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Electronic waste effects of ICT: does income level matter?

Afees Oluwashina Noah[1] · **Oladipo Olalekan David**[1] · **Christian Nedu Osakwe**[2]

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Abstract
As countries strive to meet Sustainable Development Goals 3, 11, and 13 of the United Nations, there is a growing need to employ ICT development to increase resilience and adaptation to climate-related hazards. Setting itself from the previous studies, this study builds a composite index for ICT development, incorporating three ICT indicators to investigate the contributions of ICT development to e-waste generation. The study uses data from 2013 to 2022 and the endogeneity-robust panel dynamic OLS (DOLS) estimation method. The results show that e-waste generation is strongly influenced by ICT development both globally and across income levels. Specifically, mobile lines decrease global e-waste, whereas fixed landlines and internet connections increase it. Internet connectivity increases the amount of e-waste generated in high-income countries, while mobile lines reduce it. Only mobile phones significantly reduce e-waste in high-income countries. In addition, internet connectivity has no impact on e-waste generation in lower-middle-income countries, but mobile and fixed landlines increase it. Furthermore, mobile and fixed landlines have little discernible effect on the development of e-waste in low-income nations, while internet connectivity is the primary cause. The study also confirms the Environmental Kuznets Curve (EKC) hypothesis at global, high- and upper-middle-income countries, but not for low- and lower-middle-income countries. This suggests that there is still a clear correlation between rising e-waste and economic growth in these countries. Overall, the study highlights the need for efficient recycling and disposal methods to reduce e-waste from the trade-off between ICT development and environmental degradation.

Keywords Electronic waste · Environmental Kuznets Curve · Income classifications · Information and communication technology · SDG 13

JEL Classification O33 · Q53 · Q56

1 Introduction

A digitally connected world is necessary to accomplish many Sustainable Development Goals—SDGs [29, 31]. Electrical and electronic equipment (EEE) consumption has expanded dramatically in the early twenty-first century due to economic growth, industrialization, communication, information, electronics technology, and more affordable consumer goods. Since more than half of all people on the planet now have access to the internet, the usage of information and communication technology (ICT) devices, such as tablets, cellphones, and computers, has skyrocketed [4]. The COVID-19 epidemic has sharply increased demand for electronics, particularly ICT equipment, in the IT sector [22]. The availability

✉ Afees Oluwashina Noah, 33138060@student.g.nwu.ac.za; Oladipo Olalekan David, Olalekan.David@nwu.ac.za; Christian Nedu Osakwe, christian-nedu.osakwe@uir.ac.ma | [1]School of Economic Sciences, Faculty of Economic and Management Sciences, North-West University, P.O. Box 1174, Vanderbijlpark Campus, South Africa. [2]Rabat Business School, International University of Rabat, Rabat, Morocco.

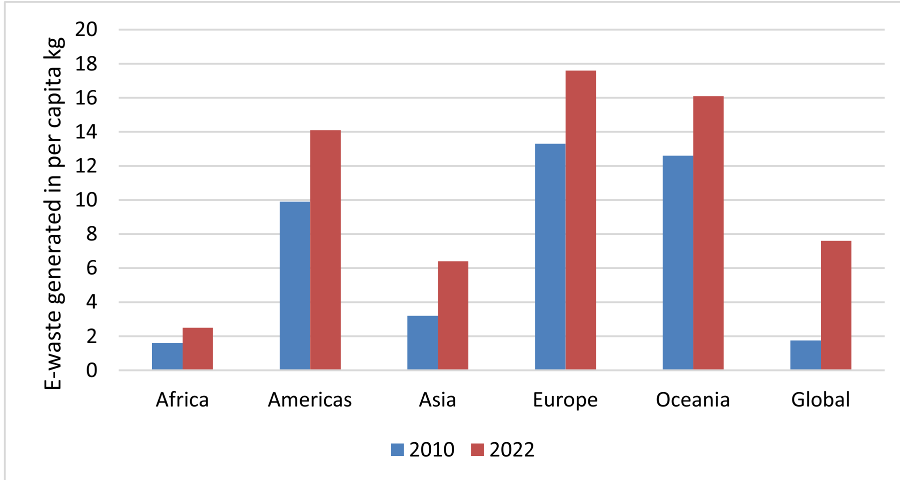

Fig. 1 Global and Regional E-waste Generated. Source: The Global E-waste Monitor (2024)

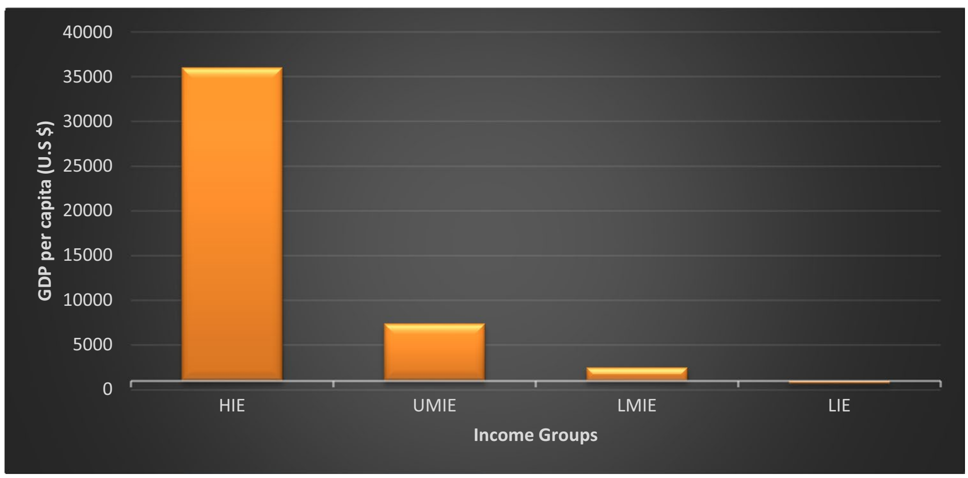

Fig. 2 Countries' Income Groups. Source: World Bank (2023). HIE is High-income countries, UMIE is Upper-middle-income countries, LMIE is Lower-middle-income countries, and LIE is Low-income countries

of ICT products to employees has become necessary because of global lockdowns and the increasing adoption of remote work. The demand for these devices has significantly increased as a result of this [15].

