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Promoting clean energy adoption for enhanced food security in Africa

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The research investigated the idea of clean energy and how it affects food security utilizing panel data from selected African nations. The World Development Indicators (WDI) for the years 2005 to 2022, the Food and Agricultural Organization (FAO), and the Country Policy and Institutional Assessment (CPIA) were the sources of data. The study engaged the generalized method of moments (GMM), and the results showed that clean energy indicators have both beneficial and adverse effects on food security. This is crucial for policy toward the actualization of sustainable development goals of no poverty (SDG1), no hunger (SDG2), clean and affordable energy (SDG7), sustainable cities (SDG11), and climate action (SDG13). The findings of this study will benefit policymakers, governments, and organizations working toward promoting clean energy, sustainable agriculture, and food security in Africa. It will also benefit farmers and communities who rely on agriculture for their livelihoods. By implementing the recommendations of the study, these stakeholders can work toward a more sustainable and secure future for Africa. Additionally, the environment and global efforts to mitigate climate change will also benefit from the reduction in greenhouse gas emissions.

KEYWORDS

clean energy, food security, low-carbon economy, sustainable agriculture practice, sustainable development

1 Introduction

According to FAO (2022) estimates, the percentage of malnutrition continues to rise globally and is comparatively higher in Africa. It estimated that in 2021 the percentage of Africans experiencing extreme shortages of food increased to approximately 23% (Anser et al., 2021). Africa has a higher rate of extreme food insecurity than other emerging countries, at approximately 23%, which is twice the global average of 11% (FAO, 2022). This has also been caused by post-harvest losses (Akpa et al., 2023) and low deployment of ICT along the agricultural value chains (Matthew et al., 2023). Furthermore, most African countries do not have adequate access to clean energy, which makes them resort to the usage of alternative sources such as firewood, coal, and biomass among others with negative health and environmental impacts (Edafe et al., 2023).

To meet their home energy demands for food preparation and heating, 2.5 billion individuals globally, as reported by the International Energy Agency (IEA) (2014), have no access to renewable power. As a result, they must depend on biomass fuels, pointing out an even greater threat in sub-Saharan Africa (SSA), where over 75% of the population uses biomass as their main source of energy (IEA, 2014). Thus, without adequate exposure to clean energy, attaining food safety, economic growth, and alleviating poverty remain unattainable objectives (World Food Submit, 1996; Wang 2010; Adewale et al., 2018; Haque and Khan, 2022; Matthew et al., 2022).

Food security is the state in which every individual, irrespective of the period, has physical, social, and economic access to adequate, secure, and nourishing food that satisfies their nutritional requirements and food choices for a life of fitness and wellness, according to the World Food Summit (1996). Moreover, food security cannot be ensured in the absence of sufficient electricity for food preparation (Bogdanski, 2012). In particular, SDG1 (no poverty), SDG2 (food and nutrition security), SDG3 (good health and wellbeing), SDG6 (management of water and sanitation), SDG7 (access and affordable energy), SDG8 (promote decent work and economic growth), SGD11 (sustainable cities), and SDG13 (combat climate change and its impact) are among the objectives that this research contends can be more effectively achieved with access to a clean technology-low-carbon economy, SGD14 (life below water) and SDG 15 (life on land).

In Africa, where food security remains a pressing concern (Osabuohien et al., 2022), understanding the nexus between clean technology adoption and food security outcomes is crucial. However, limited empirical research exists on the specific impacts of clean technology implementation on food security in the African context. Therefore, empirical evidence is essential to address the research gap. This implies that the concepts of clean energy and how it affects food security in Africa are relatively sparse in the extant literature and reported mixed findings. This paper intends to look at the concept of clean energy and its effects on food security in a selected African country for the period between 2005 and 2022, on the data sourced from various reputable sources. The study is structured into five sections. Following this introduction is section two which is made up of the literature review, and the research methodology is encapsulated in Section 3. The results are presented and discussed in Section 4, while the study concludes in Section 5. Against this background, this study formulates this hypothesis in its null forms:

> *Hypothesis* $H_0 : p > 0.05$: clean energy consumption has no influence on food security.

The hypothesis that clean energy consumption has no influence on food security in Africa is a complex and multifaceted issue that would require extensive research and analysis to support or refute. To unravel this, this study examined various potential factors in this hypothesis. These are environmental sustainability: Clean energy technologies can contribute to environmental sustainability by lowering green power and lessening climate change impacts. This could help protect agricultural systems from the adverse consequences of climate change, including extreme weather events and changing growing conditions.

Access to energy: In many parts of Africa, access to modern power supplies is limited, particularly in rural areas. Clean energy solutions could potentially improve access to energy for cooking, lighting, and productive uses, which could have indirect benefits for food security by improving living conditions and enabling income-generating activities.

2 Literature review

Different studies of literature have been reviewed empirically by different scholars on the connection between clean energy and food security in Africa. However, it is quite interesting to know that the yielded outcome has yielded mixed findings. While some opined that climate change has a favorable effect on food security, others showed negative impacts. Wang (2010) used a sample of 27 Chinese provinces to calculate the effect of global warming on food safety. The observations show that the agricultural hazard region, which serves as a stand-in for global warming, had a negative impact on rural *per capita* food consumption. This by implication means that a decrease in agriculture due to global warming will negatively impact China's food safety. This finding is consistent with the findings of Geffersa (2014) study, which examined how households' food security was affected by global warming in 15 rural Ethiopian communities between 1994 and 2009.

