




RESEARCH ARTICLE

Information and communication technologies and sustainable development in ECOWAS subregion: Evidence from a panel cointegration analysis

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This study investigated the causal linkage between information and communication technologies (ICT) and sustainable development (environmental–CO₂, economic–RGDP, and social–HDI) in the ECOWAS subregion categorized into low-income and lower-middle-income countries for the period 1995–2020. Cointegrating regression and causality methods were employed to estimate the dynamic linkage among variables in panel fully modified ordinary least squares (PFMOLS) and Dumitrescu–Hurlin causality models. The results of the study support the environmental Kuznets curve (EKC) hypothesis for low-income countries while it rejects EKC for lower-middle-income countries. The study recommends policy formulations targeted at incentivizing the use of environmentally friendly technologies that minimizes positive impact on the environment and enhance sustainable development.

1 | INTRODUCTION

African nations including other developing countries are faced with deteriorating economic prospects due largely to wide spread poverty and unemployment. However, it has been observed that in the pursuit of economic development, many countries ignore environmental degradation and its consequences, thus leading to unsustainable environment. This development birthed the paradigm shift from economic development to sustainable development, which refers to “development that cares for and propagates safe environment for present and future generations to be able to meet their needs.” Justice (2019) posits that sustainable development requires balanced integration of economic, social, and environmental dimensions of development. In recent decades, the world became a global village due to easy and faster modes of connectivity, thus enhancing economic growth and development.

To achieve sustainable development through the realization of long-term sustainable economic growth in a less threatened environment, information and communication technologies (ICTs) are considered very pertinent (Hou et al., 2015). The advancement in ICTs has

penetrated every sector of the modern economy, and all spheres of life and its utilization increase daily (Lee et al., 2017). According to the International Telecommunication Union's (ITU) Report, the number of internet users have taken a massive jump from 400 million in year 2000 to 3.2 billion in year 2015 (Kashif et al., 2019). This has obvious consequences on the environment. For instance, Houghton (2015) observed that growth in ICTs diminished environmental safety by increasing e-wastes. According to Zhang & Liu, 2015, there are cycles of ICT known as life cycle theory of ICT, which spans from production, delivery, transport and disposal, resulting in pollution. Therefore, globalization propelled by ICT and increase in technology have combined to increase environmental pollution caused by ICT. Majeed (2018) opines that ICT industry contributes 2% of global carbon emissions, which represent 830 MtCO₂ of carbon footprint emission in 2007.

According to Lashkarizadeh and Salatin (2012), ICTs facilitate environmental protection and helps in reducing the adverse impacts on the environment of human activities. It has been observed that ICT-dependent solutions foster and ensure environment sustainability by reducing emission of greenhouse gases (Uddin & Rahman, 2012). ICTs support and boost industrialization, productivity, economic

growth and public health (Asongu & Le Roux, 2017; Hafeez et al., 2019; Khan et al., 2018; Pradhan et al., 2017). Therefore, as nations advance in ICT consumption, its consequences on the environment become a cause for concern as energy consumption related to ICT consumption increases (Naser et al., 2016).

No doubt, economic development is facilitated by optimal energy consumption and ICT, which impact on the environment positively or negatively. Measuring the quantitative relationship between environmental quality and ICT growth has raised a number of controversies. These controversies resulting in divergent conclusions are not unconnected with the methods used in advancing previous studies. Wu and Raghupathi (2018) examined ICT-environment nexus employing multivariate analysis and found that ICT has positively relationship. This result supports the finding of Gouvea et al. (2018) who used inferential analytical technique. In contrast, AñónHigón et al. (2017) found a dynamic relationship between ICT and environment sustainability with an inverted U-curve shape using panel analysis. However, the present study sought to estimate the dynamic linkage among variables in panel fully modified ordinary least squares (PFMOLS) and Dumitrescu–Hurlin (DH) causality models, which are more robust and capable of the problem of heterogeneity with differences in means among the individuals and differences in individual responses to short-run disturbances from cointegrating equilibrium. Furthermore, these empirical cross-country studies ignored the different levels of economic development or economic growth or income levels prevalent in individual countries in their investigation of the impact of ICT on environmental sustainability. These gaps became the core of this paper, which seeks to investigate if differences in income levels account for different impact of ICT on environmental sustainability within the ECOWAS subregion. Countries investigated include Senegal, Nigeria, Ghana, Cote d'Ivoire, Cabo-Verde, and Benin as lower-middle-income West African countries and Togo, Sierra Leone, Niger Republic, Mali, Liberia, Guinea-Bissau, The Gambia, and Burkina Faso as low-income West African countries (Onuoha et al., 2021). The World Bank classified 189 member countries and all other economies with populations of more than 30,000. For operational and analytical purposes, economies were divided among income groups according to 2018 gross national income (GNI) per capita, calculated using the World Bank Atlas method. The groups are low income, \$1025 or less; lower middle income, \$1026–3995; upper middle income, \$3996–12,375; and high income, \$12,375 or more.

This study is expected to assist African countries develop policy framework appropriate for ICT–environment nexus for optimal environmentally friendly economic development. This paper is structured as follows: Section 1 introduces the paper, thus bringing out the gaps or problem of the study. In Section 2, we review related literature, while Section 3 exposes the framework and methods that are adopted in the advancement of this study. In Section 4, the results of the study, analysis, and discussion of results are undertaken, while in Section 5, we conclude and present the policy implications of the study.

2 | LITERATURE REVIEW

2.1 | Theoretical considerations

2.1.1 | ICT and the carbon emission

The environmental Kuznets curve (EKC) hypothesis propounded by Simon Kuznet in 1955 (Kuznet, 1955) describes the association between economic growth and the environment as inverted U-shaped. It explains that exploration, exploitation, and other economic activities during the early stage of economic advancement gives rise to release of pathogens and other pollutants that are harmful to the environment. But as income continues to grow, better and modern technologies are utilized in harnessing/exploiting resources, thus decreasing the indirect effect of rising economic activities on the environment. This decrease can further be attributed to greater environmental health consciousness and research and development as well as improved input and output methods, which are all geared toward achieving a cleaner and greener environment.

Scholars have since been investigating the validity or otherwise of the inverted U-shaped EKC hypothesis for different economies using different variables, time frame, tools of analysis, and so on. Studies by Grossman and Krueger (1991), Shafik and Banyopadhyay (1992), Kong and Khan (2019), Sisay and Belaz (2020), Phong Le and Ozturk (2020), and Maneejuk et al. (2020) all confirm the existence of EKC. Grossman and Krueger (1991) studying the impact of NAFTA on the environment validated EKC linkage between the environment and two pollutants of interest such as sulfur dioxide and suspended particulate matter, thus affirming the existence of EKC hypothesis. Shafik and Banyopadhyay (1992) using eight indicators of environmental quality for different countries found that deliberate investments over time can reduce environmental degradation. Maneejuk et al. (2020) found that out of all the forty-four countries studied, nine validates the existence of EKC.

However, other investigations have also refuted the inverted U-shaped EKC hypothesis. Pal and Mitra (2017) examined carbon emission and economic activity in India and China between 1971 and 2012 to establish validation for inverted U-shaped EKC. Using ARDL, they found an N-shaped relationship between environment and economic activities which is a departure from the inverted U-shaped. Also, Moutinho et al. (2017) using data from 13 sectors of the Portuguese and Spanish economies between 1975 and 2021 found an N-shaped association between the environment and economic growth. Amri et al. (2019) using data between 1975 and 2014 for Tunisia and employing ARDL refute the existence of EKC, while confirming that ICT insignificantly impacted environmental health. Again, an N-shaped linkage was revealed between ICT and the Turkish environment from 1980 to 2017 from a study by Baris-Tuzemen et al. (2020).

2.1.2 | ITC, economic growth, and HDI

The Solow growth theory

This economic growth theory credited to neoclassical economists Robert Solow and Trevor Swan in 1956 has as its crux that

economic growth is dependent on three factors: labor, capital, and technology. Mathematically, $E=f(L+K+Tt)$, where E is economic growth, L is labor, K is capital, and T is technology and subscript t means that technology is exogenous in the given economy. It indicates that labor and capital can be limited in an economy's space, but the impact of technology is limitless, as it can be exogenous to any given economy. This justifies the reason why technology influences the output of labor and capital directly and indirectly and so determines to a large extent economic growth outcomes (Nasab & Aghaei, 2009; Pradhan et al., 2018). This theory connects the variables of this study very well. The present study seeks to understand the impact of ICTs on sustainable development.

Using generalized methods of moments (GMM), Nasab and Aghaei (2009) on data from OPEC member countries between 1990 and 2007 found that ICT significantly impacts economic growth. Pradhan et al. (2018) examining whether the gains of ICT differ in various economic levels of advancement used panel data of 59 countries between 1995 and 2010. The study found that developing, emerging, and developed economies all gained enormously from ICT investment. Also, Toader et al. (2018), using panel data technique covering 2000–2017 for all the EU countries, found a strong positive influence of ICT on economic advancement in the studied nations.