Despite being incredibly useful, these tools and gadgets have short lifespans and are still a long way from becoming entirely recyclable [39]. With newer generations of gadgets quickly replacing previous ones due to rapid improvements in technology, Electronic waste, or "waste", is being produced at startling rates and is a concerning quantity [33]. As per the most recent statistics from the Global E-Waste Monitor in 2024, the amount of e-waste generated worldwide surged from 34 billion kg in 2010 to 62 billion kg in 2022, translating to 7.8 kg annually per person. Only 22.3% of the total amount of e-waste was formally recovered and reused in an environmentally acceptable manner. Formal collection and recycling rates were recorded at 8 billion kg in 2010 and 13.8 billion kg in 2022, growing at an average yearly rate of 0.5 billion kg. However, the amount of e-waste produced is increasing faster than official recycling initiatives [4]. Figure 1 shows details of the global and regional e-waste generated between 2010 and 2022, while Fig. 2 displays the average GDP per capita of the income groups for the selected countries from 2013 to 2022.

As e-waste generation increases without sufficient recycling, it becomes a major environmental and public health hazard [23]. According to Schindler and Demaria [35] "significant amounts of hazardous materials are added to the local waste streams by the growing e-waste stockpiles. Furthermore, important commodities found in conflict-ridden regions of Africa, such as gold, iron, copper, and trace amounts of rare metals like columbite-tantalite, are also found in e-waste". Improper recycling can allow these harmful substances to re-enter the human environment through polluted food, water, and air, which increases the risk of allergies, cancer, and other illnesses (Chiara [11]). Therefore, to reduce these risks and recover important resources, efficient e-waste management and recycling are essential.

Global warming and climate change in the contemporary era are mostly caused by extreme weather events and rising average temperatures, as a result, academics working to achieve SDG 13 now consider environmental degradation to be crucial [16]. Numerous countries have implemented management systems designed to effectively handle and retrieve valuable components from e-waste to tackle these issues. The generation of e-waste, however, is still increasing, which emphasizes the need for a better knowledge of its origins and causes to improve existing regulations. The handling and repurposing of e-waste, together with its consequences for the ecosystem and public health [32, 45] have been the subject of several research studies and systematic reviews [36]. To properly address e-waste, extensive research and legislative initiatives are needed to reduce its negative consequences and encourage sustainable practices.

There is a glaring gap in the literature regarding the macro-level components that go into creating e-waste. Prior research has mostly concentrated on systematic reviews or micro-level analyses [36, 37]. It is imperative to comprehensively comprehend the regional and global causes of electronic waste to curtail its production and alleviate its detrimental effects. The paucity of research in this area highlights the significance of thoroughly examining the macro-level variables influencing the growth of e-waste. Such studies would offer insightful information for scholarly discussion as well as useful remedies.

No empirical study has, as far as we know, thoroughly investigated how ICT development affects the production of e-waste globally and at different income levels. Even though the links between economic growth, internet penetration, and carbon emissions (CO2) have been studied by Zhang and Meng [44] and Kalia et al. [19]. Nevertheless, the wider ramifications of ICT development on e-waste have been mainly ignored in these studies. They have ignored the overall contributions of ICT development and digitalization to e-waste generation, focusing only on internet penetration as a measure of ICT progress, and encountering methodological challenges. The research has not adequately addressed the implications of digitalization on the development of e-waste globally and at country income levels, and the studies that have been done so far have frequently had methodological flaws, such as improper management of endogeneity and problems with panel data. Furthermore, developed countries have been the main focus of prior empirical studies, with less emphasis placed on developing economies, low-income nations, or the global context. This disparity emphasizes the necessity for a more thorough and methodologically sound analysis to fully comprehend how much ICT development contributes to the production of e-waste.

Rather than exploring the root causes of e-waste, recent research has primarily concentrated on managing and recycling it. This study closes these gaps and adds to the body of knowledge by investigating the global drivers of e-waste across various income levels. The main goal is to empirically examine the link between e-waste and ICT development from a global and income-level perspective. In particular, this study evaluates the impact of the ICT development indicators on e-waste generation, ascertains whether the country's income level influences this relationship, and investigates these relationships within the research parameters.

This study provides four unique contributions to empirical research by filling in the gaps in the body of existing literature. Firstly, the present study creates a comprehensive ICT index that incorporates three primary measures of ICT: internet users, mobile, and fixed telephone. This approach overcomes the drawbacks of utilizing a single indicator to quantify ICT, since a single indicator may not capture the absolute influence of ICT development. By providing a detailed and objective assessment of ICT development, this method facilitates a deeper comprehension of ICT's role in environmental sustainability with unbiased measurement. Secondly, the study further examines the individual effect of ICT indicators on e-waste to clarify the mixed reactions from the prior studies due to the use of different indicators. Thirdly, the assessment of the environmental impact of ICT development on e-waste generation is centered on income levels and globally. It looks at how ICT development and its indicators affect e-waste at various income levels, determining if this relationship is affected by the country's income level. Lastly, this study employs methods that have not been employed in previous global research, especially those that are robust against endogeneity in panel data. Therefore, compared to earlier research, this study presents more balanced and effective findings, providing policymakers with well-founded and precise suggestions. The panel dynamic ordinary least squares (DOLS) estimator was used to accomplish these goals. These dynamics could be affected by variations in low- and high-income economies' waste management infrastructure, technical advancements, economic growth, and overall development. This will help to identify the opportunities and problems that are unique to a country's income level, enabling policymakers to create tailored plans for managing e-waste through ICT development. The study is organized as follows in Sects. 2 through 5: Sect. 2 considers pertinent literature, Sect. 3 outlines the methodology, Sect. 4 offers and assesses empirical data, and Sect. 5 concludes with suggestions for practical policy.

2 Literature review

The term "e-waste," or "electronic waste," describes abandoned and outdated electronic and electrical equipment (EEE) that contains hazardous materials and is frequently illegally disposed of in developing countries [26]. Theoretically, the environmental Kuznets curve (EKC) theory can be employed to hypothetically explain the relationship between economic development and environmental degradation, such as e-waste. This hypothesis suggests an inverse U-shaped link between environmental variables and GDP per capita, based on the research of Grossman and Krueger [17]. The EKC theory states that environmental degradation is initially caused by economic growth, but that environmental improvement occurs after growth reaches a specific income level. Subsequent empirical research has extended this idea by analyzing the connection between GDP and environmental deterioration through a variety of indicators, samples, and approaches [6–8, 20].

Furthermore, the IPAT model, which Ehrlich and Holdren first presented in 1971, is a well-known paradigm for researching the variables influencing environmental deterioration. The IPAT model states that population size (P), affluence (A) as measured by GDP per capita, and technology (T) all have an impact on environmental impact (I). Dietz and Rosat [14] created the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model in response to the shortcomings of the IPAT model. This model enables empirical hypothesis testing. Since its creation, the STIRPAT model has gained popularity as a method for analyzing the environmental effects of wealth, population, and technology [9, 38, 42].