Mahrous (2019) examined the effects of global warming on food safety in the East Africa Community (EAC) country, utilizing panel data analysis for five nations spanning the years 2000–2014. The approach of pool fixed effects was applied to assess the connection between the variables. The results indicate that temperature has an impact on food safety in the East African Community (EAC) but that rainfall and expanding the region under cereal farming are helpful in maintaining food safety. In 2015, Kabubo-Mariara and Kabara calculated how global warming might affect Kenya's food safety. The paper's main topics were millet, sorghum, legumes, grain, and availability of food. The findings indicated that global warming would lead to a rise in food scarcity. Furthermore, there was a non-linear correlation between food scarcity and climate variability.

Agarwal et al. (2022) studied how India's labor mobility and household food safety were affected by global warming. The research employed principal component analysis to gather primary information from agricultural families who had adopted and had not adopted climate wise farming. The findings indicate that consumers' yield and income index were greater for men than for women. In response to climatic concerns, non-adopters preferred to eat less food overall. It follows that enhancing gender-equitable literacy is essential to preserving ecological agricultural practices and raising living standards. Geffersa (2014) looked into how, between 1994 and 2009, 15 rural Ethiopian communities' households' food security was affected by global warming. The research findings showed that food safety was adversely and profoundly impacted by global warming. The results also suggested that other components, such as land and animals, would be crucial in ensuring the food safety of the households. This supports the outcomes of Kabubo-Mariara and Kabara (2015), who found that global warming would lead to a rise in food scarcity.

Chen et al. (2017) explored how threats, change, and food safety are affected by global warming. It was determined that the effects of global warming on the agriculture sector will vary globally, with some systems benefiting and many others suffering. Implicitly, several techniques for changes were mentioned, but both public and private initiatives will be required for effective execution. Hagos et al. (2014) examined how climate variability affected Ethiopian children who were malnourished between 1996 and 2004. Information was gathered on temperature, precipitation, stunting, wasting, and underweight children for three distinct areas. The findings indicate that humidity and precipitation had a beneficial effect on infant stunting and underweight in a particular region. However, it was discovered that the meteorological conditions had little effect on waste. Hassan (2023) examined how the cyclical nature of returns on NASDAQ renewable power stocks changed in reaction to foreign energy safety. The generalized autoregressive conditional heteroskedastic models were utilized as a method to analyze the data leading to the major findings of the research. From the findings, it was established that prices of oil, coal, and natural gas and green information technology prices affect NASDAQ clean energy returns volatility negatively. In contrast, carbon price effects on NASDAQ clean energy returns volatility are positive.

Ani et al. (2022) examined Nigeria's agricultural and human safety were affected by environmental change. Both quantitative and qualitative data were used in the study to analyze the findings. Additionally used were data from special reports from international non-governmental organizations and semi-structured interviews. As a result, the results of the research were found on a thorough examination of primary and secondary data. The study's conclusions revealed the following: Global warming is the primary cause of food scarcity in Nigeria, indicating an adverse connection with food availability in that country. Additionally, it was observed that forced relocation brought on by global warming results in individuals experiencing malnutrition or less availability of food.

Dadzie et al. (2021) evaluated the food safety circumstances of farmer families in Ghana's central zone to assess the durability of climate-savvy changes and their consequences. The cross-sectional data that were statistically obtained from a selection of farmers in the central area were analyzed using the approximated Heckit treatment effect theory. It has been determined that farmers' responses to global warming in the fields are only marginally or somewhat feasible. It was also discovered that a smaller percentage of farming families have food security, even though many of them experience acute food insecurity. Therefore, the adoption of environmentally friendly agriculture is the only way to increase the safety of farming families. By recommendation, the study went further to suggest policy responsibilities on the part of decision-makers, agriculturalists, and consumers to encourage Climate Smart Agriculture (CSA) techniques in Ghanaian agricultural operations, which by default promotes crop productivity.

Soumbara and El Ghini (2023) examined the differing impacts of average temperature and rainfall on Moroccan food safety as defined by the agricultural output indicator, utilizing the annual statistics from 1961 to 2020. To investigate the short- and long-term impacts of climate change, the non-linear autoregressive distributed lag (NARDL) model, numerous econometric approaches, and the global warming and food safety concept were employed. It also looked at both the benefits and drawbacks of partial sums of the mean temperature and rainfall to see whether the effects of Moroccan food safety are asymmetric. The findings indicate a long-term link between rainfall (RF) and food production index (FPI), whereby higher TF causes higher FPI and lower RF causes lower FPI, which implies that FPI reacts to an advantageous shock in RF more potently and long-lastingly than it does to a negative shock.

Chanza and Musakwa (2022) examined traditional methods of preserving food safety in the face of global warming, utilizing knowledge from Sub-Saharan Africa. A total of 122 publications describing traditional techniques for growing, canning, and conserving a variety of food sources were included in the evaluation. The results showed that the increased recognition of the effects of global warming on agricultural economies is likely to drive the spotlight on the indigenous-food safety relationship. The FAO lists availability, accessibility, use, and stability as the four pillars of food security, and this approach takes them all into account.

