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An Asymmetric Nexus between Urbanization and Technological Innovation and Environmental Sustainability in Ethiopia and Egypt: What Is the Role of Renewable Energy?

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Abstract: The present study investigates the nexus between urbanization, technological innovation, renewable energy consumption, and environmental quality in Egypt and Ethiopia from 1980 to 2020 by employing symmetric and asymmetric frameworks. Referring to symmetric assessment, the coefficient of renewable energy consumption and technological innovation revealed a negative and statistically significant tie with environmental sustainability, valid for both proxies. Study findings suggest that clean energy integration and technological innovations in the economy decrease environmental adversity by reducing carbon emissions and ecological blames. Although the elasticity of urbanization has documented a positive and statistically significant connection with environmental sustainability, the conclusion is valid for both models. Second, in the long run, the asymmetric shocks of renewable energy consumption and technological innovation have exposed a negative and statistically significant tie to environmental sustainability, whereas in the case of urbanization, the asymmetric shocks unveiled a positive and statistically significant association to environmental sustainability. Third, the study revealed that the feedback hypothesis explains the relationship between technological innovation and environmental sustainability [TI←→EF] in Egypt and ecological footprint and urbanization in Egypt and Ethiopia. Moreover, unidirectional causality runs from ecological footprint to renewable energy consumption in Egypt and Ethiopia.

Keywords: environmental sustainability; renewable energy consumption; technological innovation; urbanization; NARDL

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1. Introduction

The concern of environmental sustainability for ensuring sustainable economic development has emerged as a frequent discussion topic worldwide due to the adversity of climate change impact on socio-economic development. Environmental degradation through excessive carbon emission and ecological imbalance is the ultimate result of excessive application of energy, precisely fossil fuel, in aggregated economic activities. Environmental imbalance challenges not only economic sustainability but also puts human well–being in jeopardized [1,2]. Global CO_2 emissions have skyrocketed due to increased production and consumption rates and nations' attempts to attain rapid economic development. Consequently, throughout time, CO_2 emissions have risen [3]. Recent global warming of 1 C has been related to severe weather events, rising sea levels, the removal of Arctic Sea ice, and other negative outcomes. As long as pollution increases at the current pace, global warming will reach the 1.5 °C barrier between 2030 and 2050. Over 1.5 degrees Celsius of warming is expected to create long-term and permanent changes, including the extinction of specific ecosystems [4]. Human demand for natural resources is increasing due to fast economic expansion and development, which causes climate change, soil degradation, pollution of the environment, biodiversity loss, and greater susceptibility to economic development [5,6].

Nature is under growing strain from human activities, including depletion and extraction of natural resources, pollution, waste, and movement of creatures [7,8]. The consolidation of a large and rising human population, fast economic expansion, and the deployment of polluting and asset-depleting technology all contribute to environmental consequences or degradation [9]. There has been a steady rise in carbon dioxide emissions worldwide since the industrial revolution because people have become increasingly dependent on fossil fuels for economic change. As a result, more attention has been paid to the link between human-caused carbon emissions and climate change. Academics and politicians have performed much research on how carbon emissions affect environmental sustainability [10], one the other hand, many researchers have documented how to mitigate environmental adversity by lowering the carbon emission in the ecosystem [11–14]. CO_2 emissions are a contributing factor in both climate change and global warming. There is a pressing need for nations to work together to find a sustainable solution to the growing threat of climate change and global warming.

Existing literature has postulated and produced many studies on macro-fundamentals effects on environmental quality improvement\sustainability [7,15–19]. The study by Khan et al. [20], for instance, investigated the effects of trade openness, environmental innovation, and institutional quality on environmental sustainability. They revealed that trade openness and renewable energy are negatively tied to carbon emission, suggesting energy transition and domestic trade expansion support achieving the environmental quality in the case of India. Orhan, Adebayo, Genç, and Kirikkaleli [12] established that FDI inflows support environmental sustainability. In their study, Omri et al. [21] unveiled that economic growth, FDI, financial development, and trade openness adversely affected environmental sustainability. Alternatively, carbon emission has intensified with the progress of economic expansion, financial expansion, and domestic trade liberalization. Further evidence can be found in the study by Zameer et al. [22] for India.

The study considered urbanization, technological innovation, and renewable energy in environmental sustainability assessment for a discussion. Literature has suggested that CO_2 emissions occur due to natural and human activity, which is the progress of urbanization. Urbanization occurs due to population growth and horizontal and vertical expansion [23]. The development of a country's economy and society is inextricably linked to its built environment, defined as the man-made surroundings that provide infrastructure and facilities for human activity. As a consequence of urbanization, the construction industry's CO_2 emissions have increased significantly. According to the urbanization and environmental sustainability nexus, it is not unanimous among scientists. According to research, three basic theoretical models might explain how urbanization and environmental pollution are linked. According to the compact city theory and the idea of urban environmental development, urbanization results in environmental pollution. Carbon emissions have increased significantly due to urbanization, related to increased overcrowding and congestion in metropolitan areas [24]. Innovation in technology helps reduce energy consumption and carbon emissions by adopting environmentally-friendly technologies and transferring them to other industries. CO_2 emissions have decreased, and environmental standards have risen due to technological innovation. Furthermore, host countries' technological advancement and environmental regulation have cut pollution levels and increased environmental sustainability [25,26]. In the case of China, Jin, Duan, Shi, and Ju [26], established innovations in the energy industry to boost the efficiency of the energy system, hence lowering CO_2 emissions. The government must thus invest in energy research to ensure minimal carbon emissions.

The motivation of the study is to assess the impact of urbanization, technological innovation, and renewable energy on environmental sustainability in Egypt and Ethiopia from the period 1980 to 2020. In particular, we are interested in figuring out the contributory role of renewable energy, technological innovation, and urbanization in ensuring environmental sustainability. According to existing literature, macro fundamentals behave differently on environmental development due to the socio-economic structure of

the economy; thus, with this study, we prefer to assess the symmetric and asymmetric association between renewable energy, technological innovation, and urbanization on environmental sustainability.

As a case study, we focus on assessing the environmental sustainability of Ethiopia and Egypt; several factors have guided us in selecting both economies. First, Ethiopia is one of the world's poorest nations, with a mostly agricultural economy and a scarcity of natural resources [27,28]. Agriculture is well-known for its resource-intensive nature, and its development to feed the world's fast-rising population is wreaking havoc on close-to-natural habitats such as land, forest, water, grassland, and animals [29,30]. Its large population has strained practically all-natural resources' long-term viability. As a result, there is a major deterioration of land, water, forest, rangeland, and animal resources, which seems self-reinforcing [31]. This leads to significant soil erosion, limited vegetative cover, unsustainable agricultural methods, the ongoing use of dung and crop leftovers as fuel, overgrazing, and wildlife death and/or migration, all of which contribute to the deterioration of available resources in a vicious cycle [32]. The process exacerbates environmental impacts such as poor water quality, biodiversity loss, and ecosystem service loss. While Egypt, as far as environmental concern, has made achievements in environmental preservation and climate change mitigation with the introduction of electric buses, increasing the use of renewable energy, and plans to prohibit plastic bags. Furthermore, in the process of carbon emission reduction, Egypt, in 2016, initiated green-economy integration as a national strategy. The government is increasingly altering its procurement practices toward environmentally friendly products and sustainable technologies.

The present study has extended the existing literature surrounding environmental sustainability in the following manners. First, with our best knowledge, the first-ever empirical study with environmental sustainability measuring carbon emission and ecological footprint focusing on Egypt and Ethiopia. When taking into account the recent literature, it is manifested that a growing number of studies with time series and panel data have been initiated and executed in exploring the impact of renewable energy consumption, technological innovation, and urbanization on environmental sustainability. However, the empirical assessment focusing on Egypt and Ethiopia's environmental issues has yet to be explored extensively; thus, we, with this study, have implemented an investigation to develop fresh insight and document the impact of renewable energy consumption, and technological innovation and urbanization on ensuring the environmental sustainability. Second, Existing literature has postulated that in measuring environmental sustainability, studies have extensively considered either carbon emission or ecological footprint, but a very negligible study has taken into account two proxies in a single study for a comparative assessment. The present study has considered carbon emission and ecological footprint to measure environmental sustainability for establishing fresh insights through a comparative assessment. Third, the present study has extended the existing literature in explaining the impact of renewable energy consumption, technological innovations, and urbanization through the asymmetric and asymmetric framework

Referring to symmetric assessment, the coefficient of renewable energy consumption and technological innovation revealed a negative and statistically significant tie with environmental sustainability, valid for both proxies. Study findings suggest that clean energy integration and technological innovations in the economy decrease environmental adversity by reducing carbon emissions and ecological blames. Although the elasticity of urbanization has documented a positive and statistically significant connection with environmental sustainability, the conclusion is valid for both models. It suggests that urbanization brings changes in the economy at the cost of environmental adversity; that is, industrialization and fossil energy consumption increase the tendency of environmental degradation, especially in the long run. Second, the asymmetric assessment study documented both the long-run and the short-run asymmetric association between renewable energy consumption, technological innovation, urbanization, and environmental sustainability. In the long run, the asymmetric shocks of renewable energy consumption and technological innovation have

exposed a negative and statistically significant tie to environmental sustainability, whereas in the case of urbanization, the asymmetric shocks unveiled a positive and statistically significant association to environmental sustainability. Third, the study revealed that the feedback hypothesis explains the relationship between technological innovation and environmental sustainability [TI←→EF] in Egypt and ecological footprint and urbanization in Egypt and Ethiopia. Moreover, unidirectional causality runs from ecological footprint to renewable energy consumption in Egypt and Ethiopia

The remainder of this paper is divided into the following sections: Section 2 deals with the literature survey focusing on the relationship between environmental sustainability, technological innovation, renewable energy consumption, and urbanization. Data, variables definition, and econometrical tools are explained in Section 3. The empirical model estimation and its interpretation are available in Section 4. Section 5 deals with the discussion of the study findings. Finally, the conclusion and recommendation are presented in Section 6.