Based on the environmental indicators used, related previous studies can be categorized into three groups: water pollution (such as water footprint, wastewater, seawater quality, and water use), land pollution (such as municipal waste, solid waste, medical waste, plastic waste, and hazardous waste), and air-related emissions (such as greenhouse gas emissions and air pollution). This study mainly focuses on the empirical literature examining the Waste Kuznets Curve (WKC), which applies the Kuznets hypothesis to waste, with an emphasis on e-waste, a type of solid waste. This study, therefore focuses only on e-waste, while other studies have examined solid waste in general [28, 41, 43]. Further research is necessary to improve our understanding of the EKC hypothesis about certain waste kinds, especially e-waste. Compared to other solid waste indicators, there is currently a dearth of research that focuses exclusively on e-waste, and the studies that have been done so far have yielded conflicting findings.

2.1 ICT and e-waste

Notable results have been found in recent research that examines the link between the various environmental and ICT indicators, while some studies support the positive connection between ICT and environmental quality [2, 10]. Conversely, others have found otherwise [1, 5], while Awad [3] found no link. This implies that mixed results make the connection between ICT service and environmental conditions inconclusive. However, there is still a dearth of literature on the connection between e-waste and ICT development, especially at the global level. Among the very few studies in this area is the one reported by Osibanjo and Nnorom [30], who found that developing countries were producing more e-waste due to the rapid expansion of ICT. Omobowale [27] provides more evidence for this tendency by showing how the importation of used ICT promotes e-waste accumulation in Nigeria while meeting the demands of modern consumers. Petridis et al. [34] explored e-waste rejection rates in 33 different nations, more internet penetration is associated with more people using smartphones and other electronic devices, which increases the amount of e-waste produced. The presence of the EKC and its interaction with internet penetration in altering pollution levels were confirmed by Zhang and Meng [44].

Additionally, using the generalized method of moments (GMM) estimator, Boubellouta and Kusch-Brandt [6] examined the Kuznets Curve hypothesis for e-waste across thirty European countries, the results showed a negative connection between the development of e-waste and ICT exports. In contrast, Kalia et al. [19] looked into how global development indices impacted the production of e-waste and found that, even in the existence of e-waste laws, higher internet penetration in developing nations is associated with a rise in the production of e-waste. Vishwakarma et al. [40] assert that a significant contributing factor to the rise in e-waste is the ICT sector. They attribute this to the speed at which technology is developing and the growing demand from consumers for technological products.

Based on the aforementioned discussions, theories, and empirical literature suggest that electronic waste could be linked to several possible factors, such as population [6], urbanization [19] and the level of economic development

[17, 42]. As previously mentioned, research by Boubellouta and Kusch-Brandt [6] showed a negative correlation between the generation of e-waste and ICT exports, whereas studies by Kalia et al. [19], Omobowale [27], Osibanjo and Nnorom [30], Petridis et al. [34], and Vishwakarma et al. [40] reported positive connections between the various ICT indicators used by the authors and the development of e-waste.

Even though there is empirical research on a number of elements that contribute to the formation of e-waste, the connection between e-waste and ICT development at the global and income classification levels has not been fully investigated in previous studies. The two global investigations, carried out by Kalia et al. [19], Zhang and Meng [44], employed analytical methodologies for static panels, which are insufficient to tackle problems related to dynamic panel analysis. The policy suggestions that are affected by these omissions are particularly those that are meant to accomplish Sustainable Development Goal (SDG) 13, which deals with the environmental deterioration brought on by climate change.

Furthermore, the length of the studies and the number of countries they looked at constrained earlier research. To close these gaps, this analysis uses a robust panel dynamic ordinary least squares (DOLS) estimate approach that accounts for endogeneity. It also uses forward orthogonal deviations to offer trustworthy empirical insights into the relationship between ICT development and e-waste. From 2013 to 2022, 179 countries were covered by the study, which divides them into four main income categories for a thorough analysis. Through a closer examination of this link, policymakers can create plans to capitalize on ICT's promise to reduce e-waste. This study's ability to produce evidence-based guidelines for national and international organizations looking to manage and mitigate e-waste using ICT interventions makes it relevant to policy. Policymakers might learn more about how different income groups are affected by the effects of ICT development on e-waste. The aforementioned information could potentially steer global collaboration, technological advancement, and public education initiatives aimed at lessening the drawbacks of the e-waste-ICT development relationship and advancing more extensive developmental objectives.

Thus, the following formulation of the hypotheses may be made in light of the body of knowledge in existence regarding the connection between the development of ICT and the generation of e-waste:

H_1: ICT development positively influences e-waste generation.

H_2: The country's income level does not matter on the e-waste-ICT development nexus

H_3: ICT indicators have the same effects on e-waste generation across the country's income classification

3 Materials and methods

3.1 Analytical techniques

This research used principal component analysis (PCA), descriptive analysis, correlation analysis, and panel dynamic ordinary least squares (DOLS) as analytical methods. As highlighted by Lau et al. [21], the DOLS technique is specially selected for estimation in this work, influenced by characteristics relevant to our data. This estimation approach was chosen because of its unique benefits. Lau et al. [21] claim that the DOLS method improves precision in dynamic panel data models by providing more accurate parameter estimates, accommodates complex data structures, and manages endogeneity issues with effectiveness.

3.2 Principal components approach

The PCA is utilized in this study to combine the three primary ICT indicators into a composite ICT index. To provide a succinct explanation, PCA is required. Karl Pearson propounded the PCA in 1901 (Pearson, 1901), and Harold Hotelling formalized it further in 1933. The procedure basically involves transforming sets of indicators into new indices that are not associated with each other, and gathering information on a different level [18]. As necessary weights, we generated the composite index for ICT development using the initial eigenvectors (loading matrix) from PCA [12, 24, 25]. This resulted in the following linear combination:

$$ICT = \varphi_1 fid + \varphi_2 moe + \varphi_3 net \tag{1}$$

where *fid*, *moe*, and *net* are the fixed telephone, mobile phone, and internet indicators, respectively, and φ_1, φ_2, and φ_3 are the weights (eigenvectors) from the PCA.

