow of the statistical analysis, including variable identification, data preparation, diagnostic testing, panel regression modelling, and model selection tests

4 Results and discussion

4.1 Descriptive statistics

The top 10 countries with the highest BC averages were identified across 34 African countries, as shown in Fig. 2. They are in descending order: Gabon, Equatorial Guinea, Zimbabwe, Eswatini, Algeria, Botswana, South Africa, Mauritius, Zambia, and Congo. Three major patterns explain these results. First, there are some small countries with high BCE, including Gabon, Equatorial Guinea, Congo, Botswana, and Zambia, which are rich in natural resources due to economic activities such as oil, hydrocarbon, or mineral extraction [56, 57]. Second, countries like Mauritius, South Africa, and Botswana are more diversified and financially developed, with deeper financial systems, higher Urbanisation, and advanced infrastructure [58]. These structural developments are associated with higher BCE values [59]. Third, countries like Eswatini, Zimbabwe, Zambia, and Congo have microeconomic and governance problems. The BCE values may be above the regional average when there are narrow production bases, political instability, and weak institutions [60–63].

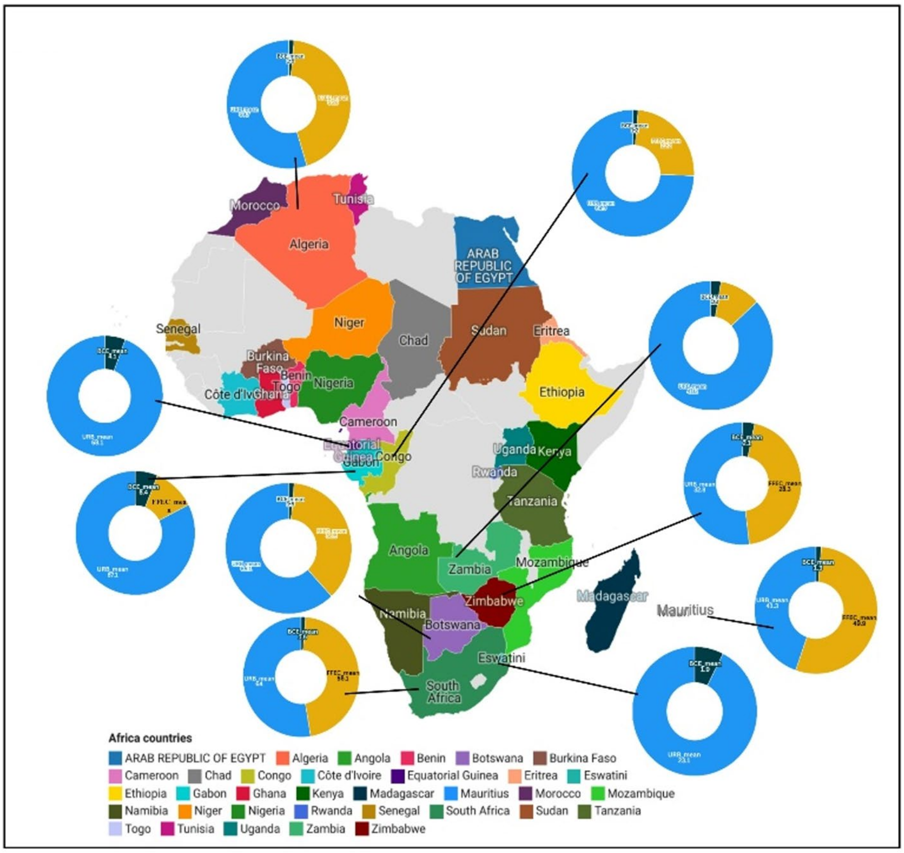

Fig. 2 Spatial Distribution of the Top 10 Countries by average black carbon emissions in Africa. These countries are, in descending order of BC, starting from Gabon, Equatorial Guinea, Zimbabwe, Eswatini, Algeria, Botswana, South Africa, Mauritius, Zambia, and Congo. Coloured countries are those included in the study, and the grey countries were excluded. Donut charts display the mean values of BCE, FFEC, and UBR for the 10 countries with the highest average BCE over the study period. See Online Appendix 3 for details