2. Literature Review

In improving the environmental quality, according to the existing literature, researchers, academicians, and policymakers have assessed and established several macro-fundamentals that can significantly support this regard [33–36]. The study, for instance, has investigated the impact of renewable and non-renewable energy consumption on carbon emission, and the study documented that renewable energy development assists in carbon emission reduction. In another study, the impact of FDI inflows on environmental sustainability has been documented with an adverse note [37]. Furthermore, the role of environmental regulation, environmental innovation, globalization, financial development, trade openness, and others has been extensively examined; however, the conclusive evidence has yet to reach because the socio-economic structure and country's economic status have produced diversity and inconsistent effects on the environment. The present study has focused on exploring the association between renewable energy consumption, technological innovation, urbanization, and environmental sustainability.

2.1. Renewable Energy and Environmental Sustainability

The economic literature of the recent past has extensively addressed the relationship between trade, renewable energy, economic growth, environmental technology innovation, and environmental assessment, and a growing number of research initiatives have examined the internal relationships between CO_2 emissions and the factors stated above. Mhenni [38] evaluated the EKC theory experimentally from 1980 to 1997 using GMM methods; the researcher analyzed carbon emissions, vehicle ownership, and fertilizer concentrations and concluded that environmental contaminants do not support the EKC hypothesis. Chebbi et al. [39] used a concentrated empirical technique to investigate the relationship between trade openness, per capita CO_2 emissions, and economic development. The empirical results established a causal relationship between carbon emissions, trade openness, and economic growth; additional research predicted a short-run relationship between trade openness and carbon emissions. Belloumi [40] previously investigated how energy use affects economic growth using the Johansen cointegration technique to demonstrate the long-run bidirectional causal relationship between economic growth and energy consumption. Fodha and Zaghdoud [41] also employed causality analysis to examine the relationship between economic policies, carbon emissions, and environmental degradation in emerging nations. VECM and Johansen causality analysis revealed a unidirectional causal relationship between economic growth and carbon emissions in short- and long-run empirical data.

Shahbaz and Lean [42] investigated the impact of macroeconomic indicators in Tunisia and how they influence energy consumption patterns. The adoption of ARDL as an empirical strategy suggested a long-run causal association between financial development, urbanization, industrialization, economic growth, environmental technologies, and energy

mix. In a recent study, Ben Jebli and Ben Youssef [43] studied the MENA region. They used VECM and granger causality analysis with structural breaks to analyze how international trade, energy consumption, GDP, patents, and per capita carbon emissions influence the economic and environmental outcomes. The research findings concluded that the short-run consumption of cleaner energy sources has a unidirectional causal association with GDP, fossil fuel consumption, trade, and carbon emission. The findings of the long-run empirical approach suggested that carbon emissions have a positive correlation with fossil fuel consumption and trade.

Our analysis of current literature advocates that most of the economic literature regarding the causal association between carbon emissions and macroeconomic variables mainly focuses on Tunisia, and authentic literature is scarce regarding Morocco. Nevertheless, many studies focusing on MENA countries have included Morocco. Arouri et al. [44] were among the pioneering research studies to examine the inter-relationship between GHG emissions, economic policies, and energy consumption for MENA countries to realize that continuous reliance on fossil fuels is the main contributor to higher carbon and GHG emissions in the Middle East and North Africa economies and development of environmental technologies is critical in safeguarding the environment. Furthermore, income elasticity satisfies the Kuznets curve in the MENA region except for Tunisia, Morocco, and United Arab Emirates. Similarly, Ben Aïssa et al. [45] analyzed how economic output, environmental patents, trade, and renewable energy consumption impact 11 African economies. The researchers showcased a causal association between trade and economic output in the short and the long run. However, the short-run causal analysis failed to establish causality amongst industrial output and green energy sources and trade, and renewable energy consumption. Jebli and Youssef [46] also relied on panel cointegration econometric methodologies to review the causal association between trade, industrial output, energy consumption, and economic output for a dataset obtained from 69 countries. The findings of the short-run analysis indicated the existence of a bidirectional causal association between industrial output and trade, trade and fossil fuel consumption, and a unidirectional causal association between renewable energy and international trade. The researchers also reported a long-run bidirectional causal association between renewable energy and trade. Furthermore, the econometric analysis of DOLS, FMOLS, and OLS indicated that continuous growth in industrial output has a positive correlation with international trade and fossil fuel consumption.

2.2. Technological Innovation and Environment Sustainability

It is expected that technological innovation will significantly impact pollution control. Technological progress and environmental legislation have decreased pollution levels and enhanced environmental sustainability in the host nations' environments. A growing number of researches have been carried out better to understand the link between technological innovation and environmental health. Using the example of China, Sun, Lu, Wang, Ma, and He [25] investigated the relationship between patent technology and CO_2 emissions. The researchers observed that technological advancement results in a significant reduction in carbon emissions. Their comparative analysis also found that, compared to other areas, the Eastern region is more effective in adopting innovations and environmentally friendly alternatives. The impact of technological advancements on China's carbon emissions was also explored by Jin, Duan, Shi, and Ju [26]. They found that technical improvements in the energy business increase energy system efficiency while simultaneously cutting CO_2 emissions using empirical evidence. Consequently, the government must invest money in energy research to keep carbon emissions at a bare minimum. Li et al. [47] studied the influence of technical advancements on CO_2 emissions in China, and their findings were similar. They concluded that technical advancements had a detrimental impact on pollution.

Researchers Chunling et al. [48] studied Pakistan's ecological footprint from 1992 to 2018 and found that governmental and private investment and developments in technology

influenced Pakistan's ecological footprint. ARDL bound testing is used to estimate the ecological footprint's long- and short-term amplitudes. According to a study, investing public and private money in energy causes an increase in the ecological footprint. In Pakistan, technological advancements have resulted in a smaller ecological impact. Yasmeen et al. [49] investigated the effects of biogas consumption, technological innovation, and FDI on the ecological footprint in B&R countries spinning from 1992 to 2017 by employing panel economic tools. According to the study, ecological footprint and biomass energy consumption negatively link the Belt and Road area. Foreign direct investment has shown that Belt and Road economies pollute hotspots (FDI). According to the data, technological advancement may help economies lessen their environmental effect. Furthermore, Lantz and Feng [50] investigated the influence of population, wealth, and technological improvement on Canada's CO_2 emissions. According to them, population growth and income levels contribute to the increase in CO_2 emissions, while technological improvement contributes to the decrease in CO_2 emissions. Their empirical results indicated that technological developments and structural changes in the economy would reduce carbon emissions. Similarly, Sohag et al. [51] examined the impact of technological breakthroughs on Malaysia's CO_2 emissions. According to their empirical evaluations, technological developments improve energy efficiency and reduce CO_2 emissions.

Additionally, the researchers emphasize that replacing obsolete technology with novel technologies can only be accomplished via public–private partnerships, stimulating innovation in renewable and energy-efficient technologies. Chen et al. [52] investigated the link between the environment and energy development in 30 nations between 1980 and 2014. Their results suggest that countries with high levels of greenhouse gas emissions may decrease pollution by increasing their investment in technological innovation. Shahzad et al. [53] investigated how new energy technologies influence the status of the environment in France. They concluded that technical improvements in the energy industry increase environmental quality. The authors of this study, Álvarez-Herránz et al. [54], looked at the relationship between air pollution and technological advancements in the energy sector in OECD nations from 1990 to 2012. According to the study's findings, developing nations should increase the proportion of their budgets allocated to the growth of the energy sector and broaden access to alternative forms of energy to cut CO_2 emissions.

2.3. Urbanization and Environmental Sustainability

As a demographic indicator, urbanization refers to the concentration of the population in urban areas as a result of economic change and social modernization. According to recent United Nations [55] projections, the world's urban population expanded from 30% in 1950 to 54% in 2014 and is predicted to rise by 2.5 billion people (about 66%) by 2050, with 90% of the growth concentrated in Asia and Africa's emerging areas. Africa's urban population rose from 15% in 1960 to 40% in 2010, with an additional 60% growth forecast for 2050. The study by Anane et al. [56] argued that if urbanization is not properly managed, this urbanization growth will have ramifications for the region's sustainable development. Thus, a thorough examination of the relationship between urbanization and environmental quality is critical for developing effective, sustainable development and climate change policies. Rapid urbanization is expected to increase energy consumption with economic expansion, resulting in increased environmental pollution.