3.3 Theoretical framework and empirical model specification

The study's model definition is founded on the Environmental Kuznets Curve (EKC) theory, which suggests that environmental deterioration deteriorates first as economic growth increases, but then recovers until a particular income threshold is reached [17]. Additionally, we incorporate the STIRPAT model, which emphasizes the influence of technology, population, and wealth on the environment [14]. Evidence from these theories and the related empirical studies [6, 9, 44], we, therefore, formulate a model for the present study as follows:

$$ELW_{it} = f(X_{it}) \tag{2}$$

Equation (2) is an expression of the connection between e-waste and its influencing factors as stated by the theories, where *ELW* represents e-waste and *X* represents economic growth and other explanatory variables. Including the intercept, parameter, and the error term in Eq. (2) can be further expressed as follows:

$$ELW_{it} = \gamma_0 + \lambda X_{it} + \varepsilon_{it} \tag{3}$$

where γ, λ, and ε are the intercept, parameters of the explanatory variables, and error term, respectively. We therefore specify the DOLS model by including the explanatory variables as follows:

$$ELW_{it} = \gamma_0 + \lambda_1 ECN_{it} + \lambda_2 ECN_{it}^2 + \lambda_3 PPL_{it} + \lambda_4 URN_{it} + \lambda_5 ICT_{it} + \varepsilon_{it} \tag{4}$$

where *ECN* represents economic growth, ECN^2 is the square of economic growth, *PPL* is population growth, *URN* is urbanization, and *ICT* is ICT development. Based on a priori expectation, λ_1–λ_5 are expected to be positive except λ_2. To validate the existence of the EKC hypothesis, the coefficients of *ECN* and ECN^2 must be positively and negatively statistically significant, respectively. Thus, using the coefficients of *ECN* and ECN^2 in Eq. 3, the turning point is calculated as follows:

$$\frac{-\lambda_1}{2 * \lambda_2} \tag{5}$$

The data set for the study includes secondary sources from 179 different nations across the globe, spanning the years 2013–2022. Data availability limits the period and number of nations considered. Following the World Bank's 2019 income classifications, Table 1 illustrates how these nations are further split into four income groups. In addition, the regressand (e-waste generation in kilos) is sourced from a report by the Global E-waste Statistics Partnership [4]. The details of the variables and their sources are presented in Table 2.

4 Results and discussion

The descriptive statistics results are shown in Table 2. These statistics include the mean, maximum, and minimum values for the analyzed variables in the full sample and the four income classifications. The details of the variables show that the low-income countries category has the lowest average e-waste generated, with 0.933 kg, while the high-income category has the highest, with a value of 16.677 kg, which is almost double the global average of 8.342 kg. The high-income countries category also has the highest e-waste generated, with a value of 28.500 kg, whereas the low-income countries category has the lowest, with a value of 0.200 kg. This implies that the level of the economy, the higher the rate of e-waste that will be generated, and vice versa.

This is also supported by the average value of the GDP per capita for these income groups. The average GDP per capita for the high-income countries category is U.S. $ 34,224.66, while the average GDP per capita for the low-income countries category is U.S. $ 602.256, which is far below the average global GDP per capita of U.S. $ 14,177.31. This also applies to almost all the remaining variables except for population growth, where the low-income countries category has the highest average value of 2.558 percent, followed by the lower-middle income, upper-middle income, and high-income categories with 1.815, 0.824, and 0.919 percent, respectively. This further indicates a wide income gap among the selected countries, which is one of the motivations for the present study to empirically examine if this factor is essential in e-waste generation among the countries.

Table 1 List of countries based on income classifications

Income group	Countries
Low-income countries	Burundi, Central African Republic, Malawi, Madagascar, Niger, Togo, Ethiopia, Mozambique, Afghanistan, Burkina Faso, Gambia, Rwanda, Mali, Sierra Leone, Chad, Uganda, Syria
Lower middle-income countries	Angola, Bangladesh, Benin, Bhutan, Bolivia, Cambodia, Cameroon, Cape Verde, Comoros, Congo Rep., Côte d'Ivoire, Djibouti, Egypt, Ghana, Honduras, India, Jordan, Kenya, Kiribati, Kyrgyzstan, Lao People's Dem. Rep., Lebanon, Lesotho, Mauritania, Micronesia, Morocco, Myanmar, Nepal, Nicaragua, Nigeria, Pakistan, Papua New Guinea, Philippines, Sao Tome and Principe, Senegal, Solomon Islands, Sudan, Swaziland, Tanzania, Timor-Leste, Ukraine, Vanuatu, Vietnam, Yemen, Zambia, Zimbabwe
Upper middle-income countries	Albania, Algeria, Armenia, Azerbaijan, Belarus, Belize, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria, China, Colombia, Dominica, Dominican Republic, Ecuador, El Salvador, Fiji, Gabon, Georgia, Grenada, Guatemala, Guyana, Indonesia, Iran, Iraq, Jamaica, Jordan, Kazakhstan, Libya, Malaysia, Maldives, Mauritius, Mexico, Mongolia, Namibia, North Macedonia, Paraguay, Peru, Republic of Moldova, Romania, Russian Federation, Saint Lucia, Saint Vincent and the Grenadines, Samoa, Serbia, South Africa, Sri Lanka, Suriname, Thailand, Tonga, Tunisia, Turkey, Turkmenistan
High-income countries	Argentina, Antigua and Barbuda, Aruba, Australia, Austria, Bahamas, Bahrain, Barbados, Belgium, Brunei, Canada, Chile, China, Costa Rica, Hong Kong, China, Macao, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Kuwait, Latvia, Lebanon, Lithuania, Luxembourg, Malta, Netherlands, New Zealand, Norway, Oman, Palau, Panama, Poland, Portugal, Qatar, Republic of Korea, Saint Kitts and Nevis, Saudi Arabia, Seychelles, Singapore, Slovakia, Slovenia Spain, Sweden, Switzerland, Trinidad and Tobago, UK of Great Britain, United Arab Emirates, United States of America, Uruguay

The four income groups are divided based on the following income criteria: < \$1026, \$1026–3995, \$3996-\$12,375, and > \$12,375 for the low-, lower-middle-, upper-middle- and high-income respectively, by World Bank guidelines (2019 GNI per capita)

Table 2 Descriptive Analysis

Variables	Statistic	ELW	ECN	PPL	URN	ICT	MOE	FID	NET
Full Sample	Mean	8.342	14177.31	1.329	58.239	99.023	109.972	16.825	51.147
	Maximum	28.500	108351.5	11.790	100.000	283.394	420.850	61.703	104.430
	Minimum	0.200	270.140	– 6.850	11.480	8.776	13.490	0.006	0.600
Low-income countries	Mean	0.933	602.256	2.558	31.444	37.141	62.092	1.587	11.529
	Maximum	5.200	922.02	3.880	61.930	33.919	133.920	20.603	34.650
	Minimum	0.200	270.140	– 6.850	11.480	12.434	23.520	0.006	0.600
Lower-middle income countries	Mean	2.611	2056.387	1.815	45.771	67.746	90.080	4.993	30.559
	Maximum	11.100	3892.420	11.790	91.200	134.417	154.500	37.839	84.120
	Minimum	0.300	1037.94	– 2.880	12.980	8.513	13.490	0.053	1.800
Upper-middle income countries	Mean	7.106	6588.372	0.824	61.119	87.698	120.437	16.689	52.399
	Maximum	11.700	11938.78	4.670	91.990	127.350	190.520	46.808	127.350
	Minimum	1.800	4007.20	– 1.760	18.460	40.735	48.900	0.908	40.735
High-income countries	Mean	16.677	34224.66	0.919	74.945	12.918	134.217	32.061	80.736
	Maximum	28.500	108351.50	9.220	100.000	49.419	420.850	61.703	104.430
	Minimum	5.233	12464.48	– 1.400	24.510	– 110.603	71.860	3.886	27.565
Sources		GEM	WDI	WDI	WDI	Authors	ITU	ITU	ITU