Figure 3 shows the spatial distribution of the top 10 countries in terms of fossil fuel consumption in Africa. They are in descending order, starting from South Africa, Algeria, Egypt, Tunisia, Morocco, Mauritius, Namibia, Botswana, Senegal, and Ghana. Fossil fuel consumption is concentrated in northern and southern Africa. South Africa, Algeria, and Egypt are the highest ranking countries because of their industrial activities, Urbanisation, and richness in fossil fuel resources [64, 65]. Tunisia and Morocco also exhibit high FFEC due to the expansion of cities, rising transportation demand, and thermal power production [66]. Zaman et al. [67] and Saad et al. [68] emphasize that smaller upper-middle-income economies such as Mauritius, Namibia, and Botswana are featured in the top 10 primarily because transportation and tourism, which require energy, depend on coal or other fossil fuels for electricity generation. Ghana and Senegal are ranked last and second-to-last on the top 10 list, but they use more fossil fuels than most other African nations.

Figure 4 represents the Spatial Distribution of the Top 10 Countries by Urbanisation in Africa in descending order, starting with Gabon, Algeria, Equatorial Guinea, Tunisia, Botswana, Congo, South Africa, Angola, Morocco, and Cameroon. The level of Urbanisation varies between 87% in Gabon to 54% in Cameroon. Doumbia [69], Tjarks [70], Fox [71] and Baliamoune [72] shows that economies that include Gabon, Equatorial