Molua (2012) investigated how different genders respond to and manage threats concerning weather change to maintain food safety in Northern Cameroon. For the three Northern regions of Cameroon, primary data from 116 female-headed homes (FHHS) and male-dominated households (MHHS) were analyzed. The survey produced data on household responses to weather change, coping mechanisms, and the economic implications of global warming. The findings from this research demonstrate that stress related to farming and supply, poverty-related easy access, and food supply use affects both FHHS and MHHS. This stress is compounded by the perceived and actual effects of the current climate's fluctuation. However, diversification of income, a short-term decision, has a good impact on food accessibility. By implication, family finances show a tendency to fluctuate, with family expenses being the most on food in the hottest months and over 70% of their earnings spent on it in the early months of the year.

Haque and Khan (2022) estimated the effect of global warming on food safety in Saudi Arabia in order to give a thorough examination of the variations in weather and precipitation between 1967 and 2016. She also estimated the effects of climatic changes on major crop production. The effects of time-invariant indicators and agriculturalist individual adaptation techniques in response to yearly fluctuations in humidity and rainfall were captured by the research using the fixed effects regression model. According to the data, the average temperature has significantly increased over the past 50 years—by 1.9°C—with the summer experiencing the most increase. The amount of precipitation, likewise, did not significantly vary. By implication, the data suggest that while rainfall benefits all crops, it is not able to significantly counteract the negative impacts of warmth.

Yahaya et al. (2018) estimated the effect of engaging in sustainable intensification of agricultural strategies (SAIPS) on the level of food safety for their homes in northwestern Ghana. To determine food availability data from 168 homes in 10 districts in Ghana's northwestern area, the Household Food Insecurity Access Scale (HFIAS) measure was the approach used. The households were divided into two groups: those receiving therapy (engaging families) and those receiving no medical care (control). The outcome of SAIPs training on inadequate food accessibility measures was assessed using the endogenous treatment effects approach. According to the findings, enrollment in the SAIPs program reduces family food scarcity accessibility by an average of three points, an estimated 11% decrease in the HFIAS score. The age of the family heads, their agricultural background, the overall number of lands they possess, their financial standing, and their line of work were other noteworthy criteria that were discovered to have an impact on the family's instability accessibility index. As a consequence, maximizing sustainable development and safety enhancement will raise the average cost of living for agricultural workers and lessen the negative social issues—such as societal inequality, contamination of the environment, and the depletion of biodiversity in northwestern Ghana—associated with food insufficient societies.

Kong et al. (2022) examined China's 2050 greenhouse gas emissions reduction plan using the country's existing mitigating techniques. In addition to demonstrating local food production, which aims to remove anticipated life-cycle-based carbon footprints in the food and farming industry by 2050, the research analyzed abatement techniques for agricultural greenhouse gas (GHG) emissions in previous studies. It also emphasized the relative contributions of each abatement option to China's decarbonization. The results showed that strategies supporting long-term growth in the agricultural and food industry had a major impact on removing greenhouse gas emissions. The study found that reducing projected greenhouse gas emissions in the agri-food industry can be achieved by prevention measures such as increasing nitrogen nutrients usage effectiveness, altering eating habits, managing compost, reducing food wastage from crop rotation, and adjusting livestock and cover manure diets. By 2050, the agri-food industry will have eliminated 5.03% of its greenhouse gas emissions, due to an effective 10% increase in nitrogen utilization. A 20% reduction in food processing and waste would prevent 1.59% of the agriculture sector's overall greenhouse gas emissions.

3 Methodology

3.1 Data and variables

In this study, the dependent variable, food security data, which was proxied by *per capita* food variability was obtained from the FAO database. Most of the independent variables used in this study including the proxies for agriculture, clean fuels, and renewable power were obtained from the WDI database. The proxy for institutions and policies was obtained from the CPIA database. To reach the goals of this research, a panel data evaluation on Sub-Saharan Africa for the period 2005 to 2021 was conducted. Table 1 provides a detailed summary of all the factors considered in this investigation.

3.2 Model specification and estimation techniques

The methods utilized in this research to scrutinize the interrelatedness between clean energy and food security in Sub-Saharan Africa were the pooled ordinary least squares (POLS) and the one-step system generalized method of moments (GMM). Both methods were adopted because of their advantages. These benefits are explored below.

The POLS technique treats the intercept term and the coefficients of the explanatory variables as constant across time and space (years and countries). The POLS technique treats all explanatory variables as non-stochastic and exogenous while exploring their effect on the dependent variable across periods and countries (Matthew et al., 2022). In this research, the POLS method was adopted as the starting point estimation technique before the generalized method of moments (GMM) was used. Although very advantageous, the POLS technique suffers setbacks (Aggarwal and Padhan, 2017). Some comprise the incapability to discourse the glitches of heterogeneity (Osabohien et al., 2023) and the inability to capture country-specific effects (Aggarwal and Padhan, 2017). The POLS assessment method is stated in Equation 1:

$$lnPCF_{it} = \beta_0 + \beta_1 \ln CF_{it}^{'} + \beta_2 \ln REC_{it}^{'} + \beta_3 \ln C'_{it} + \mu_{it} \quad (1)$$

where $lnPCF_{it}$ signifies the natural logarithm of the *per capita* food variability. β_0 signifies the intercept term, while β_1, β_2, and β_3 are the coefficients of the explanatory variables. In addition, $\ln CF_{it}^{'}, \ln REC_{it}^{'},$ and $\ln C'_{it}$ represent the covariate of the natural logarithm of clean fuels, renewable energy, and the control variables in this study, respectively. The disturbance term is represented by μ, while *i* represents the country ID between 1 and 45, and *t* signifies the duration between 1 and 17.