ELW is e-waste generated in kg, *ECN* is GDP per capita, *PPL* is population growth, *URN* is urbanization, *ICT* is ICT index, *MOE* is mobile phone, *FID* is fixed telephone, and *NET* is Internet access subscriptions. GEM is Global E-waste Monitor Statistics Partnership, TUI is Telecommunication Union International, WDI is World Bank's World Development Indicators, Authors implies Authors' Computation

The correlation matrix and PCA results are presented in Panels I and II of Table 3, respectively. The correlation matrix presented in Panel I reveals a robust positive correlation between e-waste and all ICT indicators (mobile phones, fixed telephone, and internet access). Similarly, strong positive correlations are also observed between e-waste and the control variables (GDP per capita and urbanization), except for population growth, which is negatively correlated with e-waste. It is essential to note that the substantial positive correlation observed between e-waste and all ICT indicators points

Table 3 Correlation matrix and principal component analysis results

Panel 1: Correlation matrix

Variables	ELW_	ECN	PPL	URN	MOE	FID	NET
ELW	1.000						
ECN	0.855[a]	1.000					
PPL	− 0.311[a]	− 0.098[a]	1.000				
URN	0.679[a]	0.591[a]	− 0.115[a]	1.000			
MOE	0.494[a]	0.442[a]	− 0.178[a]	0.514[a]	1.000		
FID	0.797[a]	0.649[a]	− 0.443[a]	0.547[a]	0.407[a]	1.000	
NET	0.854[a]	0.699[a]	0.364[a]	0.684[a]	0.566[a]	0.707[a]	1.000

Panel 2: PCA for ICT indicators variable

Eigenvalues variance explained by the principal components					Eigenvectors		
Components	Eigenvalue	Difference	Proportion	Cumulative	Component1	Component2	Component3
Component1	2.12836	1.51915	0.7095	0.7095	–	–	–
Component2	0.609209	0.346777	0.2031	0.9125	–	–	–
Component3	0.262432	–	0.0875	1.0000	–	–	–
MOE	–	–	–	–	0.5225	0.8113	0.2624
FID	–	–	–	–	0.5798	− 0.5637	0.5882
NET	–	–	–	–	0.6251	− 0.1551	− 0.7649

Authors' Computation. Note that 'a' signifies the statistically significant @ 1% significance level, *ELW* is e-waste generated, ICT is ICT index, *FID, NET*, and *MOE* denote the penetration rates of connected fixed lines, mobile lines, and internet access, respectively, *ECN* is GDP per capita, *PPL* is population growth, and *URN* is urbanization

to a possible linkage between e-waste generation and ICT development rather than proving a clear causal relationship. Furthermore, there are no problems with multicollinearity in the dataset; all correlation coefficients between the explanatory variables are less than 0.8 and statistically significant at the 1% level.

Moreover, Panel II of Table 3 displays the results of the PCA for ICT indicators for the full sample. The results for income category groups are excluded for the sake of conciseness. Since its eigenvalue accounts for the largest percentage of the variation (2.12836%), we used the first principal component of the ICT indicators to create a composite index for ICT development at both the global and income classification levels. Equation (1) was used to determine the weights for the appropriate eigenvectors (0.5225, 0.5798, and 0.6251) from the PCA to generate the composite index for ICT development. The groups classified by income underwent the same process.

4.1 Empirical results

The results of the aggregate ICT development at the global and income levels are shown in Table 4, and the breakdown of ICT indicators is shown in Table 5. Before interpreting and discussing the findings of the study, we examine the diagnostic test results to assess the reliability of the estimated outcomes. Tables 4 and 5 display the results of diagnostic tests, indicating that the values of the R-squared range from 0.9619 to 0.6495. This implies that the overall relationship between e-waste and the explanatory variables ranges from approximately 96.19–64.95 percent. This suggests that these variables explain a substantial portion of e-waste. The F-statistic values also examine the evidence on the overall validity of the models. These range from 1142.588 to 21.4270, all statistically significant at the 1% level, indicating the overall validity of the models. These tests validate our model parameters and offer a strong foundation for policy deliberations and conclusions.

A number of significant conclusions are shown by the DOLS results for the e-waste effect of ICT development in Table 4 at both the global and income levels. Specifically, the findings indicate that the coefficients of GDP per capita are positive and statistically significant for the full sample and across the income levels at the 1% significance level. This suggests that GDP per capita has a positive impact on e-waste generation globally and across income levels. That is, a unit increase in GDP per capita leads to a rise in electronic waste generated ranging from 0.0004 to 0.0025 kg at the global and across income levels, respectively. Furthermore, with the exception of low- and lower-middle-income nations,

Table 4 Panel dynamic ordinary least squares result for the aggregate ICT development