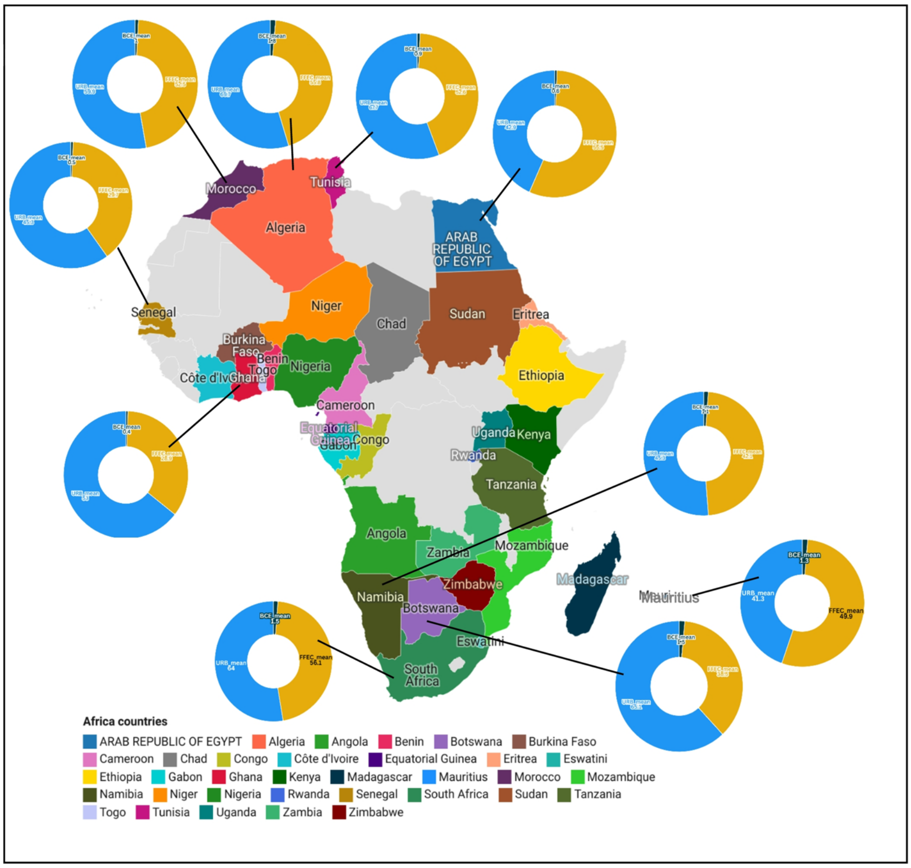

Fig. 3 Spatial Distribution of the Top 10 Countries by Average Fossil Fuel Consumption in Africa. These countries in descending order of FFEC are South Africa, Algeria, Egypt, Tunisia, Morocco, Mauritius, Namibia, Botswana, Senegal, and Ghana. Coloured countries are those included in the study, and countries shown in grey were excluded. Donut charts display the mean values of BCE, FFEC, and UBR for the 10 countries with the highest average Fossil Fuel Consumption over the study period

Guinea, Angola, and Congo are highly urbanized, as oil and mineral wealth drive industrialization and employment in the capital cities. The North African regions, such as Algeria, Tunisia, and Morocco, had undergone previous industrialization and infrastructure development, which have increased urbanisation [72, 73].

4.2 Model selection

The regression result should be analysed after selecting the appropriate panel data model. First, the F-value observed is extremely large (143.30), $p = 0.000$, indicating the inappropriateness of the pooled OLS model and a large difference between the countries. Second, the pooled model is also rejected by the Breusch-Pagan LM test ($p = 0.000$; 3269.17), indicating that the differences at the country level cannot be overturned. Finally, the Hausman test with the result of 97.26, $p = 0.000$, shows that the assumptions of the random effects model are not appropriate since its assumptions are not being met. These tests combined demonstrate that the pooled OLS is not suitable, and that fixed effects is the most suitable anCd reliable form of the model to use in this case. Thus, to avoid the omitted-variable bias from such time-invariant heterogeneity, we estimate a fixed-effect model, which identifies effects from within-country changes over time. This