The one-step system generalized method of moments (GMM): The GMM estimation method addresses some impediments of the POLS technique. A merit of the GMM estimation technique is that it is very effective when dealing with instruments (Arellano and Bond, 1991). This technique also addresses issues that arise when examining panel data with complications of endogeneity. The GMM estimation method is stated in Equation 2 below:

$$lnPCF_{it} = \beta_1 + \beta_1 lnPCF_{it-1} + \beta_2 \ln CF_{it}^{'} + \beta_3 \ln REC_{it}^{'} + \beta_4 \ln C'_{it} + \mu \quad (2)$$

where $lnPCF_{it}$ represents the natural logarithm of *per capita* food variability, and $lnPCF_{it-1}$ represents the first lag of the logarithm of *per capita* food production. In addition, $\ln CF_{it}^{'}, \ln REC_{it}^{'},$ and $\ln C'_{it}$ characterize the covariate of the natural logarithm of clean fuels,

TABLE 1 Variables, measurements, sources, and expectations.

Variable	Code	Measurement	Source	Expectations
Food security	PCF	*Per Capita* Food production	FAO	Not applicable
Agricultural input	ARABLE	Arable land (hectares)	WDI	Positive (+)
Environmental management policies	PEM	Policy and institutions for environmental management	CPIA	Positive (+)
Clean fuels	*CF*	Access to clean fuels and technologies for cooking (% of the population)	WDI	Positive/ Negative (+/−)
Renewable consumption	REC	Renewable energy consumption (% of total final energy consumption)	WDI	Positive (+)

NB: FAO, WDI, and CPIA mean Food and Agricultural Organization, World Development Indicators, and Country Policy and Institutional Assessment, respectively.
Source: Authors' compilation.

renewable energy, and the control variables in this research, respectively. β_0 is the intercept term, β_1 is the coefficient of the lagged dependent variable (*per capita* food variability), β_2, β_3 , and β_4 are the coefficients of the explanatory variables, the disturbance term is characterized by μ, *i* characterizes the country id from 1 to 45, while *t* signifies the period which spans from 1 to 17.

4 Results

4.1 Summary statistics

Table 1 illustrates the descriptive statistics of the variables which include *per capita* food variability (PCF), arable land (ARABLE), policy for environmental management (PEM), clean fuel (*CF*), and renewable energy (REC) for the full sample and the specific counties.

The average *per capita* food variability in the full sample (Sub-Saharan Africa) was 10 units. This shows that on average, *per capita* food variability in SSA is approximately 10 units. After investigating independently, it was discovered that the average *per capita* food variability in the region of West Africa (11%) was the biggest in contrast to other countries, and the Central African region (7%) has the lowest average *per capita* food variability. Additionally, the nation with 0.5 units *per capita* food variability, which is the lowest observed in SSA, was recorded in the Central African nation. The country which has 41 units *per capita* food variability, which is the highest value in the entire nation, was also included in the Central African region.

The average arable land in the full sample (Sub-Saharan Africa) was 4,194,292 hectares. This shows that on average, land suitable for growing crops in SSA is approximately 4,194,292 hectares. Subsequently analyzing independently, it was discovered that the average hectares of arable land in the West African country (5248112) was the biggest in contrast to other counties, and the Southern African region (2766658) has the minimum average hectares of arable land. In addition, the country with 135 hectares of arable land, which is the least worth in SSA, was verified in the Eastern African nation. The country which has 37,000,000 hectares of arable land, which is the maximum value in the whole region, was documented in the West African region.

The average environmental management policies as measured by the policy and institutions for environmental management index in the full sample (Sub-Saharan Africa) were an index of 3. This indicates that on average, the policy and institutions for environmental management index was 3 in SSA. After analyzing independently, it was discovered that the average index in the Southern African region (3) was the biggest in contrast to other nations, and the Central African region (3) has the least average policy and institutions for environmental management index. In addition, the country with a policy and institutions for environmental management index of 1, which is the minimum value in SSA, was recorded in the Eastern African region. The country with a policy and institutions for environmental management index of approximately 5, which is the maximum value in the entire region, was also recorded in the Eastern African region.

The average percentage of access to clean fuels in the full sample (Sub-Saharan Africa) was 22%. This shows that on average, SSA has approximately 22% access to clean fuels. After analyzing independently, it was discovered that the percentage average for access to clean fuels in the Southern Africa region (52%) was the biggest in contrast to other nations, and the West African nation (approximately 14%) has the least percentage average for access to clean fuels. In addition, the country with 0.1% access to clean fuels, which is the least value in SSA, was documented as an Eastern African country. The nation that has 100% access to clean fuels, which is the maximum value in the whole country, was also documented in the Eastern African region.

Finally, the average renewable energy consumption in the full sample (Sub-Saharan Africa) was 64.802%. This shows that on average, 64.802% of renewable energy is consumed in SSA. After examining independently, it was discovered that the percentage average renewable energy consumed in the East African region (73%) was the biggest in contrast to other countries, and the Southern African country (37%) has the minimum percentage average of renewable energy consumed. In addition, the country with approximately 1% renewable energy consumption, which is the minimum value in SSA, was documented in the Eastern African region. The country which has 97% renewable energy consumption, which is the highest percentage in the whole region, was noted in the Central African nation (Table 2).

4.2 Pooled ordinary least squares results

This research proxied food security by *per capita* food production, agricultural input (ARABLE), environment management policies (PEM), clean fuels (*CF*), and renewable energy (REC) by *per capita* food variability, arable land (hectares), policy and institutions for environment management, access to clean fuels, and renewable energy consumption, correspondingly. The POLS method was utilized in the section to scrutinize the interrelationship between clean energy and food security in Sub-Saharan Africa and its sub-regions. The outcomes are briefed in Table 3.