Variables	Full Sample		High-income		Upper-Middle		Lower-Middle		Low-income	
	Control variables	ICT index	Control variables	ICT index	Control variables	ICT index	Control variables	ICT index	Control variables	ICT index
ECN	0.0006^{a} [61.5350]	0.0005^{a} [51.3964]	0.0005^{a} [18.8185]	0.0004^{a} [16.4656]	0.0018^{a} [12.4928]	0.0017^{a} [12.4052]	0.0012^{a} [8.0363]	0.0010^{a} [7.1345]	0.0025^{a} [4.7170]	0.0017^{a} [2.5479]
ECN^2	− 4.45E-09^{a} [− 39.3545]	− 4.19E-09^{a} [− 35.4028]	− 3.24E-09^{a} [− 13.4764]	− 2.79E-09^{a} [− 11.7589]	− 7.65E-08^{a} [− 9.0211]	− 7.32E-08^{a} [− 9.3443]	− 2.96E-09 [− 0.1547]	− 8.18E-09 [− 0.4539]	− 6.83E-07 [− 3.2349]	− 4.22E-07 [− 1.5987]
PPL	− 0.8139^{a} [− 16.4172]	− 0.7215^{a} [− 13.6554]	− 0.7612^{a} [− 6.2677]	− 0.5182^{a} [− 4.3661]	− 0.4587^{a} [− 5.6933]	− 0.3773^{a} [− 4.3015]	− 0.3121^{a} [− 4.5513]	− 0.1786^{a} [− 2.6435]	− 0.6251^{a} [− 12.3541]	− 0.6231^{a} [− 12.7359]
URN	0.0298^{a} [8.4235]	0.0225^{a} [5.8168]	0.0011 [0.1098]	0.0045 [0.5014]	0.0139^{a} [2.7820]	0.0131^{a} [2.6031]	0.0270^{a} [6.8781]	0.0179^{a} [4.5475]	0.0087^{c} [1.7552]	− 0.0004 [− 0.0612]
ICT	– –	0.0138^{a} [4.8884]	– –	0.0449^{a} [6.5187]	– –	0.0126^{a} [2.2627]	– –	0.0222^{a} [6.4626]	– –	0.0144^{a} [2.6234]
T-Point	66,416	59,666	77,160	71,685	11,765	11,612	–	–	–	–
C	1.8082^{a} [9.3796]	1.0549^{a} [4.3048]	6.5600^{a} [10.6745]	6.6935^{a} [11.5632]	− 1.5955^{a} [− 2.6705]	− 2.2694^{a} [− 3.7133]	− 0.9306^{a} [− 3.3536]	− 1.9118^{a} [− 6.3510]	0.9472^{a} [3.0243]	1.0530^{a} [3.2391]
R-squared	0.9252	0.9281	0.7266	0.7623	0.6495	0.6438	0.7607	0.7931	0.7659	0.7972
F-statistic	1142.588^{a} (0.0000)	909.3490^{a} (0.0000)	65.2893^{a} (0.0000)	61.4113^{a} (0.0000)	35.7950^{a} (0.0000)	30.3746^{a} (0.0000)	65.3509^{a} (0.0000)	62.2847^{a} (0.0000)	29.1937^{a} (0.0000)	21.4270^{a} (0.0000)

Authors' Computation. Note that figures in the [] and () are t-statistic and p-values respectively, 'a', 'b', and 'c' signify statistically significant @ 1, 5, and 10% significance levels, *ELW* is e-waste generated, *ECN* is GDP per capita, ECN^2 is GDP per capita square, *PPL* is population growth, *URN* is urbanization, ICT is ICT development, and *T-Point* is turning point of GDP per capita

Table 5 Panel dynamic ordinary least squares result for the disaggregate ICT development

Variables	Full sample	High-income	Upper-middle	Lower-middle	Low-income
ECN	0.0005[a] [39.2456]	0.0004[a] [15.3049]	0.0018[a] [11.6489]	0.0010[a] [7.3606]	0.0013[c] [1.7682]
ECN^2	− 3.51E− 09[a] [− 28.5664]	− 2.58E− 09[a] [− 11.7035]	− 8.32E− 08[a] [− 8.8393]	7.44E− 10 [0.0431]	− 2.96E− 07 [− 1.0668]
PPL	− 0.4791[a] [− 8.6533]	− 0.5861[a] [− 4.9064]	− 0.4420[b] [− 4.1553]	− 0.1662[b] [− 2.4793]	− 0.5601[a] [− 10.9073]
URN	0.0151[a] [4.1059]	0.0005 [0.0526]	0.0129[a] [2.6464]	0.0182[a] [4.6827]	0.0021[b] [0.4139]
MOE	− 0.0053[a] [− 2.9472]	− 0.0197[a] [− 5.5905]	0.0132[a] [4.1903]	0.0129[a] [5.2421]	0.0036 [1.3123]
FID	0.0325[a] [4.9959]	0.0093 [0.8468]	0.0148 [1.3600]	0.0837[a] [6.4021]	0.2548 [20.6890]
NET	0.0466[a] [10.7589]	0.0716[a] [4.6718]	− 0.0059 [− 1.0675]	− 0.0089 [− 1.4511]	0.0386[a] [4.5491]
T-Point of ECN	71,225	77,519	10,817	–	–
C	0.9561[a] [4.1575]	4.8067[a] [4.2208]	− 3.1726[b] [− 4.5873]	− 1.6899[b] [− 5.4348]	0.3495[b] [2.1905]
R-squared	0.9377	0.7743	0.6883	0.8249	0.9619
F-statistic	715.4482[a] (0.0000)	51.8568[a] (0.0000)	23.4181[a] (0.0000)	53.3359[a] (0.0000)	91.3152[a] (0.0000)

Authors' Computation. Note that figures in the [] and () are t-statistic and p-values respectively, 'a', 'b', and 'c' signify statistically significant @ 1, 5, and 10% significance levels, *ELW* is e-waste generated, *ECN* is GDP per capita, *ECN^2* is GDP per capita square, *PPL* is population growth, *URN* is urbanization, *MOE* is mobile lines, *FID* is fixed landlines, *NET* is internet access, and *T-Point of ECN* is turning point of GDP per capita

the GDP per capita square coefficients are negative and statistically significant across the whole sample and all income levels at the 1% significance level. This suggests that GDP per capita square has an adverse effect on the production of e-waste in high- and upper-middle-income countries globally, but has no effect on the production of e-waste in low- and lower-middle-income countries. That is, in global, high- and upper-middle-income countries, a rise in GDP per capita unit after the turning point results in a drop in the amount of e-waste generated, which ranges from 7.32E-08 to 2.79E-08 kg.

These confirm the presence of the EKC hypothesis at global, high- and upper-middle income levels with the turning points of U.S. $66,416, U.S. $77,160, and U.S. $11,765, respectively, while this cannot be confirmed in low- and lower-middle income levels. The inverted U-shaped connection between environmental degradation (e-waste) and GDP per capita is consistent with prior research by Boubellouta and Kusch-Brandt [7, 8, 9], and Kusch and Hills [20]. The findings also indicate that despite the positive effect of ICT development on e-waste, it actually reduces the effect of economic growth on e-waste generation by reducing the turning point from U.S.$66,416 to U.S. $59,666, U.S. $77,160 to U.S. $71,685, and U.S. $11,765 to U.S. $11,612 for the global, high- and upper-middle income levels respectively.

The findings further reveal that population growth has a negative impact on e-waste globally and across income levels. This supports the findings of Boubellouta and Kusch-Brandt [7, 8] and Yilmaz and Koyuncu [42], but contradicts the conclusions of Kalia et al. [19]. The findings also demonstrate that urbanization positively influences e-waste generation globally and across income levels, except for the high-income countries. This is also consistent with previous studies by Chatti and Majeed [10], and Zhang and Meng [44], which suggests a positive impact of urbanization on e-waste generation. However, they contradict the findings of Boubellouta and Kusch-Brandt [7, 8], who reported a negative association, as well as those of Kalia et al. [19], who found no direct influence of urbanization on e-waste generation.