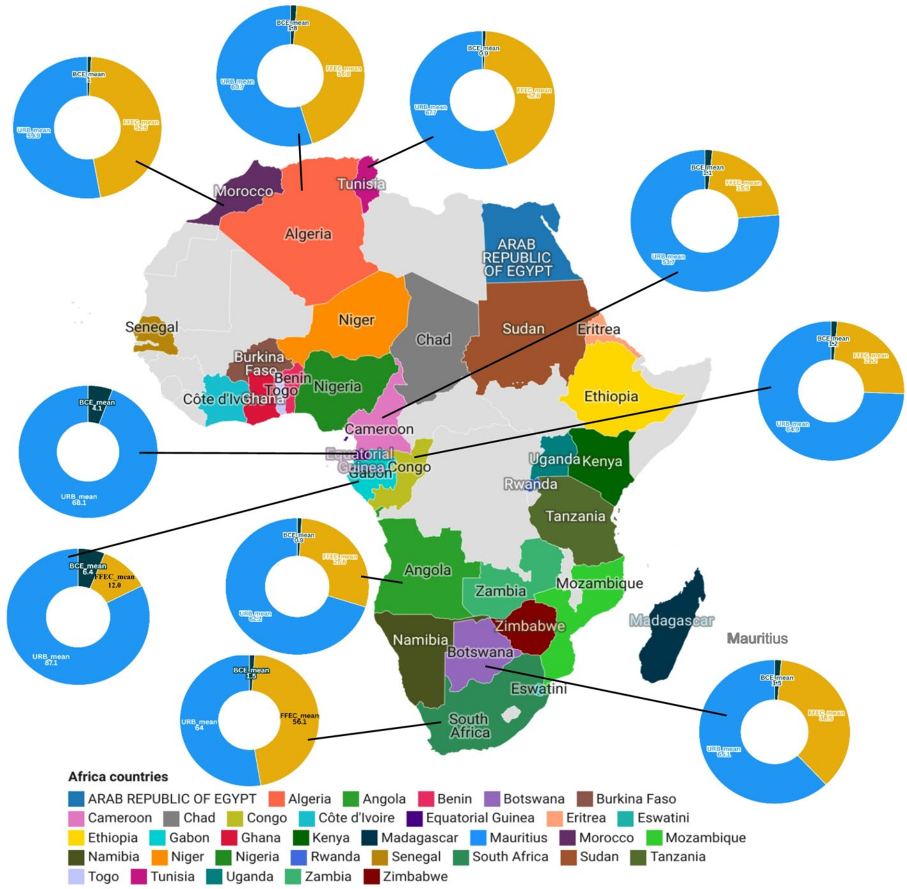

Fig. 4 Spatial Distribution of the Top 10 Countries by average Urbanisation in Africa. These countries in descending order of URB are Gabon, Algeria, Equatorial Guinea, Tunisia, Botswana, Congo, South Africa, Angola, Morocco, and Cameroon. Coloured countries are those included in the study, and countries in grey were excluded. Donut charts display the mean value of BCE, FFEC, and UBR for each of the 10 countries with the highest average Urbanisation over the study period.

Table 2 Panel data model specification tests

Specification test	Null hypothesis (H_0)	Alternative (H_1)	Test statistic (All countries)
F-test	POLS	Fixed Effects	143.30***
Breusch–Pagan LM test	POLS	Random Effects	3269.17***
Hausman test	Random Effects	Fixed Effects	97.26***

pols = pooled OLS. All tests are based on Stata output. *, **, *** denote significance at the 10%,5% and 1% levels respectively. *p*-values for all three testes are 0.000

is similar to the high intraclass correlation of 0.96, indicating that most of the variance in BCE is attributable to long-term differences between nations (Table 2).

4.3 Fixed effect estimates

Table 3 represents the coefficients of the preferred FE model. This provides both estimates with conventional standard errors and the same coefficients with clustered standard errors by country. Clustered standard errors are used for inference because they allow for heteroskedasticity and within-country serial correlation.

At the standard error that is non-clustered, Urbanisation has a negative and highly significant relationship with BCE – 0.045, $p = 0.000$. This indicates that, holding time

Table 3 Fixed effect regression results (Dependent variable: BCE)

Variable	FE coefficient	Std. Err. (conventional)	FE coefficient	Std. Err (clustered)
D_FFEC	–0.00165	0.00131	–0.00165*	0.00084
URB	–0.04515***	0.00509	–0.04515	0.02762
Constant	3.20893***	0.22384	3.20893**	1.21166

BCE = black carbon emission; D_FFEC = change in fossil fuel energy consumption; UBR = urbanisation. *, **, *** denote significance at the 10%,5% and 1% levels respectively. *p*-values for all three testes are 0.000

Table 4 Effect of urbanisation (URB) on black carbon emissions BCE: Eritrea, Ghana, Madagascar, Mauritius, Morocco, Niger, Zimbabwe have positive and statistically significant coefficients

Country	URB Coefficient	Constant
Eritrea	0.0084***	0.2873
Ghana	0.0023**	0.2995
Madagascar	0.0064***	0.4128
Mauritius	0.1003**	–2.8496
Morocco	0.0056**	0.6298
Niger	0.0724**	–0.7299
Zimbabwe	0.0868***	–0.7068

UBR = urbanisation. *, **, *** denote significance at the 10%,5% and 1% levels respectively. *p*-values for all three testes are 0.000

Table 5 Effect of fossil fuel energy consumption (D_FFEC) on black carbon emissions BCE: Ghana and Zimbabwe have positive and statistically significant coefficients

Country	D_FFEC coefficient	Constant
Ghana	0.00019**	0.2995
Zimbabwe	0.00065***	–0.7068

constant and controlling for country effects, there is a strong inverse relationship between Urbanisation and black carbon emissions. Conversely, D_FFEC has a negative, but non-significant, coefficient. There is no strong effect of changes in fossil fuel consumption in the conventional FE inference.

The FE model is preferred over the RE model according to the Hausman test. Since the panel structure implies heteroskedasticity and within-country correlation, the conclusions in this paper are based on FE results with clustered standard errors. Nevertheless, clustered FE with country-level clustering is more suitable for a macro panel. The values of D FFEC = – 0.00165, $p = 0.058$. explain that over time in a particular country, fossil fuel consumption is weakly related to a decrease in BCE.