All the variables in this research were logged. This implied that the interpretation would take the shape of a proportion. In this model, the explanatory variables would be considered substantial if the *p*-value is between the 10, 5%, or 1% significance levels. In the framework used for stating the systemic variations in the dependent variable (PCF) in both the full sample (SSA) and the four sub-regions (Central Africa, Eastern Africa, Southern Africa, and Western Africa), the explanatory variables (ARABLE, PEM, *CF*, and REC) were collectively substantial, according to the F-statistic.

The outcome in Table 3 discovered that arable land has an optimistic and statistically noteworthy effect on *per capita* food variability for the full sample. This shows that an upsurge in the hectares of arable land for planting crops in Sub-Saharan Africa would increase *per capita* food variability and, hence, food security. The POLS estimate on the full sample forecasted that a percentage rise in the hectares of arable land would result in a less than 1% increase in *per capita* food variability. This was in line with the goals set forth in this investigation as well as the research conducted by Uduma et al. (2023) on the relationship between output from agriculture and institutions in low- and middle-income African nations.

The POLS estimations showed that the effect of arable land on *per capita* food variability across the sub-regions was also positive and statistically significant. This illustrates how a rise in the hectares of

TABLE 2 Descriptive statistics of the variables.

	Full sample		Central Africa		Eastern Africa		Southern Africa		Western Africa	
Variable	Mean (SD)	Min (Max)	Mean (SD)	Min (Max)	Mean (SD)	Min (Max)	Mean (SD)	Min (Max)	Mean (SD)	Min (Max)
PCF	10.01 (7.37)	0.50 (41)	7.36 (7.75)	0.5 (41)	10.32 (7.64)	0.7 (38.8)	9.43 (5.38)	0.8 (26.9)	11.40 (7.06)	1.3 (35.6)
ARABLE	4,194,292 (6187627)	135 (37000000)	3,196,008 (3567807)	4,000 (13700000)	4,145,066 (4319355)	135 (16200000)	2,766,658 (4782364)	138,000 (13200000)	5,248,112 (8596708)	48,000 (37000000)
PEM	3.13 (0.57)	1 (4.5)	2.81 (0.40)	2 (4)	3.13 (0.69)	1 (4.5)	3.38 (0.22)	3 (3.5)	3.258 (0.48)	2 (4)
CF	21.57 (27.99)	0.1 (100)	22.79 (25.77)	0.5 (89.7)	18.96 (32.37)	0.1 (100)	52.13 (17.45)	23.7 (88.4)	13.78 (19.96)	0.3 (81.8)
REC	64.802 (26.62)	0.71 (97.42)	66.41 (27.35)	3.68 (97.42)	72.86 (27.42)	0.71 (96.01)	36.73 (20.69)	7.72 (72.68)	65.35 (20.75)	20.78 (94.42)

Source: Authors' compilation.

TABLE 3 Pooled ordinary least squares estimates.

	Full sample	Central Africa	East Africa	Southern Africa	West Africa
lnARABLE	0.213*** (0.00)	0.357*** (0.000)	0.1877*** (0.002)	0.314 (0.445)	0.260*** (0.000)
LnPEM	0.273* (0.060)	−0.083 (0.857)	0.2426 (0.244)	−4.183** (0.044)	0.7082** (0.019)
LnCF	−0.153*** (0.000)	−0.255*** (0.007)	−0.113** (0.025)	−3.883** (0.029)	−0.1826*** (0.000)
LnREC	−0.856*** (0.000)	−3.047*** (0.000)	−0.413 (0.580)	−3.881** (0.037)	−0.8486*** (0.000)
Constant	2.463*** (0.000)	10.453*** (0.000)	0.973 (0.725)	31.079** (0.030)	1.322 (0.118)
R^2	0.159	0.2379	0.1019	0.4850	0.3012
F-Stat	29.31*** (0.000)	8.90*** (0.0000)	6.07*** (0.0001)	2.82*** (0.0030)	28.55*** (0.0000)

*, **, and *** mean significant at 1, 5, and 10%, respectively.
Source: Authors' compilation.

arable land in Central Africa, Eastern Africa, Southern Africa, and Western Africa would subsequently lead to significant increases of 0.35, 0.18, 0.31, and 0.26%, respectively, in *per capita* food variability, and hence, food security.

The outcome from Table 3 also demonstrated that environmental management policy has a favorable and statistically noteworthy influence on *per capita* food variability for the full sample. The result was in line with the outlooks formed in this research. The POLS estimate predicted that a percentage increase in the environmental management policy index in Sub-Saharan Africa would lead to a 0.27% rise in *per capita* food variability in the region. This agrees with the study of Adewale et al. (2018) in their work on the purpose of environmental management in achieving food safety in Sub-Saharan Africa.

However, upon examination, the results were heterogeneous across the sub-regions. In Central and East Africa, environmental management policies are not significant in decreasing or increasing *per capita* food variability. In southern Africa, environmental management policies have an adverse statistically noteworthy effect on *per capita* food variability. A percentage increase in the environmental management policy index in the region will result in an approximately 5% reduction in *per capita* food variability. In West Africa, however, there is a beneficial and statistically substantial association between environmental management policies and *per capita* food variability. A percentage increase in the environmental management policy index in the region will result in an approximately 1% increase in *per capita* food variability. Access to clean fuels has an adverse and statistically noteworthy effect on *per capita* food variability in Sub-Saharan Africa. The finding revealed that a rise in the population's access to clean fuels is linked with a reduction in *per capita* food variability. It was predicted that a percentage increase in the population with access to clean fuels is associated with a less than 1% reduction in *per capita* food variability in SSA.