For the variable of interest, ICT development, the findings show that the coefficients of ICT development are statistically significant and positive for the full sample and across the income levels at the 1% significance level. This indicates that ICT development positively influences the development of e-waste globally and across income levels. That is, a unit increase in ICT development leads to a rise in electronic waste generated, ranging from 0.0126 to 0.0449 kg at the global and across income levels. The findings further reveal that GDP per capita and its square confirm the inverted U-shape at global, high- and upper-middle income levels.

The disaggregated impacts of ICT variables on the generation of e-waste at the global and income-specific levels are presented in Table 5. Globally, the production of e-waste is positively impacted by both fixed telephone and internet connections, while mobile phones have the opposite effect. Internet connection is linked to higher e-waste creation for the high-income group, although mobile phones have a negligible effect, and fixed telephones have no discernible effect. Only mobile phones negatively influence the development of e-waste in the upper-middle income group; fixed telephone and internet connectivity have no effect. The findings for the lower-middle income bracket show that while internet connection has no discernible effect, mobile and fixed telephone both positively influence e-waste generation. Internet connectivity also positively influences e-waste generation at the low-income level, but neither fixed telephones nor mobile phones has a substantial effect.

4.2 Discussion of findings and policy implications

This study's results aid in elucidating the complex relationship between the advancement of ICTs and the formation of e-waste at global and income levels. The findings show that ICT development positively contributes to e-waste generation both globally and across income levels, demonstrating its contribution to e-waste generation. These results underline how crucial ICT development is to reaching SDG 13. This suggests that technological developments may promote the production of e-waste, which would worsen the environment. That is, ICT may have an impact on the increase in e-waste generation that results in increased environmental degradation by facilitating improved communication, information exchange, and digital service accessibility.

This aligns with prior studies by Kalia et al. [19], and Vishwakarma et al. [40], which reported that the ICT sector plays a significant part in the growth of e-waste. This, however, contradicts the conclusions of Boubellouta and Kusch-Brandt [6], Zhang and Meng [44]. There are a number of possible reasons for the discrepancy in these findings, including the utilization of e-waste measures and ICT development. Most notably, this study's dynamic panel approach for data analysis and result estimation, as well as its evaluation of ICT development (ICT index), differ significantly from those of the previously stated research.

This could also have to do with the fact that the growth of ICT leads to faster technological innovation, more manufacturing and use of electronic equipment, and regular upgrades, all of which increase the quantity of e-waste generated globally across various economic levels. As was already noted, the way that ICT is widely deployed and efficiently recycled will largely determine how much of an impact it can have on the development of e-waste. More significantly, the results of the present study point to a trade-off between ICT development and environmental deterioration, like e-waste. Consequently, by properly disposing of and recycling e-waste, it is possible to concurrently achieve enhanced environmental quality (via the reduction of e-waste) and ICT development.

In addition to the general impacts of ICT development, the particular implications of ICT indicators on e-waste demonstrated that mobile phones have a negative impact globally, whereas fixed telephones and internet connections have a positive impact. This suggests that while mobile lines decrease the amount of e-waste generated globally, fixed telephones and internet access both promote it. The rapid technological improvements for fixed telephones and internet access equipment, such as modems, routers, and telephones, may influence the environment due to a rise in these services. As more and better models are produced, previous ones become outdated and are disposed of, adding to the amount of e-waste produced. Another possible reason for this could be the regular updates that consumers and service providers make to these devices to improve performance and speed. This creates a never-ending cycle of throwing away and replacing outdated gadgets. Furthermore, unlike mobile phone users, fixed telephones and internet consumers do not have a repair culture; hence, the tendency toward replacing rather than fixing broken or outdated devices may be linked to a rise in the production of e-waste.

The idea that a rise in mobile phone usage lowers the amount of e-waste produced is implied by the global negative impact of mobile phones on e-waste generation. This suggests that mobile technologies should be promoted globally instead of fixed telephones and large internet setups. This might have to do with the fact that mobile phones frequently have several uses, including social media, internet access, and phone calls. This lowers the total number of electronic devices manufactured and disposed of, and the requirement for distinct devices for each function. The findings also indicate that while mobile phones lower e-waste in high- and upper-middle-income countries, internet connectivity raises e-waste generation in these nations; fixed telephones have no effect on e-waste in these countries.

One possible explanation for this may be the rapid advancements in high-income nations regarding internet technology, which frequently lead to the upgrading of internet equipment to facilitate faster speeds and enhanced performance. This, in turn, causes the older equipment to be disposed of more frequently. Furthermore, the introduction of new technologies like 5G internet access requires the replacement of outdated infrastructure, which increases the quantity of e-waste generated. The fact that high- and upper-middle-income nations have strong trade-in and recycling programs that entice customers to return old phones may have an adverse effect on mobile lines. These programs reduce e-waste by refurbishing and properly recycling devices, extending their useful lives. Fixed telephone infrastructure is already well-established, so there may not be much demand for new installations, which could explain why fixed telephones have no effect on e-waste in high- and upper-middle-income nations. As a result, less material is wasted during infrastructure expansions or renovations.

Regarding low- and lower-middle-income nations, mobile and fixed landlines encourage the production of e-waste in lower-middle-income countries but have no effect on e-waste in low-income nations. The results also show that while mobile lines have no effect on e-waste generation in lower-middle-income countries, they do in low-income ones. Due to growing access and use, technology advancements, a lack of adequate recycling infrastructure, and rising consumption, mobile and fixed telephones influence e-waste in lower-middle-income nations. All of these factors add to the growing problem of e-waste. Due to the quick development and uptake of new technologies, regular upgrades of internet-enabled devices, economic variables influencing device lifespan, infrastructure development and upgrades, and difficulties with e-waste management, internet connectivity also has an impact on e-waste in low-income nations.