Nevertheless, empirical evidences have also emerged to affirm a positive connection between ICT and HDI. De La Hoz-Rosales et al. (2019), using panel data technique for 145 countries, confirms that irrespective of the level of development, ICT positively impacts human development. Iqbal et al. (2019) using panel data of five Asian countries between 1990 and 2016 found a mixed impact, while use of phones enhances human development and use of Internet impacted human development negatively. Conversely, Balouza (2019) studying six Gulf Cooperation Council Countries using three key components of health, income, and education between 2005 and 2014 found that ICT only cannot advance human development, but a wider and all-encompassing dimensional strategy that aims to enhance people's ability to appreciate ICT will achieve a wider gain.

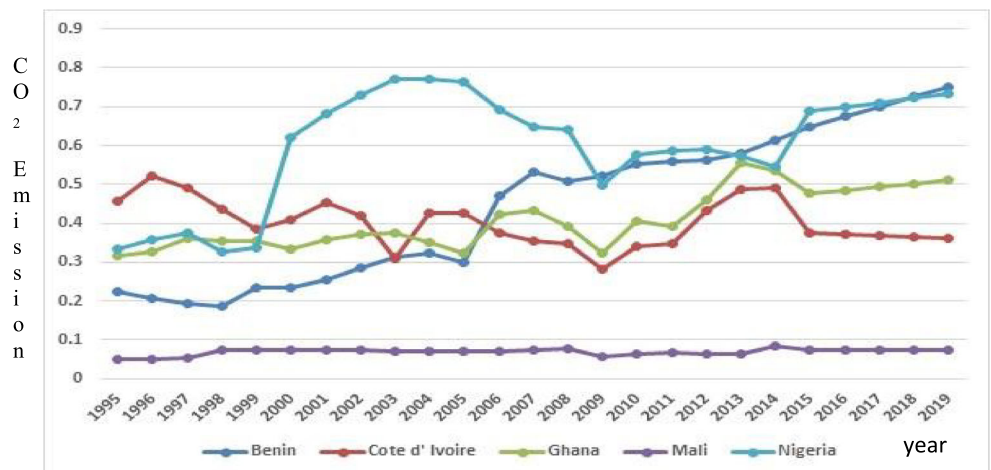
2.2 | Stylized facts

Carbon dioxide emission (CO₂) is expected to vary in both low-income and lower-middle-income countries. This variation may depend on the level of income or on other variables not connected to income levels. Figure 1 depicts the emission level of CO₂ in some targeted West African countries. Evidence shows that while Mali (low-income country) has marginal increase in CO₂ emission, countries like Nigeria (lower-middle-income country), Benin (low-income country), and Ghana (lower-middle-income country) had pronounced increase in the level of CO₂. This indicates that most African countries still grapple with rising environmental degradation due to CO₂ emission. Whether ICT helps in the reduction of CO₂ emission in low-income and lower-middle-income ECOWAS countries is what this paper seeks to investigate.

Figure 1 could be compared with the growth rate of income in the selected countries under review. Figure 2 buttresses the fact that selected ECOWAS countries show different rates of income growth given their population and ICT development. The rate of growth among these selected countries is not markedly or significantly different, suggesting that growth or development will be paramount in their economic policy and may supersede the drive for quality environment. It becomes imperative to study if ICT growth does have both positive and negative implications at the same time or otherwise in countries of similar income level given the trend observed in the growth rates of the real gross domestic product (GDP) per capita in Figure 2. In Figure 2, we notice overall sluggishness in the growth rate of nations under review. Could this sluggish growth rate put the low-income and lower-middle-income ECOWAS nations under pressure to adopt more use of ICTs, and what implications do increased use of ICTs hold for sustainable development in these nations?

Figure 3 shows the HDI for selected ECOWAS nations. HDI for Cote d'Ivoire, Nigeria, and Ghana lurked between 0.4 and 0.6 HDI and maintained general positive trend from 1990 to 2020, respectively. HDI for Mali has positive trend between 1990 and 2015 and thereafter fell sharply up till 2020, while HDI for Benin maintained upward trend between 1990 and 2017 and dropped sharply from 2017 up to 2019 and rose sharply again.

FIGURE 1 CO₂ emission as a measure of air pollution in selected West African countries. Source: Authors' compilation (2021) [Color figure can be viewed at wileyonlinelibrary.com]



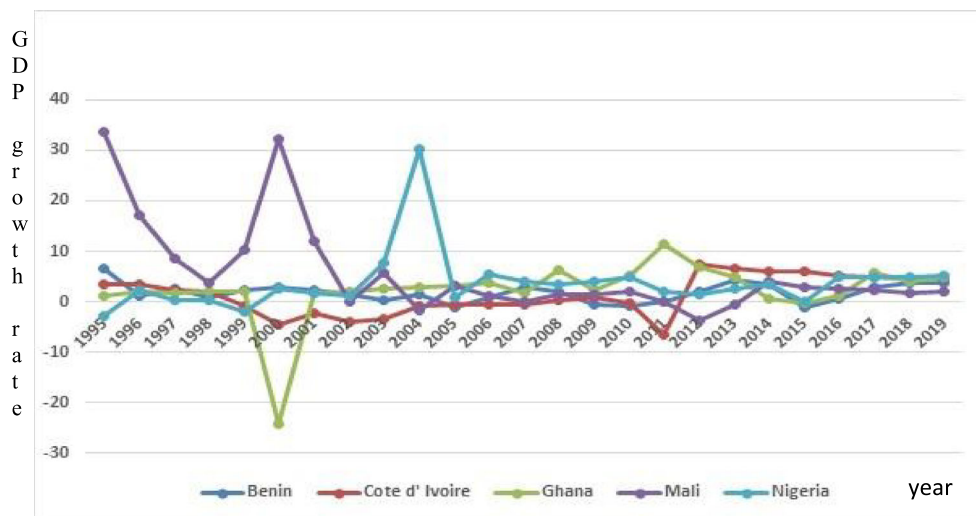


FIGURE 2 Growth rate (annual %) of real GDP per capita of selected West African countries. Source: Authors' compilation (2021) [Color figure can be viewed at wileyonlinelibrary.com]

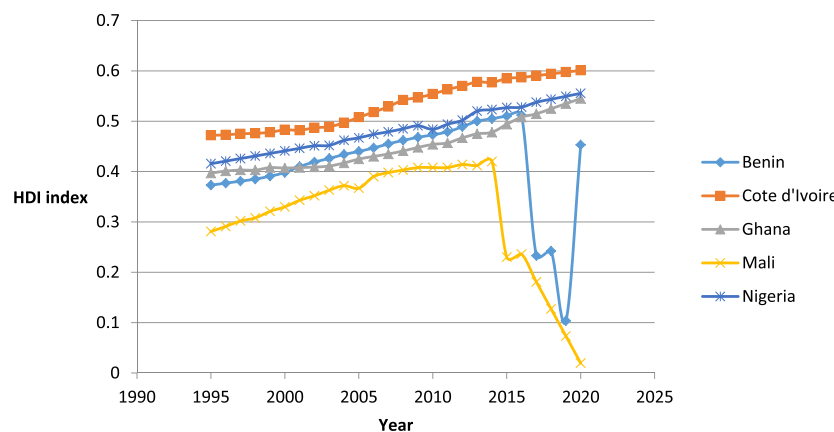


FIGURE 3 HDI for selected ECOWAS nations. Source: Authors' computation [Color figure can be viewed at wileyonlinelibrary.com]

2.3 | Empirical evidence

The increasing popularity of ICT as emerging factor linking countries with the global economy as well as its possible linkages to sustainable development has renewed interest in the subject area. The empirical literature of this study is therefore tailored in this light, with particular interest on the components of sustainable development such as carbon dioxide emission (CO_2 emission), economic growth (GDP), and human development index (HDI).

2.3.1 | Linkages between ICT and carbon dioxide emission (CO_2)

The rising concern over environmental degradation and the increasing popularity of ICT have over the years intensified search for possible linkages between the two. Studies tracing the link and effects of ICT on CO_2 emission often establish linkage between the two; however, the direction and magnitude of impacts seem to vary among countries and regions. Higon et al. (2017) examined the nonlinear association between ICT and CO_2 emission in a panel of 142 nations. They found support for inverted U-shaped linkage between ICT and CO_2

especially for the developed nations, while the reverse is the case for LDCs.

Shabani and Shahnazi (2019) employed a different econometric method for a different country, adopting ICT as explanatory variable relegating CO_2 to the position of explained variable in the quest to investigate the ICT- CO_2 linkage. The study relied on dynamic spatial Durbin model as method of analysis and found support for inverted U-shaped association for the case of Iran. Also, Albiman and Sulong (2017) established the EKC linkage between ICT and CO_2 as they tested for the nonlinear association between ICT and CO_2 in a panel of 142 states. Hence, they concluded that ICT was able to contribute to the reduction of CO_2 emissions once a threshold level of ICT development has been attained. Contrary to these findings, Amri et al. (2019) adopting ARDL method did not find support for the existence of EKC assumption for the case of Tunisia.