The harmonic progression of urbanization, economic growth, and environmental protection is a significant area of study that bridges the social and natural sciences. Urbanization, economic growth, and the natural environment are theoretically connected via positive and negative consequences [57]. In most nations, urbanization is associated with fast economic expansion, population migration from rural regions to cities and towns, the concentration of secondary and tertiary industries in urban areas, and a rise in the number of towns growing in size daily. Urbanization affects the environment by altering the amounts of harmful emissions resulting from production shifts and changes in human behavior patterns due to migration from rural to urban regions. Developing a system for

determining and evaluating the dynamic impacts of urbanization and economic growth on a country's or region's environment.

Since the 1960s, global economic and social growth has focused on the negative ecological and environmental effects of urbanization. Urbanization influences more than just economic growth and population health, education, and socialization; it also impacts and is concerned with environmental protection and remediation and natural resource exploitation [58]. With the growth of empirical study on the interaction between people and the environment in recent years, many academics have focused on solutions that balance urbanization progress with environmental protection. When referring to the nexus between urbanization and environmental assessment, existing literature has produced two lines of evidence.

Nathaniel et al. [59] have investigated the role of energy consumption, natural resources, and urbanization in environmental quality, measured by ecological footprint for the period spinning in south Africa. The study employed autoregressive distributed lagged (ARDL) in assessing long-run and short-run magnitudes. Study findings revealed that urbanization, human capital development, and natural resources support environmental quality, whereas energy consumption leads to environmental degradation. Furthermore, the directional causality test documented the unidirectional effects of Urbanization on ecological footprint. A similar line of association has also been revealed in the studies by Nathaniel [60] and Nathaniel et al. [61]. Yasin et al. [62] have investigated the effects of financial development, urbanization, and political institutions on environmental quality by taking a panel of 59 LDCs nations through the application of Sys-GMM for the period spinning from 1996 to 2016. The study documented that financial development and foreign direct investment benefit environmental development, whereas urbanization was detrimental to environmental development. Thus, the study suggests that Environmental sustainability can be achieved by reducing private vehicle use through enhancing public transportation projects, reducing industrial emissions through the introduction of energy-efficient technologies, and incorporating environmentally friendly policies into the urbanization process. The environmental pressures associated with rising urbanization may be mitigated further by adequate planning and efficient design since well-planned urban communities use less energy and need less transportation.

2.4. Limitations of the Exciting Literature

1. When taking into account the recent literature, it is manifested that a growing number of studies with time series and panel data have been initiated and executed in exploring the impact of renewable energy consumption, technological innovation, and urbanization on environmental sustainability. However, the empirical assessment focusing on Egypt and Ethiopia's environmental issues has yet to be explored extensively; thus, we, with this study, have implemented an investigation to develop fresh insight and document the impact of renewable energy consumption, and technological innovation and urbanization on ensuring the environmental sustainability.
2. Existing literature has postulated that in measuring environmental sustainability, studies have extensively considered either carbon emission or ecological footprint, but a very negligible study has taken into account two proxies in a single study for a comparative assessment. The present study has considered carbon emission and ecological footprint to measure environmental sustainability for establishing fresh insights through a comparative assessment.
3. The present study has extended the existing literature in explaining the impact of renewable energy consumption, technological innovations, and urbanization through the asymmetric and asymmetric framework.

3. Data and Model

Model Specification

Several studies have investigated the effects of renewable energy, technological innovation, and urbanization on achieving the environment sustainably. See, for instance, [63–65].

The present study has extended the existing nexus with the inclusion of the EKC hypothesis. The motivation of the study is to evaluate the effects of clean energy, technological innovation, and urbanization on the environment, which is measured by carbon emission and ecological footprint for the period 1980–2020, and the generalized empirical model is as follows.

$$ES_{CO_2|EF} \int RE,\ TI,\ UR,\ X \quad (1)$$

where environmental quality is measured by carbon emission and ecological footprint, RE stands for renewable energy consumption, TI stands for technological innovation, UR denotes urbanization, and X for a list of control variables, respectively. Table 1 exhibits the variables' definitions and data sources.

Table 1. Variable definition and descriptive statistics.

Variables	Symbol	Definition	Sources
Ecological footprint	EF	Global hectares per capita	GFN (2019)
Carbon emission	CO_2	In metric ton/capita	WDI
Renewable energy	REC	Renewable energy consumed divided by the total energy	WDI
Urbanization	UR	Urban population (% of the total population)	WDI
Technological innovation	TI	No of patent application (resident + non-resident)	WDI
Economic growth	Y	GDP per capita (constant 2010 USD)	

The current study attempts to investigate the role of renewable energy, technological innovation, and urbanization on environmental quality in Ethiopia and Egypt through the following log model: furthermore, the model has been established with the widely accepted Environmental Kuznets Curve (EKC) following [66–68].

$$lnES_{2t} = \vartheta_0 + \vartheta_1 lnY_t + \vartheta_2 lnY_t^2 + \vartheta_3 lnRE_t + \vartheta_4 lnTI_t + \vartheta_5 lnU_t + \epsilon_t \quad (2)$$

In the equation mentioned above, $lnCO_2$ *and* $lnEF$ is taken as a proxy for environmental quality, lnY is the level of economic growth, lnY^2 is the nonlinear term to investigate the EKC hypothesis. $lnRE$ represents renewable energy consumption, $lnTI$ represents the level of technological innovation, $lnUR$ refers to urbanization, and ϵ accounts for the error term.

4. Econometric Methodology

4.1. Unit Root Test

Research variables' internal properties, commonly known as stationary properties, have played a critical role in selecting an appropriate economical method for examining the empirical assessment. The present study has employed several tests of stationary with the null hypothesis of stationary, that is, the ADF test [69], the P-P test [70], and the KPSS test (Kwiatkowski [71]). The results of conventional unit root test results display in.

4.2. Combined Cointegration Test

The novel proposed combined cointegration test was developed using joint statistics to test the null of no-cointegration. According to Bayer and Hanck [72], the separate cointegration test *p*-value is combined in Fisher's formula as follows:

$$\text{EG} - \text{JOH} = -2\left[ln\left(P_{EG}\right) + \left(P_{JOH}\right)\right] \quad (3)$$

$$\text{EG} - \text{JOH} - \text{BO} - \text{BDM} = -2\left[ln\left(P_{EG}\right) + \left(P_{JOH}\right) + \left(P_{BO}\right) + \left(P_{BDM}\right)\right] \quad (4)$$

4.2.1. Autoregressive Distributed Lagged (ARDL)

The prevail limitation in conventional cointegration tests, in the process of mitigating the problem, Pesaran et al. [73] have familiarized the cointegration test with a mixed order of variables integration which is commonly known as autoregressive distributed lagged (ARDL). Since then, the ARDL approach has been extensively used in investigating long-run associations in empirical studies [7,74–77]. ARDL estimation has possessed certain benefits over traditional cointegration tests, including; (1) according to Ghatak and Siddiki [78], ARDL can address the sample issue in empirical estimation; (2) model stability and efficiency may be achieved by adopting suitable lagged specifications for mixed-order variable integration [73]; (3) impartial assessment of elasticity across the long and short term can be established [79].

Following Pesaran, Shin, and Smith [73], the generalized ADRL model for the study considered detecting long-run and short-run coefficients by performing the following equation.

$$\begin{aligned}\Delta lnES_t = \alpha_0 + & \sum_{i=1}^{n} \mu_1 \Delta lnES_{t-i} + \sum_{i=0}^{n} \mu_2 \Delta lnUR_{t-i} + \sum_{i=0}^{n} \mu_3 \Delta lnTI_{t-i} + \sum_{i=0}^{n} \mu_4 \Delta lnRE_t \\ & + \sum_{i=0}^{n} \mu_5 \Delta lnY_{t-i} + \gamma_1 \Delta lnES_{t-i} + \gamma_2 lnUR_{t-1} + \gamma_3 lnTI_{t-1} + \gamma_4 lnRE_{t-1} \\ & + \gamma_5 lnY_{t-1} + \omega_{1t}\end{aligned} \tag{5}$$

Concerning the lagged period, $(t-1)$ represents the error term (white noise) and Δ denotes the different variables. The long-run and short-run coefficients of each empirical model estimate will be accessible from $\gamma_1 \ldots \gamma_5$; $\mu 1 \ldots \mu 5$ based on linear ARDL Equation (10). Please refers to Table 2 for the hypothesis test for long-run cointegration.

Table 2. The null hypotheses for all three tests are as follows.