4.4 Empirical findings from the multiple linear regression model

Multiple linear regression was performed for each African country. The findings show that urbanisation (URB) and fossil fuel energy consumption (D_FFEC) have a greater impact on black carbon emissions (BCE) in one country than in others. In Eritrea, Ghana, Madagascar, Mauritius, Morocco, Niger, and Zimbabwe, Urbanisation has a great impact on BCE. Similarly, both fossil and Urbanisation in Ghana and Zimbabwe are statistically significant. This indicates that BCE is country specific as its drivers are based on local energy consumption and Urbanisation. Table 4 presents the Countries with positive, statistically significant coefficients at the $p < 0.05$ significance level. All the results are in Online Appendix 4. Fossil fuel consumption has a high impact in Ghana and Zimbabwe (Table 5).

The results of the MLR in Eritrea suggest that Urbanisation positively and strongly affects BCE: b(URB) = 0.0084 ($p < 0.01$), with D. FFEC held constant. This implies that at a constant amount of change in the use of fossil fuels, an increase of 1% point in the Urbanisation is associated with an increase of approximately 0.008 units in per capita BCE.

Eritrea is a low-income nation that lacks access to clean, renewable energy, particularly in the fast-growing city settlements [74]. As populations shift to towns and cities, people cook and heat with charcoal, fuelwood, and kerosene, and also use diesel generators, and these activities are major contributors to black carbon emissions [75]. The positive URB coefficient thus indicates that the trend of Urbanisation in Eritrea in the 2005–2022 period has been crisis-intensive, which supports the overall predicament that uncontrolled Urbanisation in a low-income setting is likely to increase the emission volumes of short-lived climate pollutants [76–78].

In the case of Ghana, the MLR is that both regressors are important. Urbanisation has a positive and significant coefficient of 0.0023, and fossil fuel energy consumption also has a positive and significant coefficient of 0.00019. Urbanisation has occurred at an alarming rate in Ghana, particularly with increases in the number of vehicles, traffic jams, and informal settlements that rely on charcoal and other solid fuels [79, 80]. Meanwhile, Citaristi [81] noted that the energy balance has shifted toward more oil and gas, driven by thermal generation, and that transport fuel consumption has increased. Such trends are linked to the unfinished combustion of vehicles, generators, and small-scale industries- the main sources of black carbon [1, 82]. The energy transitions in Ghana are therefore a joint cause of increased black carbon emissions; thus, cleaner urban transport, modern cooking fuels, and low-emission power generation are needed.

Mauritius records the largest positive URB coefficient (0.1003; $p < 0.05$), controlling for D_FFEC. This implies that a 1% increase in Urbanisation is associated with an increase of about 0.10 units in per capita BCE, while the effect of D_FFEC is not statistically significant. Mauritius is already highly urbanised and has a relatively high income level, extensive road networks, and a dense vehicle fleet [83, 84]. Electricity generation continues to rely significantly on coal and fuel oil, although renewables have been expanding [85]. The strong URB effect in the MLR suggests that additional Urbanisation intensifies energy demand from transport, commercial activity, and households, thereby raising black carbon emissions even after controlling for marginal changes in fossil fuel share. Because fossil fuels already dominate the energy mix, the incremental changes captured in D_FFEC may be too small to exert an independent effect beyond what is already reflected in rising urban energy use.

In Morocco, the URB coefficients are positive and statistically significant. This implies that Urbanisation raises BCE when other things are kept constant, Morocco has been under stable industrialisation and Urbanisation with large conurbations like Casablanca and Rabat growing and motorisation driving up [86, 87] Although Morocco has achieved much in its attempt to scale up renewable energy, especially solar and wind power, coal combustion generation and diesel powered road transport are of significant emission source [88, 89]. The concentration of such activities in urban areas increases air pollution from traffic and industrial emissions [90, 91]. The results of the MLR agree with this urban economic activity scale, and intensity is more significant in the BCE than marginal annual changes in the fossil fuel proportion of energy.