On the positive linkage between ICT and CO_2 , Zhou et al. (2019) adopted the input-output technique in the exploration of the association between ICT and CO_2 in China and found that ICT sector (chemicals, metal, and nonmetal) exert positive influence on carbon emission. In a similar study, Avom et al. (2020) employed mediation analysis and observed that ICT adds to carbon emission for the case of 21 SSA nations.

Contrary to positive association between ICT and CO₂ emission, Asongu et al. (2019) employed Tobit regression and fixed effect and established that ICT significantly reduces the possible adverse effects of CO₂ emission on inclusive human development for the case of 44 SSA nations. In a similar study, Ulucak and Khan (2020) applied a robust panel data estimation technique and found that ICT development reduces CO₂ through globalization for the case of BRICS nations. On the causal linkage between ICT and CO₂, Ozcan and Apergis (2018) established a one-way causal linkage running from ICT Internet use to CO₂ for the case of 20 emerging nations.

The major weakness in these empirical reviews is that no consideration was given to the levels of income, which this paper seeks to remedy.

2.3.2 | Linkages between ICT and economic growth (GDP)

Given the possible roles of ICT in the growth of economic development of any nation, studies tracing the links and effect of ICT on economic growth have also grown in length and breadth over the years. For instance, Bahrini and Qaffas (2019) employed a GMM technique to evaluate the influence of ICT on economic growth in MENA and SSA regions with panel data spanning 2007–2016 and found that ICT positively drives economic growth in both regions. A similar finding was made by earlier study of Toader et al. (2018) for the case of European Union (EU) nations. Also, Hodrab et al. (2016) using a panel of 18 selected Arab countries agreed with the findings of Toader et al. (2018). Other studies who endorsed positive linkage between ICT and economic growth include Niebel (2018) for the case of 59 nations, Pradhan et al. (2018) in G-20 nations, and Waqar (2015) for the case of 41 European nations. García (2019) explored the disaggregated influence of ICT on economic growth in Mexico and found that while mobile phones, computers, the Internet, and fiber optics exert positive effect on GDP, the Internet use reduced RGDP. The study implies that there is need to increase the number of telephone users, computer users, and Internet and fiber-optic users and on the other hand reduce the price of the Internet.

On the nonlinear linkage between ICT and economic growth, which was based on the premises that ICT services are influenced by the network, some studies posit that the effects of ICT penetration may be direct or indirect, depending on other factors in the host country. Among these scholars are Sassi and Goaid (2013) who observed a direct nonlinear impact of the ICT components on economic growth in the case of MENA region. Hence, their findings show that initial adoption of ICT impedes growth, but with nations' promotion of ICT, it will boost growth and as such concluded that the marginal influence of ICT penetration stimulates economic growth with rise of ICT adoption. Contrary to the positive nonlinear linkage, Vu (2011) established that ICT penetration exerts inverse marginal impact with increased penetration in the case of 102 nations. In a similar study, Hawash and Lang (2010) established that ICT influenced GDP negatively with growth in ICT usage, which implies that the early use of ICT brought

about direct impact, but as consumption rises, it begins to exert negative influence.

In spite of these nonlinear evidences, Andrianaivo and Kpodar (2011) found a contrary result of nonlinear impact from the use of ICT components in the case of SSA nations, which implies that the region could not experience optimal penetration within the period of study.

2.3.3 | Linkages between ICT and HDI

Another dimension of sustainable development that has been of interest to many researchers in the recent past in relation to possible linkage with ICT is the HDI. Again, most studies appear to establish a direct link or relationship between ICT and HDI. One of the recent and popular studies in this subject area is Gupta et al. (2019) that investigated the relationship between HDI and ICT in South Asian region. Using panel fixed effects modeling, the findings showed a strong positive association between ICT and HDI. Further examination of individual component-level linkages of HDI such as GDP per capita, birth life expectancy and school enrolment rate equally established positive relationship with ICT. In a similar and extended study that focused on developing countries, Farooqi et al. (2020) discovered similar results for the panel of 67 developing countries.

In another study, Ejemeyovwi et al. (2019) evaluated the effect of Internet use and innovation on human development in 15 ECOWAS states employing the fixed and random effects panel data techniques. The study concluded that Internet uses and innovation as well as their interaction have significant and direct connection with human development in the ECOWAS region. Further attempt to unbundle the region for country-specific results rather revealed mixed results, with countries such as Cape Verde having positive significant relationship, while the results of some ECOWAS members either not significant, showed significant negative relationship, or have no effect on the overall results. Also using a seemingly unrelated regression technique on a panel of 80 nations with data spanning from 2000 to 2016 in order to ascertain the impact of ICT on the three dimensions of sustainable development (economic, environmental, and social), Jayaprakash and Pillai (2021) found that ICT exerts direct and significant influence on the three dimensions of sustainable development of the countries studied. The direct linkage was also supported by Cortés and Navarro (2011) based on the level of ICT development for the case of 27 EU nations.

In a disaggregated study, De La Hoz-Rosales et al. (2019) investigated the impacts of ICT usage by individuals, businesses, and government on human development for a sample of 145 countries. Utilizing a panel data technique, the study showed that individual use of ICT exerts direct influence on HDI. Similar result was also established for use of ICT for commercial purpose at the global level, but considering only developed countries, the results appear not to be significant. However, for government use of ICT, the study found a significant impact on human development for developed countries. Iqbal et al. (2019) disaggregated ICT usage into mobile phone and Internet penetration in order to determine the influence of ICT on HDI in the case

of South Asian nations. Using Driscoll–Kraay standard error algorithm technique, they found mixed results such that use of phones boosts human development while use of internet exhibits inverse but insignificant impact on HDI. Furthermore, Bankole et al. (2011) beamed their searchlight on the impact of four dimensions (hardware, software, Internet spending, and communication investment) of ICT investment on three dimensions (standard of living, health, and education) of human development in low-income, middle-income and high-income states. The findings showed that the impact of each dimension of ICT investment varies along the dimensions of human development and group of countries. However, the components with common impact are the effect of ICT investment on living standard and education, which exhibit positive linkage. This positive linkage between ICT and HDI components was supported further by the works of BankoleDr and Mimbi (2017) for the case of African nations. Another study that found positive association between ICT and HDI includes Lee et al., 2017 who assert that ICT brings about high rate of human capacity growth and such boost health conditions and raise expected life span.

Moreover, Hwang and Shin (2017) noted that ICT serves two roles in modern times such as input and output. To them, as input role, ICT reduces market costs for coordination, while the output role is seen in its capacity to improve health and education via e-services. On the nonlinear effect, Asongu and Nwachukwu (2018) found that

ICT exerts a direct marginal effect on quality of education for the case of 49 SSA countries as a result of e-services, which enables people to have access to knowledge on the possible ways of bettering their lives. Hence, making use of e-health in medicine can lead to overall improvement in health outcomes.

3 | DATA, MODEL SPECIFICATION, AND METHODOLOGY

3.1 | Data source

The key aim of this paper is to ascertain the effect of ICT usage on sustainable development. A comprehensive longitudinal data were gathered from 1995 to 2020 with 15 nations of ECOWAS grouped into 10 low-income and 5 lower-middle-income countries, which was based on the World Bank classification of 189 member countries as earlier explained in the introductory section. Secondary data were collected from the World Bank Indicators (WDI) and the United Nations Development Programme (UNDP). The explanatory variables consist of ICT components that are calculated via principal component analysis (PCA) of four indicators of ICT development (fixed telephone subscriptions: 100 inhabitants, mobile-cellular subscriptions: 100 inhabitants, fixed broadband subscriptions: 100 inhabitants and

Low-income nations					
Number	Value	Difference	Proportion	Cumulative value	Cumulative proportion
1	2.20382	1.1372	0.551	2.20382	0.5510
2	1.06663	0.5430	0.2667	3.2705	0.8176
3	0.523655	0.3178	0.1309	3.794105	0.9485
4	0.205891		0.0515	4	1
Eigenvectors (loadings)					
Variable	PC1	PC2	PC3	PC4	
<i>FTS</i>	0.5659	−0.3988	0.2335	0.6828	
<i>FBS</i>	0.4944	0.3512	−0.7923	0.0662	
<i>MCS</i>	0.597	−0.2875	0.1844	−0.7259	
<i>FIS</i>	0.2807	0.7968	0.5326	0.0506	
Lower-middle-income nations					
1	2.5683	1.5218	0.6421	2.5683	0.6421
2	1.0465	0.772131	0.2616	3.6148	0.9037
3	0.274372	0.16355	0.0686	3.889172	0.9723
4	0.110822		0.0277	4	1
Eigenvectors (loadings)					
Variable	PC1	PC2	PC3	PC4	
<i>FTS</i>	0.5816	−0.247	0.0706	−0.7719	
<i>FBS</i>	0.547	0.2558	−0.753	0.2614	
<i>MCS</i>	0.5032	−0.508	0.3935	0.5777	
<i>FIS</i>	0.3306	0.7845	0.5226	0.0459	

TABLE 1 Principal component analysis

fixed Internet subscriptions: 100 inhabitants). The PCA is represented in Table 1.