Cointegration Test	Null Hypothesis	Alternative Hypothesis
F-bound test	$\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = \gamma_6 = 0$	Any, $\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6 \neq 0$
a *t*-test on lagged dependent variable	$\gamma_1 = 0$	$\gamma_1 \neq 0$

Pesaran, Shin, and Smith [73] and Sam et al. [80] presented two sets of asymptotic critical values, one for I(1) regressors and another for I(0) regressors. The study implemented the following equation with error correction terms to capture the short-run dynamics.

$$\begin{aligned}\Delta lnES_t = \alpha_2 + \sum_{i=1}^{n} \beta_1 \Delta lnES_{t-i} + \sum_{i=0}^{n} \beta_2 \Delta lnUR_{t-i} + \sum_{i=0}^{n} \beta_3 \Delta lnTI_{t-i} + \sum_{i=0}^{n} \beta_6 \Delta lnRE_t \\ + \sum_{i=0}^{n} \beta_7 \Delta lnY_{t-i} + \rho ECT_{t-1} + \omega_{1t}\end{aligned} \tag{6}$$

We utilized several different diagnostic tests, such as the test heteroscedasticity, serial correlation LM test, and the Ramsey RESET test. We also used the cumulative sum (CUSUM) and cumulative sum of squares tests to determine if the model was stable.

4.2.2. Nonlinear ARDL

The asymmetric shocks of urbanization, technological innovation, and renewable energy consumption on environmental sustainability will be explored by implementing the following nonlinear framework.

$$\Delta(lnES_2)_t = \sigma_0 + \Sigma_{k=1}^{p}\beta_{\alpha k}\Delta(lnES_2)_{t-k} + \Sigma_{k=0}^{p}\beta_{bk}\Delta(lnY)_{t-k} + \Sigma_{k=0}^{p}\beta_{ck}\Delta\left(lnY^2\right)_{t-k} + \Sigma_{k=0}^{p}\beta_{dk}\Delta(lnRE^+)_{t-k} + \Sigma_{k=0}^{p}\beta_{ek}\Delta(lnRE^-)_{t-k} + \Sigma_{k=0}^{p}\beta_{fk}\Delta(lnTI^+)_{t-k} + \Sigma_{k=0}^{p}\beta_{gk}\Delta(lnTI^-)_{t-k} + \Sigma_{k=0}^{p}\beta_{hk}\Delta(lnRE^+)_{t-k} + \Sigma_{k=0}^{p}\beta_{jk}\Delta(lnRE^-)_{t-k} + \beta_1(ES_2)_{t-1} + \beta_2(lnY)_{t-1} + \beta_3\left(lnY^2\right)_{t-1} + \beta_4(lnRE^+)_{t-1} + \beta_5(lnRE^-)_{t-1} + \beta_6(lnTI^+)_{t-1} + \beta_7(lnTI^-)_{t-1} + \beta_8(lnRE^+)_{t-1} + \beta_9(lnRE^-)_{t-1} + \mu_t \quad (7)$$

where the urbanization asymmetry is addressed by ($lnUR^+$, $lnIR^-$)., Technological innovation ($lnTI^+$, $lnTI^-$), and Renewable energy ($lnRE^+$, $lnRE^-$,). The positive and negative shock can be derived with the following equation,

$$lnRE^+ = \Sigma_{i=1}^{t} lnRE_i^+ + \Sigma_{i=1}^{t}\max(\Delta lnRE_i, 0) \quad (8)$$

$$lnRE^- = \Sigma_{i=1}^{t} lnRE_i^- + \Sigma_{i=1}^{t}\min(\Delta lnRE_i, 0) \quad (9)$$

$$lnTI^+ = \Sigma_{i=1}^{t} lnTI_i^+ + \Sigma_{i=1}^{t}\max(\Delta lnTI_i, 0) \quad (10)$$

$$lnTI^- = \Sigma_{i=1}^{t} lnTI_i^- + \Sigma_{i=1}^{t}\min(\Delta lnTI_i, 0) \quad (11)$$

$$lnU^+ = \Sigma_{i=1}^{t} lnU_i^+ + \Sigma_{i=1}^{t}\max(\Delta lnU_i, 0) \quad (12)$$

$$lnU^- = \Sigma_{i=1}^{t} lnU_i^- + \Sigma_{i=1}^{t}\min(\Delta lnU_i, 0) \quad (13)$$

4.3. Non-Granger Causality Test

A non-granger causality test was used to determine if the following model's variables were linked causally:

$$ES_t = \alpha_0 + \sum_{i=1}^{k}\beta_{1i}ES_{t-i} + \sum_{j=k+1}^{d_{max}}\beta_{2j}ES_{t-j} + \sum_{i=1}^{k}\gamma_{1i}REC_{t-i} + \sum_{j=k+1}^{d_{max}}\gamma_{1j}REC_{t-j} + \sum_{i=1}^{k}\varphi_{1i}EY_{t-i} + \sum_{j=k+1}^{d_{max}}\varphi_{1j}EI_{t-j} + \sum_{i=1}^{k}\delta_{1i}Y_{volt-i} + \sum_{j=k+1}^{d_{max}}\delta_{2j}Y_{volt-j} + \sum_{i=1}^{k}\delta_{1i}TR_{volt-i} + \sum_{j=k+1}^{d_{max}}\delta_{2j}TR_{volt-j} + \varepsilon_{1t} \quad (14)$$

5. Results and Discussion

5.1. Unit Root Test

Variables' stationarity properties have guided in selecting the appropriate econometrical techniques. The study implemented several unit root tests to document the variable's integration order. The result of the unit root test is displayed in Table 3. According to the test statistics, it is apparent that all the variables have espoused stationary either at a level or/and after first, neither variable have found stationary after second differences.

Table 3. Results of unit root test.

	At Level				After First Difference			
	ADF	**GF-DLS**	**PP**	**KPSS**	**ADF**	**GF-DLS**	**PP**	**KPSS**
				For Egypt				
EQ_1	−2.504	−0.818	−1.749	0.8960	−4.577	−3.369	−3.722	0.1270
EQ_2	−0.527	−2.373	−1.386	0.7370	−5.214	−2.099	−5.726	0.1760
RE	−2.51	−0.916	−0.861	0.9550	−6.535	−2.574	−5.457	0.1720
TI	−0.857	−0.203	−0.091	0.7250	−5.512	−3.725	−4.569	0.0880
UR	−1.188	−1.461	−0.11	0.8440	−4.161	−3.333	−5.633	0.1290
Y	−1.116	−2.835	−2.21	0.8850	−7.083	−2.614	−5.859	0.1080
				For Ethiopia				
EQ_1	−2.989	−1.261	−0.597	0.7770	−4.476	−2.822	−5.918	0.0830
EQ_2	−0.927	−0.797	−2.13	0.7270	−4.667	−3.855	−3.651	0.1030
RE	−2.829	−2.154	−2.899	0.8930	−4.425	−2.92	−5.624	0.1690
TI	−0.361	−0.195	−0.178	0.8020	−5.931	−4.562	−4.465	0.0990
UR	−2.722	−1.836	−0.126	0.6930	−7.334	−2.528	−3.341	0.0890
Y	−1.053	−1.939	−2.073	0.8400	−5.237	−3.769	−5.443	0.1320

5.2. Combined Cointegration Test

After assessing variables stationary, the study moves in detecting the long-run cointegration by employing the novel cointegration test proposed by Bayer and Hanck [72], and estimated results are displayed in Table 4. Referring to cointegration test statistics and critical value at 5%, it is apparent that test statistics are higher than the provided level of the household, suggesting the rejection of the null hypothesis alternatively confirmed the presence of a long-run association between EC, UR, TI, ES (CO_2 and EF). Now study moved to further estimation under the symmetry and asymmetry framework.

Table 4. Result of combined cointegration test.

		DIV	**1**	**2**	**3**	**4**	**5**
EG-JOH	Egypt	CO_2	13.938	13.765	12.356	13.497	11.157
		EF	11.848	11.182	12.891	11.303	11.016
	Ethiopia	CO_2	14.066	13.787	13.314	13.075	10.944
		EF	12.692	12.302	12.874	12.193	12.068
Critical value at 5%		CO_2	11.229	10.895	10.637	10.576	10.419
EG-JOH-BO-BDM	Egypt	EF	25.706	23.842	24.064	24.896	26.654
		CO_2	27.357	22.238	27.065	25.72	25.011
	Ethiopia	EF	24.987	27.432	27.494	22.989	25.87
		CO_2	27.172	23.256	24.712	27.547	24.138
Critical value at 5%			21.913	21.106	20.486	20.143	19.888

5.3. Long-Run and Short-Run Symmetric Investigation

The section estimates long-run and short-run coefficients of REC, UE, and EI on environmental quality by executing the earlier equation. The results of the empirical equation displayed in Table 5 represent the results in columns (1) and (3) with carbon emission as a proxy measuring environmental quality and in columns (2) and (4), where the ecological footprint is a measure of environmental quality.

Table 5. Long-run and short-run coefficient: ARDL bound testing.