In addition to the advancement of ICT, the control variable results show a better grasp of global e-waste across socioeconomic levels. In particular, the findings demonstrate that, while the inverted U-shape is absent at lower and lower-middle-income levels, GDP per capita and its square confirm it at global, high, and upper-middle-income levels. This implies that while early economic growth causes e-waste to increase, there is a threshold that must be crossed before additional economic growth causes e-waste generation to decrease. This supports the EKC hypothesis at the global, high-, and upper-middle income levels, where the respective turning points are $66,416, $71,160, and $11,765. The findings also demonstrate that even though ICT development positively influences e-waste, economic growth actually lessens the effect of e-waste generation by lowering the turning point for global, high-, and upper-middle income levels, respectively, from US$66,416 to US$59,666, US$77,160 to US$71,685, and US$11,765 to US$11,612. Except for high-income nations, it can be assumed that all income groups do not generally follow a trajectory that finally converges to a sustainable route, where economic expansion raises the amount of e-waste to a specific threshold. This is especially true given the global GDP per capita threshold of $66,416. Additional economic growth for the upper and high middle classes (based on their respective thresholds) could benefit the environment because it will reduce e-waste due to expanding services and a decline in industrial share. But without reaching the EKC turning point, both low- and lower-middle-income countries are still in the stage where economic growth is strongly correlated with rising e-waste.

Moreover, the conclusion that population expansion has a negative effect on the generation of e-waste worldwide and across income levels raises the possibility that, in contrast to predictions and certain earlier research, more populous nations may produce less e-waste per person. This may be the result of things like reduced per capita usage of electronics in crowded places, particularly in low-income areas. Lastly, it is discovered that, with the exception of high-income nations, urbanization positively influences e-waste generation globally and across all income levels. This association is expected because electronic device usage is generally higher in metropolitan areas. The absence of a noteworthy correlation between urbanization and e-waste generation in high-income nations may be attributed to pre-existing e-waste management frameworks and maybe a saturation point in the expansion of electronic device utilization.

5 Conclusion

There is an increasing need to leverage the potential influence of ICT growth to achieve the United Nations SDGs 3, 11, and 13, which emphasize strengthening resilience and adaptation ability to climate-related hazards. These goals are being worked towards by governments at the global and various economic levels. Therefore, being one of the environmental degradations that affect people worldwide and at all income levels, it is crucial to look at how ICT development may have contributed to the increase in e-waste generation. We used the endogeneity-robust panel dynamic OLS (DOLS) estimation approach, and the analysis spans the years 2013–2022. By combining three ICT variables to formulate a composite index for ICT development, this study sets itself apart from previous studies on the subject matter.

The following findings from this study add to the existing literature. Focusing on our variables of interest, ICT development has a positive and significant impact on e-waste generation across the board, as indicated by estimation results of the DOLS approach. This highlights the contribution of ICT development to e-waste generation globally and across income levels. More specifically, mobile phones decrease the amount of e-waste generated globally, whereas fixed telephones and internet connectivity have a positive impact. Internet access positively influences e-waste generation, while mobile phones reduce it, and fixed telephones do not influence e-waste generation in high-income countries. Only mobile lines have a negative effect on the quantity of e-waste among upper-class consumers; internet connection and fixed telephones have no effect on e-waste.

The findings for lower-middle income groups show that e-waste generation is positively influenced by both fixed and mobile telephones, but not influenced by internet connectivity. Mobile and fixed telephones have little effect on the development of e-waste at the low-income level; only internet connectivity has a positive influence. The findings also demonstrate that, globally, high- and upper-middle-income levels, GDP per capita, and its square support the inverted U-shape. With the turning points of US$66,416, US$77,160, and US$11,765, respectively, this also demonstrates the existence of the EKC hypothesis at the global, high-, and upper-middle income levels, however, it does not exist at the low- and lower-middle income levels. This suggests that rather than having reached the EKC turning point, both low- and lower-middle-income nations are still in the stage where economic growth directly correlates with growing e-waste.

Drawing from the empirical results, it is suggested that governments and policymakers worldwide make use of ICT development to get a deeper understanding of e-waste concerns and consequently increase ICT's contribution to environmental quality to attain SDGs 3, 11, and 13. International standards must be established for the recycling and disposal of e-waste to guarantee uniform and efficient management across all income brackets. In addition to successfully solving these issues and lessening the negative consequences of e-waste, international cooperation is required due to the global nature of ICT development and e-waste generation. Collaborative efforts are crucial to guarantee that low- and middle-income nations have the infrastructure and resources required to handle e-waste efficiently. Promoting the shift to a circular economy in which goods are made to be recyclable, repairable, and reused is also essential. To improve international e-waste management standards, it is also critical to promote adherence to treaties like the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal.

High-income nations should also develop policies that promote the use of cloud services and digital solutions that lessen dependency on physical devices to lessen the effect that internet access has on e-waste generation. Additionally, by supporting programs for recycling mobile devices and encouraging sustainable advancements in mobile technology, they should keep up the momentum behind mobile telephones' efforts to reduce e-waste. These nations have reached a turning point where economic expansion may help to reduce e-waste; thus, enforcing strict legislation to control and minimize it is essential. Upper-middle-income nations must implement measures to control the beneficial impact that fixed and mobile telephones have on the production of e-waste. This entails encouraging the use of used electronics, improving the infrastructure for recycling e-waste, and pushing for the introduction of more effective and environmentally friendly technology.

Lower-middle-income nations must create regulations to limit the growth in the e-waste generation from mobile and fixed telephones, as well as improve the infrastructure for e-waste collection and recycling. It is also crucial to invest in recycling facilities and training programs to increase capacity for managing e-waste. Low-income nations should concentrate on putting plans into place to control how internet access affects the production of e-waste by encouraging digital literacy and ethical device use. Promoting the usage of shared ICT resources can assist in lowering the average number of devices needed per person. To create sustainable e-waste management systems, it is also essential to establish the fundamental infrastructure for e-waste collection and recycling, as well as to look for partnerships and international support.

Aid programs should give priority to SDGs 3, 11, and 13, which would increase markets and technical accessibility for low- and lower-middle-income nations. The development of e-waste management infrastructure, such as collection sites, recycling centers, and effective transportation for managing e-waste in urban settings, must also be given top priority by cities. Targeted public awareness initiatives regarding the significance of appropriate e-waste disposal and recycling are crucial to reducing adverse environmental effects as urbanization increases.

The strategic creation of ICT policies to lower the generation of e-waste worldwide and across different income levels is greatly aided by our study. It emphasizes how crucial it is to take ICT growth into account as a major component in attaining environmental quality. Future studies should examine whether the findings of this research apply to individual nations, regions, or economic blocs, especially in emerging nations. This would improve our comprehension of the problem and offer more pertinent policy implications for particular situations. Also, the study's applicability to rapidly changing ICT trends and technology may be limited by its reliance on data from 2013 to 2022. In addition, the study does not investigate the fundamental causes of the Environmental Kuznets Curve hypothesis' failure for low- and lower-middle-income nations, even while it supports the theory for specific income categories. Last but not least, just the generation of e-waste was examined in this study; recycling and collecting of e-waste were left out due to inadequate data. These offer chances for more in-depth investigation in the future.

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