The dependent variables include the three dimensions of sustainable development (environmental dimension—CO₂ emissions, economic dimension—economic growth [RGDP], and social dimension—HDI), which are described as follows:

- Environmental dimension proxied by CO₂ emission is the explained variable for the environmental dimension of sustainable development (Asongu & Nwachukwu, 2018; Jayaprakash & Pillai, 2021). It is measured in per capita metric tons and sourced from WDI.
- Economic growth is employed as the regressand representing the economic dimension of sustainable development. It is measured as GDP in constant 2010 USD (as also employed by Jayaprakash & Pillai, 2021). The data are also collected from WDI.
- HDI is the third predicted variable employed to represent the social dimension of sustainable development. This is a composite of life expectancy, education, and living standard (Asongu & Le Roux, 2017; Cortés & Navarro, 2011; Jayaprakash & Pillai, 2021). The HDI entails the level of human development made by a nation in such sectors as health, life expectancy, education, and income per capita. Therefore, ICT is anticipated to exert positive influence on HDI.
- The control variables include urbanization, which is measured as urban population growth (annual %). This is used as one of the control variables in the three dimensions of sustainable development.
- Fossil fuel use measured as fossil fuel energy use (% of total) is employed as a control variable in the carbon emission model, which can contribute positively to environmental degradation. It is employed to determine the impact on carbon dioxide emissions in the phase of ICT.
- Financial sector denoted by credit to private sector (percentage of GDP) is employed as a control variable in the economic dimension model to ascertain the influence of bank lending on growth. It is hoped that CPS will enhance economic growth by mobilizing resources and prompting innovation (Albiman & Sulong, 2017).
- Openness to trade is described as import plus export divided by GDP, and it captures country's trading activities in the global market. It is another control variable in economic growth model. Also, a positive influence on economic growth is expected since it makes possible foreign technology transfer and promotion of domestic production and thus economic growth (Albiman & Sulong, 2017).
- Economic freedom is a part of human freedom signifying the state of autonomy nation's exercise over property ownership and labor force (Vondrová & Fifeková, 2016). It is an index of rule of law; insufficient government; efficient regulation; etc., which is graded on a scale of 0–100, where 100 denotes the optimum freedom. In this study, we employed it as a control variable for HDI model because it is capable of influencing HDI of a nation positively. One or two components of economic freedom index have been used by other researchers such as Añón-Higón et al. (2017).
- Population used here is measured as annual population growth rate, which counts people living within a territorial boundary. It is also a control variable in the HDI model.

3.1.1 | PCA

To compute ICT index, four ICT variables were transformed using the PCA. The PCA, which is a specific type of factor analysis, transforms variables into a smaller set based on their variance to form a composite index (Latif et al., 2018), thus enabling an in-depth analysis while assisting in understanding the true nexus between ICT and sustainable development. The PCA has a number of steps, which includes standardized variables creation, determination of eigenvectors, data matrix construction, correlation matrix calculation, etc. The result is presented in Table 1.

The PCA in Table 1 is divided into low-income nations and lower-middle-income nations. In the panel of low-income nations of Table 1, the first section presents the maximum eigenvalues for the 1st, 2nd, 3rd, and fourth factors, which are 2.20382, 1.06663, 0.523655, and 0.205891 respectively. These factor values correspond to 55%, 27%, 13%, and 5% proportion variations of 1st, 2nd, 3rd, and fourth factors, respectively. In the second panel of low-income nations of Table 1, we present the eigenvectors comprising the four principal component factor loadings. ICT index was constructed with PC1 because it has only positive values and captures most of the information on variables compared to other components.

In the panel of lower-middle-income nations of Table 1, the first section indicates that 2.5683, 1.0465, 0.274372, and 0.110822 correspond to the maximum eigenvalues for the 1st, 2nd, 3rd, and fourth factors, respectively. These eigenvalues correspond to 64%, 26%, 6%, and 3% of proportion variations of 1st, 2nd, 3rd, and fourth factors, respectively. In the second panel of the lower-middle-income nations of Table 1, we find the eigenvectors consisting of the four principal component factor loadings. ICT index for lower-middle-income ECOWAS nations was constructed with PC1 because it has only positive values and captures most of the information on variables compared to other components.

Table 2 shows the correlation analysis of the PCA for both low-income ECOWAS and lower-middle-income ECOWAS nations,

TABLE 2 Correlation for principal component

Low-income countries				
	FTS	FBS	MCS	FIS
FTS	1.0000			
FBS	0.8173	1.0000		
MCS	−0.8431	−0.6221	1.0000	
FIS	0.7643	0.4262	0.5734	1.0000
Lower-middle-income nations				
	FTS	FBS	MCS	FIS
FTS	1.0000			
FBS	0.8419	1.0000		
MCS	0.8653	0.6412	1.0000	
FIS	−0.7756	−0.4756	−0.6631	1.0000

Source: Author's compilation, 2022.

respectively. While FBS and FIS are positively and strongly correlated with FTS, MCS is negatively and strongly correlated with FTS for low-income ECOWAS nations. Similarly, FBS and MCS are positively and strongly correlated with FTS, while FIS is negatively and strongly correlated with FTS for the lower-middle-income ECOWAS nations.

3.2 | Model specification

The empirical specification to determine the causal linkage between ICT and sustainable development is based on the EKC hypothesis paralance, with ICT and ICT-squared adopted as additional independent variable (such as used by AñónHigón et al., 2017; Heil & Selden, 2001; Grossman & Krueger, 1991; etc.). Sustainable development is proxied by the three dimensions of sustainable development (environmental—CO₂ [carbon dioxide emission], economic—RGDP, and social—HDI). Hence, we specify the following reduced form equation that relates ICT with sustainable development and other covariates in their logarithmic forms:

$$LCO_{2it} = \alpha_0 + \alpha_1 ICT_{it} + \alpha_2 ICTSQ_{it} + \alpha_3 LRGDP_{it} + \alpha_4 LFOS_{it} + \alpha_5 LURB_{it} + \mu_{it} \quad (1)$$

$$LRGDP_{it} = \beta_0 + \beta_1 ICT_{it} + \beta_2 ICTSQ_{it} + \beta_3 LURB_{it} + \beta_4 LOPN_{it} + \beta_5 LCPS_{it} + \varepsilon_{it} \quad (2)$$

$$LHDI_{it} = b_0 + b_1 ICT_{it} + b_2 ICTSQ_{it} + b_3 LURB_{it} + b_4 LECOF_{it} + b_5 LPOP_{it} + e_{it} \quad (3)$$

where

CO₂ denotes carbon dioxide emissions per 1000 metric tons, index of information and communication technologies, ICTSQ, is the squared ICT used to validate the EKC hypothesis,

RGDP stands for real gross domestic product (economic growth),

HDI stands for log of human development index (social dimension of sustainable development),

LURB stands for log of urbanization,

LOPN stands for log of trade openness,

ICPS stands for log of credit to private sector, which denotes financial development status of the economies,

LECOF stands for log of economic freedom,

LPOP stands for log of population growth rate,

α_0 , β_0 , and b_0 are the intercepts of CO₂, RGDP, and HDI, models respectively,

α_1 – α_5 , β_1 – β_5 , and b_1 – b_5 are coefficients of the explanatory variables for the three specifications to be estimated,

μ_{it} , ε_{it} , and e_{it} are the stochastic terms,

i denotes the country ($i = 1, y, \dots, 15$) grouped into 10 low-level income and five lower-middle-income nations, and

t denotes the time period ($t = 1995, y, 2020$).

To analyze the models, we employed data from a balanced panel ranging from 1995 to 2020 for 15 ECOWAS nations, which was further classified into low lower-middle-class countries, following the World Bank classification of 2019.

Based on the EKC framework concerning ICT and economic growth, as ICT is introduced to industries due to growth process, it will be causing rise in emissions via the scale effect, which may emanate from heavy computers and software as against those from communication devices (that reduce emissions). However, with the presence of ICT capital, extra ICT adoption could result in optimization of production processes, which will in turn enhance efficiency in energy and thereby curb emission intensity via the technological impact (Albiman & Sulong, 2017).

Hence, for Model 1, carbon emissions are meant to rise as ICT adoption progresses ($\alpha_1 > 0$); but at advanced levels of ICT usage, carbon dioxide emissions may tend to decrease ($\alpha_2 < 0$). Hence, based on a priori expectation of the parameters of the ICT and ICTSQ terms, the EKC will exhibit various shapes, which include:

- $\alpha_1 < 0$ and $\alpha_2 > 0$ = indicates a U-shaped linkage among the variables.
- $\alpha_1 > 0$ and $\alpha_2 < 0$ = implies an inverted U-shaped relationship.
- $\alpha_1 < 0$ and $\alpha_2 < 0$ or $\alpha_1 > 0$ and $\alpha_2 > 0$ = no evidence for EKC hypothesis.