	DIV: CO_2		**DIV: Ecological Footprint**	
Panel–A: long-run cointegration				
	(1)	(2)	(3)	(4)
	Egypt	Ethiopia	Egypt	Ethiopia
Fpass	12.641	10.614	12.991	10.552
Wpass	10.551	8.881	16.244	9.331
tBDM	−5.815	−4.228	−9.441	−4.612
Panel–B: Long-run coefficient				
GDP	0.0874 (0.045) [1.901]	0.1255 (0.019) [0.824]	0.0174 (0.017) [2.083]	25525 (0.02) [0.824]
GDP^2	−0.7389 (0.051) [−14.46]	−0.2741 (0.01) [−2.684]	−0.7389 (0.027) [−2.228]	−0.7417 (0.048) [−0.268]
RE	−0.1967 (0.026) [−7.547]	−0.2161 (0.016) [−2.024]	−0.1276 (0.03) [−0.984]	−0.1216 (0.01) [−2.024]
TI	−0.113 (0.043) [−2.595]	0.1738 (0.049) [1.757]	−0.1277 (0.029) [−1.075]	0.1388 (0.041) [1.757]
UR	0.1041 (0.023) [4.398]	0.1906 (0.037) [1.275]	0.0841 (0.015) [0.108]	0.1286 (0.01) [1.275]
C	−1.5613 (0.021) [−71.49]	−1.6582 (0.009) [−3.875]	−2.6134 (0.017) [−3.073]	−0.1582 (0.036) [−3.875]

Table 5. *Cont.*

	DIV: CO_2		DIV: Ecological Footprint	
Panel–C: Short-run coefficient				
GDP	0.3815 (0.052) [7.241]	0.0547 (0.037) [0.812]	0.0815 (0.02) [1.908]	0.1473 (0.044) [0.812]
GDP^2	−0.894 (0.012) [−73.404]	−0.0489 (0.014) [−0.267]	−1.9406 (0.018) [−2.047]	−0.0898 (0.047) [−0.267]
RE	−0.0492 (0.03) [−1.59]	−0.0451 (0.002) [2.197]	−0.0928 (0.0021) [−0.971]	−0.0515 (0.002) [2.597]
TI	−0.042 (0.041) [−1.01]	0.0157 (0.048) [2.084]	−0.052 (0.016) [−1.151]	0.057 (0.046) [2.084]
U	0.0432 (0.025) [1.701]	−0.0821 (0.037) [−1.233]	0.0132 (0.0023) [5.108]	−0.0212 (0.041) [−1.233]
ECT(−1)	−0.6261 (0.038) [−16.104]	−0.5308 (0.049) [−11.645]	−0.6261 (0.017) [−4.552]	−0.3308 (0.053) [−11.645]
Panel–D: Residual Diagnostic test				
x^2_{Auto}	0.448	0.959	0.533	0.031
x^2_{Het}	0.186	0.691	0.329	0.782
x^2_{Nor}	0.53	0.471	0.988	0.241
x^2_{RESET}	0.411	0.745	0.744	0.907

Note: the values () report standard error and [] for t-statistics.

The study investigated long-run cointegration by employing bound testing (Fpass) following Pesaran, Shin, and Smith [73], the joint probability test (Wpass), and tBDM following Banerjee et al. [81] for all model assessments. Panel–A in Table 4 reports the test statistics of different assessments; it is apparent that all the test statistics are statistically significant at a 1% level, suggesting the long-run association among research variables in all four tested models. Once the long run is available, the study moves in gauging the elasticities of each indented variable on the target variable.

Refers to the long-run coefficients of REC, UR, and TI on environmental sustainability; please see Panel–B in Table 5. Referring to the estimated output displayed in columns (1) and (3) with environmental sustainability carbon emission measures. The study documented that renewable energy inclusion supports carbon emission management in the environment, suggesting that renewable energy consumption has a negative and statistically significant association with environmental quality in Egypt (Ethiopia) with a coefficient of −0.1967 (−0.1276). Study findings suggest renewable energy integration instead of fossil fuel in industrial output can reduce the present state of carbon emission in the ecosystem. More precisely, a 1% growth in renewable energy integration in Egypt (Ethiopia) can decrease the present trend in carbon emission in the environment by 1.967% (1.276%). Our findings are in line with existing literature such as Adebayo and Kirikkaleli [17], Wang et al. [82], Andriamahery, and Qamruzzaman [7]. In the short run (see Panel–C, Table 3), the study documented a similar line of the image that is negative and statistically significant in Egypt (Ethiopia) with a coefficient of −0.0491 (−0.0928). According to the elasticity of renewable energy consumption on environmental quality achievement through carbon emission, the study has documented that energy transition from fossil fuel to renewable energy/clean energy can improve environmental imbalance both in the long-run and short-run horizon even the long magnitudes are more prominent than short-run.

Refers to the renewable energy–ecological footprint nexus (see results displayed in columns (2) and (4)). In the long run, study findings have documented negative and statistically significant associations in Egypt (a coefficient of −0.2161) and Ethiopia (a coefficient of −0.1216), suggesting environmental quality has improved with renewable energy consumption. More particularly, a 10% increase in renewable energy consumption

can reduce ecological footprint by 2.161% in Egypt and 1.216 in Ethiopia, eventually supporting environmental development with ecological balance. Our findings are in line with existing literature such as Nathaniel and Khan [83], Udemba [84], and Sahoo and Sethi [85]. Furthermore, renewable energy consumption has been negative and statistically significant in the short run, with an ecological footprint in Egypt (a coefficient of −0.0451) and Ethiopia (a coefficient of −0.0515), implying that clean energy consumption boosts environmental quality.

Energy-efficient technological integration through technological innovation has emerged as an alternative mode of environmental development by lowering carbon emissions and ecological development. The study has documented a negative and statistically significant nexus between technological innovation and carbon emission; see results displayed in columns (1) and (3) of Table 5 in Egypt (a coefficient of −0.113) and Ethiopia (a coefficient of −0.1277). In particular, a 10% development in technological innovation can reduce carbon emission in the ecosystem in Egypt by 1.13% and in Ethiopia by 1.277%. Thus promotion of technological innovation in industrial development should have the capacity to boost environmental sustainability by lowering the carbon emission rate. Our study findings are in line with Adebayo and Kirikkaleli [17]. Mensah et al. [86] investigated the impact of technological breakthroughs on CO_2 emissions in the 28 OECD countries studied from 1990 to 2014. Their results revealed that technological innovation might help reduce CO_2 emissions. Furthermore, the findings indicated that the EKC hypothesis did not exist for the OECD economies. From 2004 to 2012, Cho and Sohn [87] investigated the relationship between green patent applications and carbon emissions in Italy, Germany, France, and the United Kingdom. Their empirical results highlighted the importance of green technology in reducing carbon emissions.

Moreover, a positive and statistically significant linkage was revealed between technological innovation and ecological footprint (see results reported in columns (2) and (4) of Table 5) in Egypt (a coefficient of 0.1738) and Ethiopia (a coefficient of 0.1388). Study findings of negative nexus between TI and CO_2 have been supported by the literature such as ash and the positive nexus between TI and ecological footprint in line with empirical findings such as Ahmad et al. [88], Yasmeen et al. [49]. Referring to the short-run assessment (see Panel–C), technological innovation revealed a negative and statistically significant tie with carbon emission in Egypt (a coefficient of −0.042) and in Ethiopia (a coefficient −0.052) and a positive and statistically significant interlinkages with an ecological footprint in Egypt (a coefficient of 0.0157) and Ethiopia (a coefficient of 0.057).

The nexus between urbanization and environmental quality (see results reported in columns (1)–(3) of Table 5), the study documented negative and statistically significant linkage in Egypt (Ethiopia) both in the long-run and short-run. In the long run, a 10% development in urbanization can create destructive forces in augmenting the present carbon emission level by 1.041% (0.841%). In contrast, in the short run, the effects of urbanization can be observed on the environment by 0.432% (0.132%). Study findings postulated that Urbanization has a detrimental role in achieving environmental sustainability; that is, urbanization has augmented the level of carbon emission in the ecosystem, which is in line with existing literature such as Busu and Nedelcu [89]. Ciupăgeanu et al. [90]. Furthermore, the urbanization effects on the ecological footprint (see columns (2) and (4) in Table 5) study exposed positive and statistically significant associations in Egypt (a coefficient of 0.1906) and Ethiopia (a coefficient of 0.1286), suggesting a 10% progress in urbanization can result in an increase in ecological footprint in Egypt by 1.906% and Ethiopia by 1.286%. Our findings are in line with empirical findings such as Nathaniel [60], Nathaniel, Bekun, and Faizulayev [59], and Destek et al. [91]. Study findings advocated that urbanization accelerates economic growth by allowing industrialization for a higher level of aggregate output, which eventually leads to a higher level of energy consumption, especially for conventional energy consumption. Furthermore, urbanization has augmented the economy's financial development and promoted industrial development in remote areas, eventually leading to energy consumption and inefficient technological integration, resulting in environmental

degradation [92]. Apart from energy demand escalation, urbanization has induced demand for infrastructural development, wastage management, and trade internationalization, eventually augmenting environmental degradation [93].

The coefficient of error correction terms (ECT) has revealed negative and statistically significant in all four model estimations, suggesting the long-run convergence due to the prior period shock to disequilibrium. The study has performed several residual diagnostic tests in ensuing empirical model estimation consistency and efficiency; the result of the diagnostic test is displayed in Panel–D of Table 5. According to all the test statistics, the empirical estimation is free from autocorrelation, residuals are normally distributed, and no issue for heteroskadacity.