Niger. The URB coefficient is 0.0724, which is large and significant at $p < 0.05$. A 1% point increase in Urbanisation is associated with about 0.07 units in BCE. Niger is one of the poorest and fastest urbanising countries in the world, with extremely low electrification levels and a continued reliance on traditional biomass for cooking and heating in both rural and urban areas [92–94]. Households and small businesses in cities are frequently reliant on wood, charcoal, and diesel generators, and motorisation is rising with no significant change in vehicle quality or transport infrastructure. They are the characteristics of a high-carbon, black-carbon-emitting environment [95–97]. According to the MLR findings, Urbanisation, not fossil fuel changes, is the most important factor in explaining BCE in Niger, highlighting the need for clean cooking policies and contemporary energy availability in rapidly urbanising urban centers.

Zimbabwe, where both explanatory variables are significant and positive in the MLR. Therefore, holding D_FFEC constant, an increase in urbanisation levels increases BC; while holding URB constant, an increase in the fossil fuel share increases BC. Even after years of macroeconomic instability, Zimbabwe's urban areas have grown. In cities, power outages are frequent, and residential areas and households use wood, coal, and kerosene for cooking and heating, while industries or businesses rely on diesel-powered generators [98–100]. Coal will play a major role in power generation and parts of industrial processes. Southern Africa, including Zimbabwe, is reported to be one of the hotspots for black carbon due to coal combustion, biomass burning,, and an aging vehicle fleet [101, 102]. The MLR estimates reflect the following realities: Urbanisation is increasing significantly, and the increased reliance on fossil fuels, especially coal and diesel, is also a significant contributor (although it is independent). This mix suggests that Zimbabwe, unless it receives serious policy intervention, is likely to have high black carbon emissions as it continues to develop.

4.5 Policy implication and recommendations

The MLR findings suggest that policy interventions to reduce black carbon emissions in African countries should focus on urbanisation patterns and on how energy is produced and used. The analysis shows that Urbanisation has positive, statistically significant effects on BC in Eritrea, Ghana, Madagascar, Mauritius, Morocco, Niger, and Zimbabwe. In contrast, changes in fossil fuel consumption are significant only in Ghana and Zimbabwe. These results suggest that, in many cases, it is not Urbanisation or fossil fuel use, but the interaction between rapid Urbanisation, energy poverty, and carbon-intensive technologies that drives black carbon emissions.

Due to the rapid Urbanisation, BCE has increased over time. Because of that, the authorities need to focus on implementing renewable energy methods in urban areas. Increasing access to modern and clean household energy in urban and semi-urban areas is important. Policies that accelerate the adoption of LPG, grid power, and other clean cooking energy sources, along with improved cookstove programs for the poorest households, can help reduce the use of charcoal, fuelwood, and kerosene, the leading sources of black carbon in African cities. At the same time, the expansion of electricity networks can help reduce the widespread reliance of households, companies, and institutions on small diesel generators.

Transport policy is also important. In every nation where URB is an important factor, the process of Urbanisation has been coupled with the rising number of vehicles and the increasing congestion. Black carbon from diesel vehicles, which is usually the largest single source in urban areas, can be reduced by developing efficient public transport systems, enhancing non-motorized transport infrastructure, and adopting fuel quality and vehicle emission standards. In countries like Mauritius and Morocco, where motorization has already reached a fairly high level, the focus should be on shifting urban mobility towards mass transportation and strengthening regulation of industrial and vehicle emissions. In economies at a lower level of urbanisation, such as Eritrea, Madagascar, and Niger, simple investments in public transport, road quality, and vehicle inspection can lead to a significant reduction in high-emitting, poorly maintained vehicles.