For Models 2 and 3, ICTSQ is adopted to capture the nonlinear linkages between RGDP and ICT and between HDI and ICT (Hawash & Lang, 2010; Sassi & Goaid, 2013; Vu, 2011). The nonlinear association may adopt the following shapes:

- β_1 and $b_1 > 0$ and β_2 and $b_2 < 0$ = nonlinear negative marginal effect (similar to inverted EKC hypothesis-diminishing returns)
- β_1 and $b_1 < 0$ and β_2 and $b_2 > 0$ = nonlinear positive marginal effect (U-shaped EKC hypothesis-increasing returns)
- β_1 and $b_1 < 0$ and β_2 and $b_2 < 0$ or β_1 and $b_1 > 0$ and β_2 and $b_2 > 0$ = no evidence for nonlinear linkage

3.3 | Methodology/estimation techniques

The following steps were adopted in the estimation of our model:

- Firstly, we described the data properties of our variables using descriptive statistics and correlation analysis to be sure that variables are not.
- Secondly, we estimated the cross-sectional dependency (CSD) test, which helps in the choice of panel unit root test.
- Thirdly, after confirming CSD across the panel, we conducted second-generation panel unit root test such as CADF and CIPS being the right unit root test to determine the integrating status of the data.

- The existence of non-stationarity (unit root) informed the Pedroni and Kao cointegration test and to ascertain the long-term association between the variables.
- Having confirmed the presence of a long run linkage, we adopt a panel cointegration technique and estimate the cointegrating relationship via PFMOLS and panel dynamic ordinary least squares (PDOLS) techniques, which were developed by Pedroni (1996, 2001) and Kao and Chiang (2001).
- Finally, direction of causation, we employed Dumitrescu and Hurlin (2012) test.

3.3.1 | CSD test/panel unit root tests

This is a pretest for the decision on the generation of panel unit root test to adopt (Tugcu, 2018). Thus, Breusch and Pagan (1980) LM test, Pesaran (2004) LM test, Pesaran (2004) CD test, and Baltagi et al. (2012) LM test were adopted, with the null assumption that no CSD existed. In the case of rejection of H_0 , first-generation unit root tests (such as LLC [Levin, Lin, and the Chu], Hadri, IPS [Im-Pesaran-Shin], Fisher-type ADF, and/or PP) are advocated but, if not, employ second-generation unit root test (such as Breitung and Pesaran CIPS [cross-sectional augmented Im-Pesaran-Shin] and/or CADF [cross-sectional augmented Dickey-Fuller]). We therefore employed both CIPS and CADF for robust outcome. The result is reported in Table 5.

3.3.2 | Heterogeneous panel cointegration

According to Granger (1981), non-stationary data that become stationary after first differencing will be tested for long-run relationship using cointegration estimation technique. But the Engle and Granger (1987) approach involve a simple two-step and as such suffer from several problems, prompting the study to adopt the panel cointegration tests developed by Pedroni (2004), which enables (i) the use of panel data, (ii) overcomes problem of small samples, and (iii) allows for heterogeneity in the slopes and intercepts of the cointegrating equation.

Pedroni's tests based on the estimated residuals can be expressed in a long-run model as below:

$$Y_{it} = \alpha_i + \sum_{j=1}^m \beta_{ji} X_{jit} + \varepsilon_{it}, \tag{4}$$

where $\varepsilon_{it} = \rho_i \varepsilon_{i(t-1)} + w_{it}$, which are the estimated residuals from the panel regression. The seven statistics are assumed to be normally distributed and the null hypothesis is that $\rho_i = \text{unity}$ (i.e., no cointegration). Rejection of the null hypothesis entails the existence of a long-run relationship among the variables, and thus, a more explicit modeling approach (PFMOLS) developed by Kao et al. (1999) would be employed to test for a long-run relationship.

3.3.3 | Fully modified OLS in heterogeneous cointegrated panels

Pedroni (1996 and 2001) proposed the adoption of fully modified OLS in panel cointegration analysis. The major reason for carrying out dynamic cointegration is that of the problem of heterogeneity with differences in means among the individuals and differences in individual responses to short-run disturbances from cointegrating equilibrium. Thus, PFMOLS regression is specified as

$$\begin{aligned} Y_{it} &= \alpha_{1i} + \beta X_{it} + \mu_{it} \\ X_{it} &= \alpha_{2i} + X_{it-1} + \varepsilon_{it} \end{aligned} \tag{5}$$

where $\varepsilon_{it} = (\mu_{it}, \varepsilon_{it})^1$ being the vector error process is stationary with asymptotic covariance matrix Ω_i and X_i, Y_i are the variables that cointegrate for each member of the panel with cointegrating vector β when Y_{it} is integrated of order one. The terms α_{1i}, α_{2i} allow either variable to exhibit idiosyncratic nonzero drifts for individual members of the panel.

3.3.4 | DH causality test

Analyzing the short-term and long-run linkages among requires proper knowledge about the direction of relationship for maximum policy implication (Salahuddin et al., 2016; Shahbaz et al., 2013). Hence, we adopt the DH causality test proposed by Dumitrescu and Hurlin (2012), which has some merits over the traditional Granger (1969) causality test. The merits include, aside from considering fixed coefficients just as the case of Granger, the test that also estimates the heterogeneity of both the regression model and the causal relationships.

4 | EMPIRICAL RESULTS AND DISCUSSION OF FINDINGS

4.1 | Data descriptive properties

The data are described in Table 3a, which shows that 2.825, 6.3896, 7.311, 0.946, and 0.047 are the average values of carbon emission, economic growth, HDI, and ICT, respectively, for low-income nations. RGDP has the highest average value. In like manner, the mean values of carbon dioxide emission, RGDP, HDI, and ICT for lower-middle-income states are 0.812, 7.451, 0.455, and 1.522, respectively, with the value of RGDP being the highest also.

The result of correlation test in Table 3b shows there is no linear dependence of the variables on each order since none exhibited a value up to 0.8 in all the specifications.

TABLE 3 Descriptive statistics and correlation results

(a) Descriptive statistics						
Variable	Low-income nations					
	Mean	SD	Min	Max	Observations	
LCO ₂	-2.825	0.324	-3.222	-0.518	260	
LRGDP	7.311	0.251	5.243	7.039	260	
LHDI	-0.946	0.216	-1.324	-0.669	260	
ICT	-0.047	1.431	-1.332	6.034	260	
ICTSQ	2.206	4.674	0.231	36.415	260	
LFOS	-1.821	1.351	-3.456	3.807	260	
LURB	4.223	0.312	2.552	8.286	260	
LOPN	4.233	0.401	3.211	5.741	260	
LCPS	2.453	0.643	-0.417	3.815	260	
LECOF	3.521	1.562	0.133	4.127	260	
LPOP	1.522	0.211	-1.654	2.067	260	
Lower-middle-income nations						
LCO ₂	-0.812	0.367	-1.300	0.422	130	
LRGDP	7.451	0.242	6.754	8.333	130	
LHDI	-0.455	0.221	-0.888	-0.612	130	
ICT	-1.522	1.384	-1.412	5.111	130	
ICTSQ	2.563	5.339	0.336	25.323	130	
LFOS	0.466	1.352	-3.521	3.222	130	
LURB	3.411	0.351	3.326	8.193	130	
LOPN	4.263	0.244	3.221	4.553	130	
LCPS	2.672	0.452	1.611	4.111	130	
LECOF	4.447	0.143	3.655	4.562	130	
LPOP	0.661	0.311	0.242	1.313	130	
(b) Correlation result						
Low-income nations—CO ₂ model						
	<i>lco₂</i>	<i>ICT</i>	<i>ICTSQ</i>	<i>LRGDP</i>	<i>LFOS</i>	<i>LURB</i>
<i>LCO₂</i>	1.0000					
<i>ICT</i>	0.3612	1.0000				
<i>ICTSQ</i>	0.4152	0.4123	1.0000			
<i>LRGDP</i>	0.5215	0.4271	0.4216	1.0000		
<i>LFOS</i>	0.1231	0.2611	0.1342	0.4135	1.0000	
<i>LURB</i>	0.4212	0.4152	0.3174	0.3211	-0.1423	1.0000
	<i>IRGDP</i>	<i>ICT</i>	<i>ICTSQ</i>	<i>LURB</i>	<i>LOPN</i>	<i>LCPS</i>
<i>LRGDP</i>	1.0000					
<i>ICT</i>	0.3314	1.00000				
<i>ICTSQ</i>	0.2511	0.4123	1.00000			
<i>LURB</i>	0.4123	0.4152	0.3174	1.00000		
<i>LOPN</i>	0.0412	0.1842	0.021	0.3244	1.00000	
<i>LCPS</i>	0.4216	0.3511	0.2524	0.0521	0.063	1.00000
	<i>LHDI</i>	<i>ICT</i>	<i>ICTSQ</i>	<i>LURB</i>	<i>LECOF</i>	<i>LPOP</i>
<i>LHDI</i>	1.0000					
<i>ICT</i>	0.4412	1.00000				
<i>ICTSQ</i>	0.2331	0.4123	1.00000			