This relationship was also recorded at all sub-regional levels. With a negative and statistical impact on *per capita* food variability in Central, Eastern, Southern, and Western Africa, any percentage rise in the population with access to clean fuels is associated with a 0.26, 0.11, 3.88, and 0.18% reduction in *per capita* food variability, respectively. Renewable energy also has an adverse and statistically substantial effect on *per capita* food variability in Sub-Saharan Africa. The outcomes in Table 3 revealed that a percentage increase in the region's consumption of solar, hydraulic, and other forms of renewable energy will reduce *per capita* food variability by approximately 1%.

This relationship is also seen in all the sub-regions with exemption to East Africa where renewable energy consumption is not statistically significant in reducing *per capita* food variability. However, with negative and statistical impacts, a percentage increase in Central, Southern, and Western Africa's consumption of renewable energy will result in approximately 3, 4, and 1% reduction of *per capita* food variability, respectively.

4.3 GMM estimation results

The one-step system generalized method of moments was utilized in this segment to scrutinize the correlation between clean energy and food security in Sub-Saharan Africa and its sub-regions. The outcomes are briefed in Table 4. Similar to the pooled ordinary least squares estimations, the explanatory factors in this model would be described as substantial if the *p*-value falls within the significance level at 1, 5, and 10%. The AR (1) and AR (2) were utilized to check for autocorrelation in the outcomes, and from Table 4, there was no occurrence of autocorrelation in the region and sub-regions as the coefficients of AR (1) were statistically momentous whereas the coefficients of AR (2) were not statistically noteworthy.

Table 4 illustrates that arable land has a positive and statistically significant impact on *per capita* food variability in Sub-Saharan Africa. This outcome agrees with the POLS estimates demonstrated in Table 3. Additionally, the GMM estimates in Table 4 forecasted that a percentage rise in the hectares of arable land for growing crops is linked with a 0.27% increase in *per capita* food variability, in Sub-Saharan Africa, in the near term. This shows a rigid connection between the variables.

The GMM estimates showed that there were also positive and highly substantial effects at 10% levels in all the sub-regions, disregarding Southern Africa whose approximations were inconsequential. There is also an inflexible association between arable land and *per capita* food variability in these sub-regions. A percentage rise in the hectares of arable land will result in a 0.33, 0.32, and 0.19% increase in *per capita* food variability in the near term in Central, Eastern, and Western Africa correspondingly. The environmental management policy proxied by PEM has an adverse and highly noteworthy effect on *per capita* food variability in Sub-Saharan Africa. This does not correspond with the pooled OLS estimates illustrated in Table 3. Estimates in Table 4 indicated that a percentage surge in the environmental management policy index is linked with a 0.39% decline in *per capita* food variability, in Sub-Saharan Africa, in the near term. This implies an inflexible association between the variables.

Similarly, the GMM estimations showed statistical significance in all the sub-regions eliminating Central Africa whose estimates were negligible. In East and West Africa, a percentage increase in the environmental management policy index will result in a 0.36% and 0.47 increase in *per capita* food variability, respectively in the short term. This indicates a positive and inelastic relationship between the variables in the regions. However, in Southern Africa, there exists a negative relationship between the variables. A percentage rise in environmental management policy will lead to an approximately 6% decline in *per capita* food variability in the short term. This suggests an elastic association.

Table 4 also reveals that access to clean fuels has an adverse and highly substantial effect on *per capita* food variability in Sub-Saharan Africa. This aligns with the estimations of pooled ordinary least squares that are compiled in Table 3. According to estimates in Table 4, in the short term, similarly, a percentage rise in the population's access to clean fuels is linked to a 0.19% decline in *per capita* food variability in Sub-Saharan Africa.

The GMM estimates revealed that the nexus between the two variables was also adverse and statistically substantial in all the sub-regions. This also aligns with the pooled ordinary least squares estimations shown in Table 3. From the estimates, in the short run, *ceteris paribus*, a percentage increase in the population's access to clean fuels will result in a 0.21, 0.21, 4.4, and 0.11% decrease in *per capita* food variability in Central, Eastern, Southern, and Western Africa, respectively. This also indicated an inelastic relationship between variables in Central, Eastern, and Western Africa and an elastic relationship in Southern Africa.

Renewable energy consumption has an adverse and highly substantial effect on *per capita* food variability in Sub-Saharan Africa. This agrees with the pooled ordinary least squares estimations demonstrated in Table 3. Estimates in Table 4 indicated that a percentage rise in the consumption of renewable energy such as solar, hydraulic, and other forms is linked with a 1.13% decline in *per capita* food variability in Sub-Saharan Africa in the near term. This suggests an elastic association between the variables.

The GMM estimations showed that the association between the two variables was also adverse and statistically significant in all the sub-regions. This also aligns with the pooled ordinary least squares computations compiled in Table 3 except for Eastern Africa. From the estimates, in the short run, *ceteris paribus*, a percentage rise in the consumption of renewable energy will result in a 2.9, 1.6, 4.3, and 0.6% decrease in *per capita* food variability in Central, Eastern, Southern, and Western Africa, respectively.