5.4. Long-Run and Short-Run Asymmetric Assessment

The results of asymmetric empirical model estimation following a nonlinear framework are displayed in Table 6; particularly, the results displayed in columns (1) and (2) deal with carbon emission as a proxy of environmental quality, and in columns (3) and (4) is considered the environmental quality by ecological footprint.

Table 6. Results of long-run and short-run coefficients: NARDL Estimation.

	DIV: Carbon Emission (CO_2)		**DIV: Ecological Footprint (EF)**	
Panel–A: asymmetric cointegration				
	(1)	(2)	(3)	(4)
	Egypt	Ethiopia	Egypt	Ethiopia
Fpass	12.641	10.614	12.991	10.552
Wpass	10.551	8.881	16.244	9.331
tBDM	−5.815	−4.228	−9.441	−4.612
Panel–B: Long-run coefficients				
Y	0.213 (0.01) [20.5]	0.195 (0.018) [10.74]	0.132 (0.038) [3.438]	0.142 (0.027) [5.142]
Y^2	−0.185 (0.052) [−3.508]	−0.745 (0.069) [−10.774]	−0.275 (0.039) [−7.009]	−0.216 (0.043) [−4.974]
REC^+	−0.1502 (0.041) [−3.654]	−0.131 (0.023) [−5.73]	−0.165 (0.051) [−3.204]	−0.157 (0.05) [−3.119]
REC^-	−0.1541 (0.014) [−10.442]	−0.183 (0.021) [−8.534]	−0.258 (0.046) [−5.588]	−0.118 (0.025) [−4.598]
TI^+	−0.212 (0.011) [−19.152]	−0.153 (0.042) [−3.596]	−0.147 (0.051) [−2.883]	−0.032 (0.014) [−2.213]
TI^-	−0.171 (0.041) [−4.107]	−0.147 (0.031) [−4.675]	−0.142 (0.039) [−3.605]	−0.121 (0.028) [−4.312]
UR^+	0.168 (0.045) [3.739]	0.098 (0.038) [2.566]	0.119 (0.037) [−3.154]	0.104 (0.019) [5.384]
UR^-	0.087 (0.043) [2.028]	0.154 (0.04) [3.824]	0.165 (0.041) [−3.983]	0.085 (0.014) [5.93]
Panel–C: short-run coefficients				
C	10.51 (0.025) [1.92]	−0.381 (0.008) [−45.097]	−0.232 (0.022) [−10.237]	−0.133 (0.028) [−4.609]
Y	0.234 (0.014) [4.391]	0.23 (0.013) [17.498]	0.451 (0.036) [12.403]	0.712 (0.021) [33.888]
Y^2	−0.71 (0.036) [−2.342]	−0.145 (0.021) [−6.794]	−0.092 (0.039) [−3.126]	0.088 (0.032) [2.741]
REC^+	−0.088 (0.047) [−1.762]	−0.081 (0.026) [−3.052]	−0.023 (0.013) [−2.224]	−0.051 (0.015) [−3.255]

Table 6. *Cont.*

	DIV: Carbon Emission (CO_2)		**DIV: Ecological Footprint (EF)**	
REC^{-}	−0.045 (0.016) [−2.918]	−0.026 (0.035) [−0.759]	−0.062 (0.026) [−2.366]	−0.077 (0.05) [−1.543]
EI^{+}	−0.049 (0.03) [−2.927]	−0.065 (0.027) [−2.388]	−0.021 (0.034) [−0.632]	−0.145 (0.035) [4.129]
EI^{-}	−0.085 (0.019) [−2.677]	−0.039 (0.035) [−1.093]	−0.134 (0.035) [−3.813]	−0.538 (0.029) [−18.157]
UR^{+}	−0.097 (0.04) [−2.349]	0.024 (0.017) [1.376]	−0.018 (0.01) [−1.86]	−0.135 (0.013) [−9.797]
UR^{-}	0.057 (0.028) [3.792]	−0.047 (0.037) [−1.268]	0.116 (0.013) [8.594]	0.115 (0.033) [3.447]
CointEq (−1)	−0.341 (0.019) [−6.934]	−0.23 (0.012) [−18.332]	−0.39 (0.043) [−8.878]	−0.424 (0.016) [−26.185]
Long-run and short-run symmetry test				
W_{LR}^{REC}	12.748	13.861	10.653	8.261
W_{LR}^{TI}	10.628	11.867	9.575	14.269
W_{LR}^{UR}	8.636	8.235	13.367	13.881
W_{SR}^{REC}	9.203	14.517	10.188	11.515
W_{SR}^{TI}	10.029	8.47	9.888	12.354
W_{SR}^{UR}	8.829	11.408	13.167	13.859
Residual diagnostic test				
x^2_{Auto}	0.7759	0.6715	0.7998	0.7614
x^2_{Het}	0.7403	0.8299	0.8378	0.8409
x^2_{Nor}	0.7679	0.7706	0.8445	0.7545
x^2_{RESET}	0.8208	0.8208	0.6973	0.7786

Note: the values () report standard error and [] for t-statistics.

For long-run asymmetric cointegration, the statistics of Fpass, Wpass, and tBDM have been documented statistically significant at a 1% level in all four model assessments, suggesting the presence of asymmetric cointegration between renewable energy consumption ($REC^{+/-}$), technological innovation ($TI^{+/-}$), urbanization ($UR^{+/-}$) and environmental quality in Egypt and Ethiopia. Once the asymmetric cointegration is detected, the next step is to evaluate the long-run and short-run asymmetric elasticity.

Asymmetric effects of renewable energy consumption are positive and negative shocks in REC on carbon emission see columns (1) and (2) and on ecological footprint see columns (3) and (4). In referring to results displayed in columns (1) and (2), the study documented a negative and statistically significant linkage with carbon emission in Egypt [a coefficient of $REC^{+} = -0.150$ and $REC^{-} = -0.1541$] and in Ethiopia (a coefficient of $REC^{+} = -0.131$ and $REC^{-} = -0.183$). In particular, a 10% positive variation in renewable energy consumption can reduce carbon emission in Egypt by 1.5% and 1.315 in Ethiopia. In contrast, a similar rate of reluctance in integrating RE can augment environmental degradation by accelerating carbon emission by 1.541% in Egypt and 1.83% in Ethiopia. Study findings postulate that energy transition from fossil fuels to renewable sources is reasonably an alternative in mitigating carbon injection into the ecosystem. Furthermore, excessive use of conventional energy with less reliance on renewable sources can curse the environmental quality. Asymmetric impact of renewable energy on ecological footprint, see columns (3) and (4), has documented negative and statistically significant tie in Egypt [a coefficient of $REC^{+} = -0.165$ and $REC^{-} = -0.258$] and in Ethiopia (a coefficient of $REC^{+} = -0.2571$ and $REC^{-} = -0.118$]. More specifically, a 1% positive development in renewable energy inclusion in Egypt (Ethiopia) can positive causes in improving the environmental development by 1.65% (2.57%), whereas a similar rate of a negative trend in renewable energy sources inclusion can result in further degradation of environmental qual-

ity by 2.58% in Egypt and by 1.18% in Ethiopia. Regarding the nexus between renewable energy consumption and ecological footprint, the study postulated that policies encouraging the inclusion of renewable energy sources should be taken care of appropriately so that environmental quality should not be the cost of further development.

The nexus between asymmetric shocks of technological innovation and environmental quality is measured by carbon emission. Study documented negative and statistically significant connection in Egypt (a coefficient of $TI^{+} = -0.212$ and $REC^{-} = -0.171$] and in Ethiopia (a coefficient of $REC^{+} = -0.153$ and $REC^{-} = -0.147$). Specifically, a 10% positive variation in technological innovation can increase environmental quality by lowering carbon emissions by 2.12% in Egypt and 1.53% in Ethiopia. Moreover, a 10% downward trend in technological innovation in the economy critically plays a detrimental role in further degrading environmental quality. The increase in additional carbon emissions into the ecosystem by 1.71% in Egypt and by 1.47% in Ethiopia. Furthermore, the asymmetric shocks of technological innovation on ecological footprint revealed negative and statistically significant linkage, see columns (3) and (4), in Egypt (a coefficient of $TI^{+} = -0.147$ and $TI^{-} = -0.142$] and in Ethiopia (a coefficient of $TI^{+} = -0.032$ and $TI^{-} = -0.121$). In particular, a 10% development in technological innovation in the economy will improve Egypt's ecological footprint by 1.17% and Ethiopia by 0.32%. In contrast, a 10% decrease in technological advancement can further degrade environmental quality in both nations by 1.42% and 1.21%, respectively. Ke et al. [94] pustulated that technological innovation inhibits environmental degradation by including energy-efficient technological support in industrial output. Indeed, one of the most important strategies for reconciling the conflict between the economy and the environment is innovation. Previous studies have shown that technological progress either degrades or improves the quality of the ecological environment [95].