Given that both Urbanisation and the share of energy consumption from fossil fuels contribute significantly to the BCE, Ghana and Zimbabwe need a more integrated policy package. In these nations, reducing black carbon emissions will not only be possible through the management of urban growth, but will also depend on shifting the energy system away from diesel and heavy fuel as power sources. Increased investments in renewables, especially solar and wind power, can reduce the need for further generation from fossil fuels as electricity consumption increases. Ensuring high combustion efficiency and appropriate technologies to control particulate emissions, along with the use of natural gas as a transition fuel, can lead to low BCE. Simultaneously, the specific steps aimed at replacing old coal plants, limiting the consumption of high-sulphur diesel, and eliminating diesel generators by introducing grid- or battery-based solar systems should prove particularly effective in these two countries.

On the whole, the MLR analysis indicates that policies that favour clean household energy, low-emission transport, trustworthy and cleaner electricity generation, and managed urban growth have the greatest potential to reduce black carbon emissions in the countries researched.

5 Conclusion

This paper examined the correlation between fossil fuel energy, Urbanisation, and black carbon emissions (BCE) in 34 African nations between 2005 and 2022 using both panel fixed-effects models and country-specific regressions. Most changes in BCE at the continental level indicate that countries have long-term structural differences from short-run changes. Domestically, the alterations in the consumption of fossil fuel energy have only a weak negative correlation with BCE, and Urbanisation is not significantly strong when clustered errors are taken into consideration. However, according to the MLR findings, Urbanisation in Eritrea, Ghana, Madagascar, Mauritius, Morocco, Niger, and Zimbabwe significantly increases BC. In contrast, fossil fuel energy consumption in Ghana and Zimbabwe further significantly increases BC. There is a significant positive correlation between fossil fuels and Urbanisation in Ghana and Zimbabwe.

These findings imply that the processes of Urbanisation and energy system development are highly influential in the formation of black carbon in Africa. Urbanisation, which relies on charcoal, wood fuel, kerosene and diesel generators, coal and oil-based power and transport, greatly accentuates BCE. To break this link, integrated policies are needed to increase access to modern cooking fuels and electricity, and better fuel and vehicle standards. Similarly, promotion of renewable energy and clean fuel technologies through concessionary investments is required, especially in rapidly urbanising countries.

Several limitations of this study should be acknowledged. First, the analysis relies exclusively on secondary data sources, including the World Bank and Our World in Data. Although these databases are widely recognized for their reliability, they may still contain measurement errors, periodic data revisions, and variations in underlying data-collection methodologies across countries, which could affect data consistency. Second, the dataset contains a small number of missing observations for certain years, which may slightly influence the completeness of the panel analysis. Thirdly, due to data availability constraints, the study is limited to 34 African countries. In particular, data for Mali, Libya, and Somalia were excluded due to insufficient or inconsistent coverage during the study period. Consequently, the findings should be interpreted with caution, as they may not fully represent the entire African continent. Fourth, several potentially relevant factors, such as industrial policies and local emission control measures, were not included in the analysis due to limited data availability. Omitting these factors may lead to underestimation or overestimation of black carbon emissions. Finally, the study period (2005–2022) may not fully capture the most recent developments in technological innovation, environmental policies, or urbanisation trends that could influence black carbon emissions.

Future research should address these limitations by expanding the geographical coverage within African countries and incorporating additional variables that may influence black carbon emissions, such as environmental policy and regulatory stringency, deforestation, urban planning, land-use patterns, and governance quality. Given the relatively limited body of literature on black carbon emissions in Africa, further research in this area is particularly important. Such studies could benefit from applying more advanced methodological approaches, including dynamic panel models, spatial econometric techniques, causal inference methods, and high-resolution satellite or city-level data. Addressing these limitations would help generate more robust, policy-relevant evidence on the determinants and implications of black carbon emissions across Africa.

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

Supplementary Material 4

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Author contributions

All authors contributed to the conception and design of the project. PP, BS, NS and PW composed the writing of the manuscript. ND provided guidance on completing the data analysis. SY and ND provided critical knowledge during the drafting of the paper and supervised the entire study. The authors have read and approved the final manuscript.

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Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

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