TABLE 3 (Continued)

Low-income nations—CO ₂ model						
	<i>lco₂</i>	<i>ICT</i>	<i>ICTSQ</i>	<i>LRGDP</i>	<i>LFOS</i>	<i>LURB</i>
<i>LURB</i>	0.2342	0.4152	0.3174	1.00000		
<i>LECOF</i>	-0.1521	0.2143	0.0341	-0.4215	1.00000	
<i>LPOP</i>	0.0635	-0.0316	-0.0512	-0.211	-0.1321	1.00000
Lower-middle-income nations						
	<i>LCO₂</i>	<i>ICT</i>	<i>ICTSQ</i>	<i>LRGDP</i>	<i>LFOS</i>	<i>LURB</i>
<i>LCO₂</i>	1.0000					
<i>ICT</i>	0.5352	1.00000				
<i>ICTSQ</i>	0.4721	0.4112	1.00000			
<i>LRGDP</i>	0.6213	0.6321	0.4223	1.00000		
<i>LFOS</i>	-0.2145	-0.3125	-0.4522	-0.2311	1.0000	
<i>LURB</i>	0.2211	0.2311	0.5213	0.2431	-0.2162	1.00000
	<i>IRGDP</i>	<i>ICT</i>	<i>ICTSQ</i>	<i>LURB</i>	<i>LOPN</i>	<i>LCPS</i>
<i>IRGDP</i>	1.0000					
<i>ICT</i>	0.2631	1.00000				
<i>ICTSQ</i>	0.3522	0.4112	1.00000			
<i>LURB</i>	0.4312	0.2311	0.5213	1.00000		
<i>LOPN</i>	0.1138	0.2521	0.3423	0.1321	1.00000	
<i>LCPS</i>	0.5214	0.6143	0.2431	0.2413	0.3151	1.00000
	<i>LHDI</i>	<i>ICT</i>	<i>ICTSQ</i>	<i>LURB</i>	<i>LECOF</i>	<i>LPOP</i>
<i>LHDI</i>	1.0000					
<i>ICT</i>	0.3129	1.00000				
<i>ICTSQ</i>	0.5121	0.4112	1.00000			
<i>LURB</i>	0.4152	0.2311	0.5213	1.00000		
<i>LECOF</i>	0.2241	0.5416	0.3165	0.2243	1.00000	
<i>LPOP</i>	-0.4264	-0.5316	-0.3721	-0.1532	-0.2522	1.00000

Source: Author's computation.

4.2 | CSD and unit root test

The result of CSD is presented in Table 4, and all the LM tests show that there is presence of CSD at the 1% level of significance for the two income groups. This implies that the second-generation panel unit root tests are expected to supply more accurate information. Therefore, we proceeded further to employ unit root tests that allow for CSD such as CADF and CIPS. The results of the panel unit root tests presented in Table 5 indicate that all the variables are integrated of the first order, that is, I(1). This evidence of first-order integration of all the variables informed testing for cointegration among the variables in the respective models.

4.3 | Results of cointegration analysis

We conducted the Pedroni panel long-run equilibrium test that has seven test statistics using Stata (panel V, panel rho, panel t, panel adf, group v, group rho, and group adf). As a check of robustness, we also

estimated the Kao cointegration using EViews. The decision of cointegration among variables on the Pedroni outcome depends on the number significant statistics, which is justified using a rule of thumb of at least $stat = 2$. However, the result shows that in both low-income and lower-middle-income countries, the null hypotheses are rejected at 1% and 5% levels of significance, meaning that a long-term association exists among the variables in both income groups. This is further indicated by the higher number of outcomes being greater than 2. Also, Kao statistics has probability values less than 1% and 5% significant levels, which indicates cointegration. The result is presented in Table 6.

4.4 | Estimation of cointegrating relationships

Having confirmed the existence of cointegration among the variables (as indicated by both Pedroni and Kao cointegration tests), the study estimates the cointegrating relationships using PFMOLS estimator. The outcome is presented in Table 7. The findings of the

TABLE 4 Results of cross-sectional dependency test

Variables	Breusch–Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD
	Low income countries			
LCO ₂	354.22***(0.000)	36.44***(0.000)	35.51***(0.000)	18.32***(0.000)
LRGDP	321.12***(0.000)	28.24***(0.000)	28.21***(0.000)	7.32***(0.000)
LHDI	593.23***(0.000)	57.54***(0.000)	57.52***(0.000)	21.254***(0.000)
ICT	821.12***(0.000)	85.94***(0.000)	85.69582***(0.000)	29.24***(0.000)
ICTSQ	376.55***(0.000)	34.91***(0.000)	34.63***(0.000)	11.44***(0.000)
LFOS	267.42***(0.000)	23.11***(0.000)	23.196***(0.000)	6.67***(0.032)
LURB	634.23***(0.000)	62.76***(0.000)	61.51***(0.000)	23.33***(0.000)
LOPN	162.66***(0.000)	12.42***(0.000)	12.49***(0.000)	5.56***(0.000)
LCPS	295.36***(0.000)	26.71***(0.000)	26.32***(0.000)	15.55***(0.000)
LECOF	229.22***(0.000)	19.23***(0.000)	19.41***(0.000)	6.53***(0.000)
LPOP	343.25***(0.000)	31.53***(0.000)	31.64***(0.000)	2.55***(0.010)
	Lower-middle-income countries			
LCO ₂	67.77***(0.000)	12.34***(0.000)	12.75***(0.000)	5.86***(0.000)
LRGDP	120.45***(0.000)	24.47***(0.000)	24.63***(0.000)	6.52***(0.000)
LHDI	208.36***(0.000)	44.63***(0.000)	44.22***(0.000)	14.44***(0.000)
ICT	202.52***(0.000)	43.65***(0.000)	42.34***(0.000)	14.92***(0.000)
ICTSQ	86.24***(0.000)	17.17***(0.000)	16.65***(0.000)	6.23***(0.000)
LFOS	131.36***(0.000)	27.23***(0.000)	27.83***(0.000)	11.32***(0.000)
LURB	122.35***(0.000)	25.51***(0.000)	25.27***(0.000)	8.55***(0.000)
LOPN	19.87***(0.037)	2.02***(0.039)	2.44***(0.052)	2.34****(0.006)
LCPS	105.01***(0.000)	21.20***(0.000)	21.23***(0.000)	9.57***(0.000)
LECOF	48.42***(0.000)	8.43***(0.000)	8.34***(0.000)	2.61****(0.013)
LPOP	77.62***(0.000)	15.08***(0.000)	14.32***(0.000)	10.27***(0.000)

Note: Null hypothesis: no cross-sectional dependency.

* $p < 0.1$. ** $p < 0.05$. *** $p < 0.01$.

Source: Author's computation using EViews 10.

PFMOLS indicated the existence of a statistically significant long-run cointegrating linkage between dependent and explanatory variables of the three models (representing sustainable development) in both income groups. However, for low-income nations, ICT, LRGDP, and LFOS exert positive and statistical significant effect on LCO₂ emission, while ICTSQ has negative and significant relationship with LCO₂. Also, ICT and LCPS are significantly and positively related to economic growth (LRGDP), while ICTSQ and LOPN exert inverse influence on LRGDP with only OPN being significant at 10% significance level. On the HDI specification, ICT, LURB, and LPOP have direct and significant impact on HDI, while ICTSQ exert significant reducing influence on HDI.

Considering the linkages between CO₂ emission and ICT in the lower-middle-income countries, the result shows that ICTSQ and RGDP have direct and significant effect on CO₂, while ICT, FOS, and URB exert inverse but insignificant influence on CO₂. For the economic dimension, ICT significantly adds to RGDP, while ICTSQ reduces RGDP in an insignificant manner. Other explanatory variables have positive but insignificant impact on RGDP. On the last

model, which is the social dimension, both ICT and ICTSQ exhibit positive and negative significant effect on HDI, respectively, while urbanization, economic freedom, and population growth reduce HDI.