5 Discussion

The POLS and GMM techniques were used to examine the interrelationship between clean energy and food security in Sub-Saharan Africa and its sub-regions. The discoveries are outlined in Tables 3, 4.

The discoveries from both methods showed that arable land has a positive effect on *per capita* food variability in Sub-Saharan Africa. As

TABLE 4 GMM results.

	Full sample	Central Africa	East Africa	Southern Africa	West Africa
lnARABLE	0.270*** (0.000)	0.327*** (0.000)	0.315*** (0.000)	0.327 (0.473)	0.187*** (0.000)
lnPEM	−0.392*** (0.001)	−0.327 (0.182)	0.355*** (0.001)	−5.526** (0.032)	0.468*** (0.007)
lnCF	−0.194*** (0.000)	−0.207*** (0.000)	−0.211*** (0.000)	−4.422** (0.028)	−0.109*** (0.000)
lnREC	−1.132*** (0.000)	−2.868*** (0.000)	−1.552*** (0.000)	−4.316** (0.039)	−0.629*** (0.000)
constant	3.692*** (0.000)	10.289*** (0.000)	4.102*** (0.004)	36.094** (0.029)	1.644*** (0.001)
AR (1)	−9.61*** (0.000)	−6.48*** (0.000)	−4.14*** (0.000)	−3.83*** (0.001)	−4.42*** (0.000)
AR (2)	−1.45 (0.152)	0.36 (0.716)	0.81 (0.414)	−1.14 (0.273)	−0.88 (0.398)

*, **, and *** mean significant at 1, 5, and 10%, respectively.
Source: Authors' compilation.

stated earlier, this finding follows the conclusion stated in the study by Uduma et al. (2023). This effect in the entire dataset was also mirrored in the sub-regions. In Sub-Saharan Africa, an upsurge in the available hectares of land suitable for agricultural cultivation will lead to higher food production, improved nutrition, and lowered dependency on imports. With more land available for cultivation, farmers can grow a larger variety of crops. This can result in higher yields and a more diversified food supply. Additionally, expanding arable land is essential for the accomplishment of several Sustainable Development Goals (SDGs). A few of these are SDG2—Zero Hunger, SDG8—Decent Work and Economic Growth, and SDG10—Reduced Inequality. This supports the findings of Uduma et al. (2023) that arable land plays a contributing role to agricultural productivity and food security.

To achieve this expansion of arable land in Sub-Saharan Africa, concerned governments should prioritize land tenure security and promote equitable access to arable land, invest in rural infrastructure development, and allocate resources for agricultural research and development to improve crop diversities and investment in training and educational initiatives to enhance the skills and knowledge of the farmers. The two techniques also revealed that environmental management policy remains a contributor to food safety in Sub-Saharan Africa. This supports the findings of Adewale et al. (2018). However, the contribution made to food security was heterogeneous across techniques. The POLS estimated a positive relationship, while a negative relationship was indicated by the GMM estimator. This indicates that environmental policies can have both positive and negative impacts on food safety in Sub-Saharan Africa. Although these policies intend to protect natural resources and ecosystems through sustainable resource management and climate change mitigation, their implementation can have unintended consequences on agricultural practices and food production.

For instance, while land use restriction may be important for environmental conservation, it can limit the expansion of agricultural land and constrain food production. In addition, compliance with environmental regulations often requires additional investment from farmers. The financial burden and complexities associated with compliance may affect small-scale farmers and hamper their capacity to capitalize on farming productivity and potentially reduce food availability. To minimize the negative impacts, it is crucial to implement policies that are context-specific and inclusive and consider the diverse needs of different stakeholders.

Furthermore, both the techniques mentioned above also revealed that the population's access to clean fuels does not result in the rise in the *per capita* food variability in Sub-Saharan Africa. Transitioning to clean fuels requires investment in infrastructure, technology, and capacity building. In Sub-Saharan Africa, the shift from traditional fuels to clean fuels may not be implemented effectively or efficiently due to resistance to change, lack of awareness, or technical challenges. When this transition is poorly managed, it can disrupt existing cooking practices, cause economic dislocation for fuel producers and vendors, and create temporary disruptions in fuel supply. Such challenges can affect food security by impacting livelihoods and food production processes.

Both techniques also indicated that renewable energy consumption has significant and negative effects on food security in Sub-Saharan Africa. Several factors are responsible for this negative effect. First, the rate of green power technology such as power plants and photovoltaic cells can be relatively high. If this cost of transitioning is passed on to consumers, it could potentially increase energy prices. Higher energy costs may lead to increased production costs in the agricultural sector and result in decreased food processing and production. Furthermore, some renewable energy projects may compete with agricultural land and resources. If land previously used for food production is diverted for biofuel crops, it could reduce the accessibility of arable property for farming food crops. Additionally, the competition for water resources between energy production and agricultural needs could pose challenges to irrigation and crop production, potentially affecting food security.

Therefore, based on the result, we reject the null hypothesis, implying that clean energy has a substantial impact on food safety. The rejection of the hypothesis that "clean energy consumption has no influence on food security in Africa" implies that there is evidence signifying a connection between clean energy consumption and food security in the African context. In essence, clean energy often aligns with environmental sustainability. If the hypothesis is rejected, it might imply that sustainable energy practices positively impact the environment, consequently benefiting agriculture. For example, reduced pollution and climate change mitigation measures can contribute to stable and reliable agricultural conditions. In addition, clean energy initiatives may improve access to energy in rural zones where farming is a primary source of livelihood. If the hypothesis is rejected, it might indicate that providing clean energy access to rural communities positively affects their agricultural productivity and, consequently, food security.