The study documented urbanization and environmental quality as positive and statistically significant connected in all four empirical assessments. Referring to results displayed in columns (1) and (2), the asymmetric shocks of urbanization established positive and statistically significant association with environmental quality in Egypt [a coefficient of $UR^{+} = 0.168$ and $UR^{-} = 0.087$] and in Ethiopia (a coefficient of $UR^{+} = 0.098$ and $UR^{-} = 0.154$). study findings advocate that a 10% growth in urbanization will intensify the environmental degradation with excessive carbon emission into the ecosystem by 168% in Egypt and Ethiopia by 0.98%, respectively. Moreover, the slowing down of the urbanization process by 10% can result in environmental development of 0.875 in Egypt and 1.54% in Ethiopia, respectively. Referring to results available in columns (3) and (4) that are asymmetric effects of urbanization on ecological footprint. A positive and statistically significant tie is available between them. Specifically, a 10% positive innovation in urbanization decreases the ecological footprint, that is, the degradation of environmental quality in Egypt by 1.19% and 1.04% in Ethiopia.

Conversely, a similar delay rate in urbanization can improve ecological development by 1.65% in Egypt and 0.85% in Ethiopia. Urbanization revealed a curse for environmental degradation, and it is because industrialization increased energy demand, especially the application of fossil fuel and non-renewable sources. Excessive use of conventional energy add carbon emission; furthermore, urbanization increases human wastage and other practicalities, which increases ecological imbalance and expedites degradation.

The standard Wald test has been employed in assessing the asymmetric relationship in the long-run and short-run with the null hypothesis of "symmetry". According to Wald test statistics (see panel –D), all the test statistics are statistically significant at a 1% level of significance, suggesting the rejection of the null hypothesis and alternatively established asymmetric association between REC, TI, UR, and environmental sustainability in Egypt and Ethiopia. The final verdict of asymmetric linkage is applicable in both the long-run and short-run. Furthermore, the study has implemented several residual diagnostic tests to ensure the model is efficient and robust. The diagnostic test statistics documented that

empirical models are free from serial correlation, residuals are normally distributed, and no issues relating to heteroskadacity.

Tables 5 and 6 report the empirical estimates for the asymmetric and symmetric ARDL approaches. It is evident from the findings that empirical outcomes for GDP and GDP^2 are significant under both empirical approaches. The positive coefficients for GDP and negative coefficient values for GDP^2 validate the EKC hypothesis for Egypt and Ethiopia. Our findings confirm that environmental quality initially deteriorates in both countries due to industrial activities but ultimately decreases after certain economic growth levels have been achieved.

5.4.1. Causality Test—VECM

The following section evaluates directional causality between environmental quality, renewable energy consumption, technological innovation, urbanization, and economic growth in Ethiopia and Egypt. The results of the directional causality test are displayed in Table 7, including panel A (B) for carbon emissions (Ecological Footprint) as a measure of environmental sustainability. The study documented several directional causalities; in particular, the feedback hypothesis hold in explaining the causal effects between REC and carbon emission [$CO_2 \leftarrow\rightarrow$REC]; technological innovation and carbon emission [TI$\leftarrow\rightarrow CO_2$] in both countries, and urbanization and carbon emission [UR$\leftarrow\rightarrow CO_2$] in Ethiopia. Furthermore, urbanization exposed unidirectional causality with carbon emission [UR$\rightarrow CO_2$].

Table 7. Results of short-run and long-run causalities.

	Short-Run Coefficients						**Target Causalities**
Panel–A: Environmental sustainability measured by carbon emission							
	CO_2	REC	TI	UR	Y	ECT (−1)	
CO_2		8.561 **	6.843 *	13.916 ***	3.431	−0.1308 ***	$CO_2 \leftarrow\rightarrow$REC; TI$\leftarrow\rightarrow CO_2$; UR$\rightarrow CO_2$; TI$\leftarrow\rightarrow$REC; UR$\rightarrow$REC; UR$\leftarrow\rightarrow$TI; Y$\leftarrow\rightarrow$TI; UR$\rightarrow$Y
REC	15.054 ***		10.651 **	9.229 **	5.957	0.0321	
TI	14.156 ***	6.271 *		12.055 ***	7.79 *	−0.0948 **	
UR	5.573	10.627	12.709 ***		6.441 *	0.0662	
Y	5.01	11.128 ***	13.983 ***	9.967 **		0.2624	
CO_2		11.462 ***	14.109 ***	12.868 ***	14.749 ***	−0.2628 ***	$CO_2 \leftarrow\rightarrow$REC; $CO_2 \leftarrow\rightarrow$TI; $CO_2 \leftarrow\rightarrow$UR; $CO_2 \leftarrow\rightarrow$Y; TI$\rightarrow$REC; Y$\leftarrow\rightarrow$TI; REC$\rightarrow$UR; UR$\rightarrow$Y.
REC	13.54 ***		6.001 *	4.626	3.311	0.0002	
TI	9.053 **	2.791		5.864	8.59 *	0.0635	
UR	15.024 ***	9.171 **	1.806		3.928	−0.0627 **	
Y	12.07 ***	13.279 ***	11.929 ***	6.196 *		0.2465	
Panel–B: Environmental sustainability measured by ecological footprint							
EF		4.925	12.371 ***	10.283 ***	12.97 ***	−0.0474 ***	TI$\leftarrow\rightarrow$EF; EF$\rightarrow$REC; UR$\leftarrow\rightarrow$EF; Y$\leftarrow\rightarrow$EF; REC$\leftarrow\rightarrow$Y; UR$\leftarrow\rightarrow$Y, Y$\rightarrow$TI
REC	14.211 ***		5.664	5.396	6.421 *	0.1211	
TI	13.117 ***	8.259 *		5.919	11.059 ***	−0.2208 ***	
UR	10.462 ***	9.812	5.215		9.221 **	0.0494	
Y	11.765 **	7.088	4.458	12.148 ***		0.0169	
EF		5.702	3.785	12.97 ***	2.944	−0.2457 ***	EF$\leftarrow\rightarrow$UR; EF$\rightarrow$TI; EF$\rightarrow$REC; EF$\rightarrow$Y; TI$\leftarrow\rightarrow$UR; REC$\leftarrow\rightarrow$UR
REC	8.964 *		14.792 ***	13.734 ***	5.588	−0.0632 *	
TI	11.991 ***	5.825		10.285 ***	6.51 *	0.1158	
UR	6.692 *	6.89 *	4.675		13.093	0.0989	
Y	7.316 *	3.183	6.39 *	14.17 ***		0.1825	

The superscript of */**/*** denotes the level of significant at a 10%, 5%, and 1%, respectively.

Refers to causalities with ecological footprint proxied by environmental sustainability. The study revealed that the feedback hypothesis explains the relationship between technological innovation and environmental sustainability [TI$\leftarrow\rightarrow$EF] in Egypt and ecological footprint and urbanization in Egypt and Ethiopia. Moreover, unidirectional causality runs from ecological footprint to renewable energy consumption in Egypt and Ethiopia.

5.4.2. Empirical Model Robustness Test with FMOLS, DOLS, CCR

Next, following the existing literature, the study extended the empirical assessment to validate the nature of the association between renewable energy consumption, urbanization, technological innovation, and environmental sustainability by Dynamic OLS, fully modified OLS following Phillips and Hansen [96], and Canonical Cointegrating Regression (CCR) familiarized by Stock and Watson [97]. The robustness test results display in Table 8.

Table 8. Results of Robustness test.

Regressors	**FMOLS**			**DOLS**			**CCR**		
Panel–A: environmental sustainability measured by Carbon emission									
	Co-Eff	error	Statistic	Coeff	error	Statistic	Coeff	error	Statistic
For Egypt									
REC	−0.1001	0.0781	−1.2816	−0.1934	0.0523	−3.6978	−0.2126	0.046	−4.6217
UR	0.1037	0.0323	3.2105	0.2626	0.0498	5.2730	−0.2139	0.0791	−2.7041
TI	−0.1903	0.0336	−5.6636	−0.1421	0.0529	2.6862	−0.1804	0.0332	5.4337
Y	0.1242	0.0342	3.6315	0.232	0.0413	5.6174	0.2362	0.0518	4.5598
Y^2	−0.1041	0.0424	−2.4551	−0.1164	0.074	−1.5729	−0.1835	0.0482	−3.8070
R^2		0.9906		0.9835				0.9825	
Adj-R^2		0.9783		0.9761				0.9783	
For Ethiopia									
REC	−0.1319	0.0414	−3.18599	−0.2514	0.0552	−4.5543	−0.2491	0.0419	−5.9451
UR	−0.1087	0.0427	−2.5456	0.2848	0.0638	4.4639	0.1522	0.0572	2.6608
TI	−0.149	0.0654	−2.2782	−0.2347	0.0468	−5.0149	−0.1581	0.0356	−4.4410
Y	0.1907	0.0355	5.3718	0.2509	0.0499	5.0280	0.1514	0.0369	4.1029
Y^2	0.1222	0.0302	4.0463	0.179	0.0663	2.6998	0.2245	0.0786	2.8562
R^2		0.9828		0.9783				0.9865	
Adj-R^2		0.9804		0.9777				0.9755	
Panel–B: environmental sustainability measured by ecological footprint									
Regressors	Co-Eff	error	Statistic	Coefficient	error	Statistic	Coefficient	error	Statistic
REC	−0.173	0.0513	−3.3723	−0.1533	0.0654	−2.3440	−0.1952	0.0787	−2.4803
UR	0.1156	0.0646	1.7894	0.2434	0.0296	8.2229	−0.2189	0.0374	−5.8529
TI	−0.1894	0.0579	−3.2711	−0.1307	0.031	−4.2161	−0.1937	0.0398	−4.8668
Y	0.178	0.0362	4.9171	0.2657	0.0314	8.4617	0.2101	0.0544	3.8621
Y^2	0.1111	0.0766	1.4503	0.1252	0.0712	1.758427	0.1878	0.0565	3.3238
R^2		0.9974		0.9833				0.995	
		0.9758		0.9771				0.9803	
Regressors	Co-Efficient	error	Statistic	Coefficient	error	Statistic	Coefficient	error	Statistic
REC	−0.1907	0.0328	−5.8140	−0.2535	0.0386	−6.5673	−0.1631	0.0386	−4.2253
UR	−0.1014	0.0696	−1.4568	−0.2177	0.0481	−4.5259	−0.1942	0.0312	−6.2243
TI	−0.1178	0.0643	−1.8327	−0.1624	0.0438	−3.7077	−0.194	0.0438	−4.4292
Y	0.1498	0.0626	2.3929	0.2192	0.0302	7.2582	0.1674	0.0782	2.1406
Y^2	−0.1784	0.0734	−2.4305	−0.1722	0.0452	−3.8097	−0.2566	0.0364	−7.0494
R^2		0.9773		0.9984				0.9832	
Adj-R^2		0.9784		0.979				0.9762	