4.5 | DH causality test

Results in Table 8 show that for the case of low-income countries, a one-way causal linkage runs from ICT to CO₂, FOS to ICT, ICT to URB, RGDP to URB, and FOS to URB, while a bidirectional causality exists between CO₂ and FOS when carbon emission is used to proxy sustainable development. Using economic growth to capture economic dimension of sustainable development, a unidirectional relationship runs from RGDP to URB, RGDP to CPS, ICT to URB, ICT to CPS, URB to OPN, and CPS to OPN, whereas a two-way causality exists between ICT and OPN and between CPS and URB. The result also shows that there is no causal linkage between ICT and RGDP. Also, adopting the social dimension of sustainable

TABLE 5 Results of panel unit root test (CIPS and CADF)

Variables	CIPS		CADF		Decisions
	Level	First difference	Level	First difference	
Low-income nations					
LCO ₂	-2.136	-3.885***	-2.136	-3.885***	I(1)
LRGDP	-2.099	-4.458***	-2.099	-4.458***	I(1)
LHDI	-1.42	-4.063***	-1.42	-4.063***	I(1)
ICT	-0.711	-2.526***	-0.711	-2.526***	I(1)
ICTSQ	-2.103	-3.958***	-2.103	-3.958***	I(1)
LFOS	-2.084	-4.681***	-2.084	-4.681***	I(1)
LURB	-1.624	-3.131***	-1.624	-3.131***	I(1)
LOPN	-1.643	-4.532***	-1.643	-4.532***	I(1)
LCPS	-2.228	-3.796***	-2.25	-3.796***	I(1)
LECOF	-1.402	-5.421***	-1.402	-5.421***	I(1)
LPOP	-0.935	-2.570***	-2.042	-3.422***	I(1)
Lower-middle-income nations					
LCO ₂	-1.583	-4.326***	-1.583	-4.326***	I(1)
LRGDP	-0.711	-2.469***	-0.711	-2.469**	I(1)
LHDI	-1.067	-3.08***	-1.067	-3.08***	I(1)
ICT	-1.559	-3.297***	-1.559	-3.297***	I(1)
ICTSQ	-2.021	-5.086***	-2.021	-5.086***	I(1)
LFOS	-1.935	-4.538***	-1.935	-4.538***	I(1)
LURB	-2.088	-2.414***	-2.302	-2.414***	I(1)
LOPN	-1.866	-4.284***	-1.866	-4.284***	I(1)
LCPS	-1.99	-4.701***	-1.99	-4.701***	I(1)
LECOF	-2.105	-5.398***	-1.795	-3.055***	I(1)
LPOP	-1.672	-2.511***	-1.89	-3.424***	I(1)

*Significant at 10%.

**Significant at 5%.

***Significant at 1%.

Source: Authors' computations.

development (HDI model), a unidirectional causal linkage runs from ICT to URB, ECOF to ICT, and ECOF to POP, while a bidirectional causal association exists between ICT and HDI, between POP and HDI, between ICT and POP, and between ECOF and URB for the case of low-income states.

Considering the outcome of lower-middle-income states in the carbon emission model, a unidirectional association runs from CO₂ to RGDP, CO₂ to FOS, CO₂ to URB, ICT to FOS, URB to ICT, RGDP to FOS, and URB to FOS, while a two-way causality exists between ICT and CO₂. For the economic growth model, the findings show a one-way casual association running from URB to RGDP, URB to ICT, and ICT to OPN, while no causal linkage exists between ICT and RGDP. Finally, when HDI was adopted for sustainable development, a unidirectional association runs from HDI to ICT, HDI to ECOF, URB to ICT, ECOF to ICT, URB to POP, and POP to ECOF, while a bidirectional between POP and HDI.

4.6 | Results and discussions

Economic variables are usually non-stationary, which primarily cause spurious regressions. So, to overcome this problem, we employed panel unit root tests such as CIPS and CADF tests because they counter the issue of homogeneity and because they are robust to CSD and heterogeneity. Hence, estimated result revealed that all the CIPS and CADF statistics are statistically significant at 5% and 1% after differencing them once. This means that for both income groups, the variables are I(1) series (see Tables 4 and 5). This integration of first order requires cointegration test for the variables before proper regression.

As can be seen from Table 6, we employed both Pedroni and Kao tests for robust analysis, and the results suggest that we reject H₀ and accept the alternative hypothesis for both income classes. This further entails the presence of long-run relationships between ICT and the

TABLE 6 Results of cointegration analysis

Test stat	LCO ₂ model Value	LRGDP model	LHDI model
Low income countries			
<i>Panel V</i>	-0.5902	-2.633**	-0.02498
<i>Panel rho</i>	2.18**	1.371	1.913*
<i>Panel t</i>	0.1711	-4.237***	2.029**
<i>Panel adf</i>	4.118***	3.277***	6.313***
<i>Group rho</i>	3.54***	2.721**	3.491***
<i>Group t</i>	0.7955	-0.5764	3.489***
<i>Group adf</i>	4.199***	3.958***	6.605***
<i>KAO t-stat</i>	-3.859532***	-2.06202**	1.671762**
<i>Prob</i>	0.0001	0.0196	0.0473
Lower-middle-income countries			
<i>Panel V</i>	-0.1188	-0.9766	-0.3831
<i>Panel rho</i>	0.2452	1.953*	2.072**
<i>Panel t</i>	-2.857**	2.114**	1.492
<i>Panel adf</i>	3.108****	3.164***	4.211***
<i>Group rho</i>	3.07***	2.792**	2.935**
<i>Group t</i>	-2.69**	2.766***	2.749**
<i>Group adf</i>	4.549***	3.268***	3.828***
<i>KAO t-stat</i>	-2.309558***	-1.713691**	-2.565351***
<i>Prob</i>	0.0105	0.0433	0.0052

Note: H₀, no cointegration.

* $p < 0.1$. ** $p < 0.05$. *** $p < 0.01$.

Source: Authors' computation using EViews 10 and Stata 15.

three dimensions of the sustainable development (CO₂, RGDP, and HDI). Hence, to determine the cointegrating linkages among the variables, we employed PFMOLS technique developed by Kao and Chiang (2001). The empirical result for the PFMOLS is presented in Table 7, and the findings show that for the low-income ECOWAS nations, ICT, LRGDP, and LFOS exert direct and statistically significant influence on LCO₂ emission, while ICTSQ has negative and significant association with LCO₂. This implies that a 1% rise in ICT, LRGDP, and LFOS leads to 11.3%, 72.3%, and 12.5% increase in carbon emission, respectively, while a unit rise in ICTSQ leads to 14.1% reduction in CO₂ emission. Urbanization, on the other hand, has positive but insignificant impact on CO₂ emission. The positive and inverse influences of ICT and ICTSQ, respectively, confirm the EKC hypothesis on the relationship between ICT and carbon emission. These findings are in tandem with the findings of Higon et al. (2017), Albiman and Sulong (2017), and Shabani and Shahnazi (2019), but contradict the findings of Amri et al. (2019). The inverted U-shape of the EKC hypothesis implies that at the initial stage of ICT development, ICT adoption brings about rise in carbon dioxide emission due to use of heavy computers, but at more advanced stage of ICT development, CO₂ emission declines (Albiman & Sulong, 2017). The direct and significant impact of RGDP

on CO₂ implies that increase in economic activities will lead to carbon emission. This is because economic growth means production of more goods and services, which is usually enhanced by the use of ICT, and as such, production of more goods and services will raise demand for ICT goods and services such as electricity use and then CO₂ emissions (Lee & Brahmaresne, 2014).

Also, considering the economic dimension (RGDP model) of sustainable development for the case of low-income nations, it was observed that increase in ICT and LCPS brings about significant rise in economic growth, while openness to trade exerts inverse influence on LRGDP. However, squared term of ICT had negative but insignificant effect on economic growth. This means that ICT has a negative but insignificant marginal impact on economic growth. This result by sign of coefficient-wise attunes to the findings of Vu (2011) and Hawash and Lang (2010) but contradicts the findings of Sassi and Goaid in 2013. The outcome implies that the initial adoption of ICT brought about a significant direct effect on economic growth, but as consumption increases, it begins to exert negative but insignificant influence. On the other hand, financial development variable was seen to exert direct and significant influence on economic growth in terms of low-income nations, which means that a 1% rise in credit to private sector will enhance RGDP by 12.3%. This is in line with the results of Sassi and Goaid (2013) for Turkey but against the outcome for Egypt.

Considering the impact of ICT on social dimension represented by HDI, the result shows that ICT, urbanization, and population growth rate have positive and significant influence on HDI. This implies that a 1% rise in ICT, URB, and POP will lead 21.4%, 6.3%, and 8.2% increases in HDI. ICT and ICTSQ having positive and negative impacts, respectively, imply that ICT has a negative marginal impact on HDI for the low-income nations. This also means the existence of a nonlinear linkage between ICT and HDI. These findings contradict the outcome of Asongu and Nwachukwu (2018). By implication, ICT exertion of negative marginal effect on HDI may be because ICT adoption in the low-income nations has not received high penetration to access to knowledge on the possible ways of bettering their lives via e-learning and e-health in medicine that can lead to overall improvement in health outcomes. The positive linkage between ICT and HDI corroborates the findings of BankoleDr and Mimbi (2017) and Lee et al. (2017). The inverse linkage between the squared term of ICT and HDI is in tandem with the findings of Iqbal et al. (2019) who found a statistically indirect influence of Internet usage on HDI. This, according to them, could be attributed to inadequate resources of the low-income states with which to equip their citizens for a sufficient knowledge-based economy in order to obtain maximum benefits from modern technology (Iqbal et al., 2019).