The latest efforts to obtain alternative energy sources, as evidenced by the papers "Use of biogas plants on a national and international scale" and "Competitive algae biodiesel depends on advances in mass algae cultivation," highlight the growing interest in sustainable and renewable energy solutions. Biogas plants, which convert organic waste into biogas for energy production, have the potential to provide a decentralized and environmentally friendly energy source. Additionally, advancements in mass algae cultivation for biodiesel production could offer a promising alternative to traditional fossil fuels. These efforts align with the global push toward reducing dependence on other forms of power and reducing the effects of global warming. By exploring and investing in innovative technologies such as biogas and algae biodiesel, there is potential to not only address energy needs but also contribute to environmental sustainability and food security by utilizing organic waste and non-arable land for energy production. Overall, the research and development of alternative energy sources such as biogas and algae biodiesel demonstrate a commitment to finding sustainable solutions that can benefit both energy production and food safety in Africa and beyond.

In line with the study, "clusters in transition to circular economy: evaluation of relation" and "insect rearing on biowaste represents a competitive advantage for fish farming" delve deeper into the efforts to address greenhouse gas (GHG) removal and environmentally promising practices, the transition to a circular economy, as discussed in the first paper, highlights the need to re-evaluate the association between industrial clusters and their effect on the environment. By adopting circular economy principles, such as reusing and recycling materials, there is potential to reduce GHG emissions and minimize waste generation. Furthermore, the paper on insect rearing on biowaste emphasizes the competitive advantage this practice presents for fish farming. By utilizing biowaste as a feed source for insects, which are then used as a sustainable protein source for fish, it may be possible to lessen the environmental effect of traditional fish feed production while also addressing food security and resource efficiency. These studies underscore the importance of exploring innovative and sustainable practices to address environmental challenges and promote sustainable development. By focusing on the GHG removal and environmentally promising practices, there is potential to lessen the effects of global warming, as well as to foster emerging economic advancement and promote environmental stewardship.

6 Summary and conclusion

Food security is a global issue; therefore, promoting sustainable food security is the responsibility of every country in every continent. Moreover, Africa as a developing region is concerned with several ways' food availability, utility, accessibility and stability can be achieved. This has resulted in several studies on the subject matter. However, this research studied the interrelationship between clean energy and food safety, using access to clean fuels and renewable energy as proxies for clean energy. The estimates showed a negative relationship between these proxies with food safety. It is, however, crucial to remain cognizant that while these factors may pose challenges to food safety, the overall benefits of clean fuels and renewable energy, such as reduced health risks and environmental impact, reduced environmental degradation, and enhanced energy security are substantial and should be considered as well.

This study employed the POLS as the baseline estimator and the one-step system GMM to tackle endogeneity issues. By analyzing the connections between clean energy and food security in Sub-Saharan Africa, the research was able to meet its goals. In light of this, solving these issues calls for an all-encompassing strategy that takes into account the socioeconomic environment, encourages cost-effectiveness, upgrades facilities, and supports renewable power transitions. In addition, targeted interventions, technology advancements, and regulatory changes can assist in minimizing any possible harm to food security while optimizing the advantages of adopting renewable energy.

To better explain the relationship between profitability and cost-competitiveness in a territory's industry, it is important to consider the perspective of investors. Investors are attracted to profitable industries because they offer the potential for strong returns on investment. When a territory's industry is profitable, it signals to investors that there is a favorable business environment and potential for growth. Investors also consider the overall business environment of a territory, including factors such as labor costs, tax rates, and regulatory burdens. A cost-competitive territory with a profitable industry is more likely to attract investment because it offers the potential for strong returns and a favorable business environment.

Furthermore, a profitable industry in a cost-competitive territory is more likely to attract skilled workers and innovative businesses. This can create a positive feedback loop, where the presence of profitable businesses attracts more investment and talent, leading to further growth and success for the territory's industry. In summary, profitability is a crucial factor for investors when considering the cost-competitiveness of a territory's industry. A profitable industry not only provides opportunities for strong returns on investment but also creates a positive business environment that attracts further investment and talent.

As for an empirical examination of the interrelationship between clean energy, low-carbon economy, and food security in Africa, this topic would require in-depth research and analysis to understand the complex dynamics at play. It would involve studying the effect of clean power initiatives on food safety, as well as the potential economic benefits of transitioning to a low-carbon economy in the African context. This type of study could provide valuable insights for policymakers and investors looking to support sustainable development in the region.

As a recommendation for further study, it would be important to consider the likely trade-offs and synergies between clean energy consumption and food security in Africa. For example, the expansion of bioenergy production for clean energy could compete with land and water resources for food production, potentially impacting food security. On the other hand, investments in renewable energy infrastructure could also improve access to energy for agricultural activities, leading to increased food production and storage capabilities. Furthermore, understanding the potential effects of clean power consumption on food safety would also require an analysis of the policy and governance frameworks in place. For example, policies that promote clean energy development while also ensuring sustainable land use and resource management could help mitigate potential negative impacts on food security.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

NL: Methodology, Writing – original draft. DA: Conceptualization, Writing – review & editing. LG: Data curation, Results. RO: Data curation, Formal analysis, Methodology, Writing – original draft. AJ: Writing – review & editing.

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Conflict of interest

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

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