5.5. Discussion of Results

Urbanization has exposed adverse associations to environmental sustainability, suggesting that economic progress with infrastructural development and industrialization has caused environmental consequences. More precisely, In the long run, a 10% development in urbanization can create destructive forces in augmenting the present carbon emission level by 1.041% (0.841%). In contrast, in the short run, the effects of urbanization can be observed on the environment by 0.432% (0.132%). Study findings postulated that Urbanization

has a detrimental role in achieving environmental sustainability; that is, urbanization has augmented the level of carbon emission in the ecosystem, which is in line with existing literature such as Busu and Nedelcu [89]., Nathaniel [60], Nathaniel, Bekun and Faizulayev [59], and Destek, Ulucak and Dogan [91]. Study findings advocated that urbanization accelerates economic growth by allowing industrialization for a higher level of aggregate output, which eventually leads to a higher level of energy consumption, especially for conventional energy consumption. Furthermore, urbanization has augmented the economy's financial development and promoted industrial development in remote areas, eventually leading to energy consumption and inefficient technological integration, resulting in environmental degradation. Apart from energy demand escalation, urbanization has induced demand for infrastructural development, wastage management, and trade internationalization, eventually augmenting environmental degradation.

The biggest danger to biodiversity is habitat loss. Furthermore, urbanization destroys and disrupts natural ecosystems. While forest interior habitats deteriorate and perish due to deforestation and fragmentation, forest edge habitats thrive [98]. As a result of these reasons, urban populations are becoming more diverse and populous. Other urban features, such as roads, limit population dispersal and increase mortality rates; they also enable the introduction of alien species. The "urban heat island effect" refers to the phenomenon in which cities often have higher average temperatures than their rural counterparts. Urban heat islands alter precipitation patterns, promote ozone generation, disrupt biogeochemical processes, and endanger humans and wild animals. Furthermore, urbanization impacts the whole ecosystem of the area through precipitation and air pollution and the number of thunderstorm-filled days is higher in areas near major industrial complexes. Not only may urban areas impact weather patterns, but they can also influence water runoff patterns. Cities produce more rain, limiting water penetration and depleting groundwater resources. This implies that runoff happens more quickly when peak flows are higher. Flood levels, as well as floods and water toxicity downstream, continue to grow.

Clean energy integration with renewable sources has played a critical role in managing environmental adversity by lowering carbon emissions and ecological development. The present study has documented a positive association with environmental sustainability that renewable energy consumption assists in reducing carbon emission and ecological footprint improvement. In the long run, study findings have documented negative and statistically significant associations in Egypt (a coefficient of -0.2161) and Ethiopia (a coefficient of -0.1216), suggesting environmental quality has improved with renewable energy consumption. More particularly, a 10% increase in renewable energy consumption can reduce ecological footprint by 2.161% in Egypt and 1.216 in Ethiopia, eventually supporting environmental development with ecological balance. Our findings are in line with existing literature such as Nathaniel and Khan [83], Adebayo and Kirikkaleli [17], Wang, Bui, Zhang, Nawarathna, and Mombeuil [82], and Andriamahery and Qamruzzaman [7]. Sources of clean energy, including Solar, wind, and geothermal energy, are crucial for mitigating climate change and other environmental challenges. Renewable energy sources address the environmental challenges by lowering and emitting greenhouse gases and contribute little to traditional air pollution; their generation and distribution result in emissions and pollutants. Renewable energy will play a key part in power generation because we can reuse these resources to create useful energy. Typically, energy resources are classified as fossil, renewable, or nuclear. Renewable energy sources such as hydropower, wind, solar, biomass, ocean energy, biofuel, and geothermal account for 15–20 percent of global energy production.

As a consequence of rising energy consumption driven by a fast-expanding population, the globe is becoming a global village. This growing energy consumption necessitates the usage of fossil fuels such as coal, gas, and oil, resulting in unsustainable conditions and a host of issues such as fossil fuel depletion, environmental and geopolitical disputes, greenhouse effect, global warming, and shifting fuel costs. Because renewable energy is ecologically friendly and emits fewer greenhouse gases, it is referred to

as sustainable energy. It also helps society in several ways, including economic, social, and environmental.

According to study findings, environmental innovation has emerged as a catalyst in managing the environmental quality of technological innovation for environment support to energy efficiency, which eventually reduces environmental adversity. In particular, a 10% development in technological innovation can reduce carbon emission in the ecosystem in Egypt by 1.13% and in Ethiopia by 1.277%. Thus, the promotion of technological innovation in industrial development should have the capacity to boost environmental sustainability by lowering the carbon emission rate. Our study findings are in line with Adebayo and Kirikkaleli [17]. In a study, Mensah, Long, Boamah, Bediako, Dauda, and Salman [86] investigated the impact of technological breakthroughs on CO_2 emissions in the 28 OECD countries studied from 1990 to 2014. Their results revealed that technological innovation might help reduce CO_2 emissions. Furthermore, the findings indicated that the EKC hypothesis did not exist for the OECD economies. From 2004 to 2012, Cho and Sohn [87] investigated the relationship between green patent applications and carbon emissions in Italy, Germany, France, and the United Kingdom. Their empirical results highlighted the importance of green technology in reducing carbon emissions. The study finding is in line with existing literature see, for instance, Ahmad, Jiang, Majeed, Umar, Khan, and Muhammad [88]. The study by Khan et al. [99] advocated that it is imperative to encourage technological innovation in the economy with the collaboration of public and private investment to promote environmental quality. Attaining environmental sustainability will need effort across several fronts, including harnessing and using the potential of technological innovation, carbon capture and storage technologies, more effective irrigation techniques, and industrial processes to minimize waste and pollution. At the same time, existing public and private mechanisms at the national level can foster some necessary technological innovations, particularly in meeting the needs of the world's ecological balanced and marginalizing the environmental adversity on populations in the current and future generations.

6. Conclusions and Policy Implications

The motivation of the study is to engage an empirical investigation to explore the role of renewable energy consumption, urbanization, and technological innovation in managing environmental sustainability, which is measured by carbon emission and ecological footprint in Egypt and Ethiopia for the period 1980–2020.

The key study findings are as follows.

1. Refers to symmetric assessment, the coefficient of renewable energy consumption and technological innovation revealed a negative and statistically significant tie with environmental sustainability, valid for both proxies. Although the elasticity of urbanization has documented a positive and statistically significant connection with environmental sustainability, the conclusion is valid for both models.
2. Second, the asymmetric assessment study documented both the long-run and the short-run asymmetric association between renewable energy consumption, technological innovation, urbanization, and environmental sustainability.
3. Third, the study revealed that the feedback hypothesis explains the relationship between technological innovation and environmental sustainability [TI$\leftarrow\rightarrow$EF] in Egypt and ecological footprint and urbanization in Egypt and Ethiopia. Moreover, unidirectional causality runs from ecological footprint to renewable energy consumption in Egypt and Ethiopia.

On a policy note, the study has suggested that

(a) It is important to stimulate technological innovation not just to guarantee cleaner consumption at home but also cleaner manufacturing;
(b) Through public–private partnerships, investments in renewable energy consumption should be promoted, while the disadvantages of public–private partnerships in

nonrenewable energy sources should be discouraged or redirected to the renewables sector; and

(c) Promote public–private partnerships for the use of renewable energy.

The present study is not out of certain limitations: first, the study of renewable energy is considered a source of clean energy; however, the effects of energy efficiency can be added in the future study. Second, institutional development articulates that governmental effectiveness can be considered in ensuring environmental sustainability. Third, macro-fundamental uncertainty has an immense impact on policy formulation and effective implementation. Thus, it is suggested to incorporate economic policy uncertainty in empirical assessment.

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