In terms of lower-middle-income countries, the result indicates that a rise in ICTSQ brings about positive and significant impact on CO₂, while ICT, FOS, and URB exert inverse but insignificant influence on CO₂. This did not validate U-shaped relationship between ICT and CO₂ in the lower-middle-income nations. Economic

TABLE 7 Result of cointegrating relationship

Long-run coef	Panel fully modified OLS (PFMOLS)					
	Pooled estimation		Pooled estimation		Pooled estimation	
	Spec. 1—LCO ₂	Prob. value	Spec 2—LRGDP	Prob. value	Spec. 3—LHDI	Prob. value
Low-income nations						
ICT	0.113***	0.0000	0.211***	0.0010	0.214***	0.0000
ICTSQ	-0.141**	0.0230	-0.091	0.1214	-0.123***	0.0000
LRGDP	0.723***	0.0000				
LFOS	0.125***	0.0000				
LURB	0.124	0.1424	0.2015	0.1522	0.0633*	0.0635
LOPN			-0.212*	0.0657		
LCPS			0.123**	0.014		
LECOF					-0.204	0.219
LPOP					0.0821**	0.0321
No. of observations	250		250			250
R-squared	0.9431		0.8941			0.6723
Lower-middle-income countries						
ICT	-0.0831		0.6282	0.2104***	0.0000	0.1461*** 0.0002
ICTSQ	0.226*		0.0712	-0.1227	0.173	0.1712** 0.0214
LRGDP	0.325***		0.0000			
LFOS	-0.1100		0.7132			
LURB	-0.164		0.2524	0.0611	0.321	-0.152*** 0.0012
LOPN				0.03123	0.335	
LCPS				0.2314	0.153	
LECOF						-0.541*** 0.000
LPOP						-0.235*** 0.000
No. of observations	125			125		125
R-squared	0.82342			0.94231		0.49312

Note: PFMOLS stands for panel fully modified OLS and Spec means specification.

*Significance level at 10%.

**Significance level at 5%.

***Significance level at 1%.

Source: Author's computations.

activities indicated by RGDP causes carbon emission in the zone, which is similar to the outcome of the low-income nations. For the economic dimension, ICT significantly adds to RGDP, while ICTSQ reduces RGDP in an insignificant manner. Other explanatory variables have positive but insignificant impact on RGDP. The ICT and its squared term outcome imply that the marginal direct change in the linkage between the penetration of computers and growth reduces as the penetration rises. This is in line with the findings of Vu (2011).

Considering the last model, which is the social dimension, both ICT and ICTSQ exhibit positive and significant effect on HDI. This means that ICT penetration at both early stage and advanced stage boosts HDI as a result of access to e-learning, e-health usage in medical services, and overall improvement in the standard of living

of the people in the states. This attunes to the findings of Ejemeyovwi et al. (2019) and Gupta et al. (2019). On the other hand, urbanization, economic freedom, and population growth reduce HDI significantly, meaning that a 1% rise in URB, ECOF, and POP will result to 15.2%, 54.1%, and 23.5% reductions in HDI, respectively.

Finally, on the causal linkages among the variables, there is one-way causal linkage from ICT to CO₂, a bidirectional causal association between ICT and HDI, and no causal linkage between RGDP and ICT for the case of low-income group. For the case of lower-middle-income countries, the result shows there is a bidirectional causality between ICT and CO₂, a unidirectional association runs from HDI to ICT, and no causal linkage existed between ICT and RGDP.

TABLE 8 DH causality result

Low income	
LCO ₂ model	Prob.
<i>ICT does not cause LCO₂</i>	0.061
<i>LFOS does not cause LCO₂</i>	0.026
<i>LCO₂ does not homogeneously cause LFOS</i>	0.073
<i>LFOS does not cause ICT</i>	0.000
<i>ICT does not cause LURB</i>	0.000
<i>LRGDP does not cause LURB</i>	0.0041
<i>LFOS does not homogeneously cause LURB</i>	0.001
LRGDP model	
<i>LRGDP does not cause LURB</i>	0.000
<i>LRGDP does not homogeneously cause LCPS</i>	0.000
<i>ICT does not cause LURB</i>	0.0062
<i>LOPN does not homogeneously cause ICT</i>	0.000
<i>ICT does not cause LOPN</i>	0.000
<i>ICT does not cause LCPS</i>	0.000
<i>LURB does not homogeneously cause LOPN</i>	0.002
<i>LCPS does not cause LURB</i>	0.000
<i>LURB does not homogeneously cause LCPS</i>	0.0111
<i>LCPS does not homogeneously cause LOPN</i>	0.0123
<i>LURB does not homogeneously cause LCPS</i>	0.000
<i>LCPS does not homogeneously cause LOPN</i>	0.0621
LHDI model	
<i>ICT does not cause LHDI</i>	0.000
<i>LHDI does not cause ICT</i>	0.000
<i>LPOP does not homogeneously cause LHDI</i>	0.042
<i>LHDI does not homogeneously cause LPOP</i>	0.000
<i>ICT does not cause LURB</i>	0.000
<i>LECOF does not homogeneously cause ICT</i>	0.0304
<i>LPOP does not cause ICT</i>	0.0024
<i>ICT does not homogeneously cause LPOP</i>	0.007
<i>LECOF does not cause LURB</i>	0.0212
<i>LURB does not homogeneously cause LECOFC</i>	0.0677
<i>LECOF does not cause LPOP</i>	0.0721
<i>LECOF does not cause LPOP</i>	0.0721
Lower middle income	
LCO ₂ model	Prob.
<i>ICT does not cause LCO₂</i>	0.005
<i>LCO₂ does not homogeneously cause ICT</i>	0.003
<i>LCO₂ does not cause LRGDP</i>	0.0012
<i>LCO₂ does not homogeneously cause LFOS</i>	0.012
<i>LCO₂ does not homogeneously cause LURB</i>	0.001
<i>ICT does not cause LFOS</i>	0.000
<i>LURB does not cause ICT</i>	0.001
<i>LRGDP does not cause LFOS</i>	0.042
<i>LURB does not homogeneously cause LRGDP</i>	0.000

TABLE 8 (Continued)

Low income	
LCO ₂ model	Prob.
LRGDP model	
<i>LURB does not cause LRGDP</i>	0.0001
<i>LURB does not homogeneously cause ICT</i>	0.001
<i>ICT does not cause LOPN</i>	0.0001
LHDI model	
<i>LHDI does not cause ICT</i>	0.000
<i>LHDI does not homogeneously cause LECOF</i>	0.014
<i>LPOP does not cause LHDI</i>	0.000
<i>LHDI does not homogeneously cause LPOP</i>	0.0001
<i>LURB does not cause ICT</i>	0.002
<i>LECOF does not homogeneously cause ICT</i>	0.001
<i>LURB does not cause LPOP</i>	0.000
<i>LPOP does not homogeneously cause LECOF</i>	0.002

Source: Authors' compilation.

5 | CONCLUSION AND RECOMMENDATION

ICTs are seen as a means to achieving sustainable development through the realization of long-term sustainable economic growth in a less threatened environment (Hou et al., 2015). It is noteworthy that the advancement in ICTs has penetrated every sector of the modern economy and all spheres of life and its utilization increase daily (Lee et al., 2017) with obvious consequences on sustainable environment within ECOWAS subregion. The establishment of the EKC relationship between ICT and CO₂ emphasizes that at the initial stage of ICT development, ICT adoption brings about rise in carbon dioxide emission due to use of heavy computers, but at more advanced stage of ICT development, CO₂ emission declines. This, therefore, serves as an impetus to adopt ICT but more especially modern ICT as the advantages far more outweigh the disadvantages especially in the long-run. This outcome is further confirmed by the absence of an EKC association between ICT and CO₂ for lower-middle-income states, implying that as nations grow and develop, they tend to embrace modern ICT, which would have negative relationship with environmental degradation.

With regard to economic dimension (RGDP) component of sustainable development, ICT has a negative but insignificant marginal impact on per capita GDP in both low-income and lower-middle-income countries. This result is not surprising considering the fact that ECOWAS subregion has not fully keyed into the huge untapped benefits of ICT relative to developed countries. The market for ICT is large, and so are the benefits, which are capable of changing or positively revolutionizing the dwindling economic fortunes of Africa. ICT exerted a negative marginal effect on social dimension component (HDI) of sustainable development for low-income ECOWAS countries

but had a positive marginal impact on the HDI for low-middle-income countries. All of the results buttress the need to embrace ICT whose benefits far more outweigh the costs in the long run.

We conclude that ICT adoption and utilization would help ECOWAS subregion tremendously in bridging their development gaps and achieve sustainable development. We, therefore, recommend policy formulations in both low- and lower-middle-income ECOWAS targeted at incentivizing investment in and use of environmentally friendly technologies that will minimize the positive impact of ICT on the environment, thereby enhancing sustainable development.

5.1 | Policy implications

In this study, we submit that the ECOWAS subregion is in great need of development, adoption, and utilization of ICT in order to achieve sustainable development. Governments' minimum quantum leap whether as incentive, grant, or dearer loans is pertinent to drive this process. Therefore, appropriate modern ICT that is amenable to local, economic, and social environment of ECOWAS subregion ensures sustainable environment should be adopted as a policy objective.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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