ELECTRONIC WASTE EFFECTS OF GLOBALIZATION AND DIGITALIZATION: Global and Regional Insights from a Dynamic Panel Threshold Study

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ABSTRACT

The responsibilities of globalization and digitization in helping countries reach UN SDG 13, which is focused on improving adaptive and resilience capacity to climate-related risks, are becoming increasingly important. This study, which covers the period 2013 to 2022 for 174 countries, provides empirical insight into the hitherto ambiguous relationship between globalization, digitization, and the development of electronic waste (e-waste), globally and regionally. The potential non-linear link between economic growth and e-waste generation is examined using a dynamic threshold model. Findings from the study show that, with the exception of Europe, globalization promotes the production of e-waste at the regional and global levels. While digitalization reduces e-waste generation in America and Europe, it promotes the production of e-waste in Africa and Asia. In particular, mobile phones, aside from Europe, increase e-waste generation both globally and regionally. Fixed telephones decrease e-waste generation globally and in America, increase it in Africa, and have no impact in Asia and Europe. Internet connection increases the production of e-waste globally, in Europe and Africa, but decreases it in America and Asia. The analysis also supports the Environmental Kuznets Curve (EKC) hypothesis by identifying specific thresholds of economic growth below which the influence of growth on e-waste *generation decreases. To cross these thresholds, policymakers should initiate sustainable development approaches. Each region is recommended to implement customized plans to ensure that economic growth is accompanied by a decline in e-waste production. This underscores the need for global collaboration, strict laws, and effective e-waste management systems.*

Keywords: Digitalization, Electronic waste, Globalization, Dynamic threshold

JEL classification: F6, O33, Q56

1. Introduction

Recent trends show that global e-waste generation rose sharply from 34 billion kg in 2010 to 62 billion kg in 2022, or 7.8 kg per person yearly. Out of the generated global e-waste, only 22.3% was formally gathered and recycled in an ecologically-friendly manner. Efforts to collect and recycle e-waste have improved in recent times from 8 billion kg in 2010 to 13.8 billion kg in 2022, indicating an average of 0.5 billion kg per year. However, these efforts still fall short of the rapid increase in e-waste production (Baldé et al., 2024). This imbalance between recycling and e-waste production has resulted in a severe environmental and human health hazard (Nixon et al., 2009). Significant amounts of harmful 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 iron, copper, gold, etc., are also found in e-waste (Mukherjee et al., 2023; Schindler & Demaria, 2020). 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 Frazzoli et al., 2022).

Also, globalization has led to a notable increase in the transnational movement of electronic goods, resulting in shorter product life cycles and higher consumption, both of which have increased the development of e-waste (Fawole et al., 2023). Without question, globalization has made significant advancements in global digitalization possible, enhancing communication, technology, and information sharing. Achieving multiple Sustainable Development Goals (SDGs) will require a world that is digitally connected (Orisakwe et al., 2020; Oteng-Ababio et al., 2020). Notwithstanding the advantages of digitalization, activities related to the production, use, and disposal of e-waste that are not sustainable compromise these advantages. While digitalization promotes scientific innovation and economic prosperity, it also hastens the obsolescence of e-waste. Particularly in the wake of the COVID-19 epidemic, digitalization has completely changed how societies function and transformed a variety of occupations.

Significant concerns regarding the environmental effects of digitalization in a specific country or region have been brought up by its broad acceptance and penetration. Comprehending these dynamics can facilitate the formulation of effective strategies for recycling, managing e-waste, and guaranteeing environmentally-friendly disposal methods. Additionally, a study of this kind can offer insightful information about the international cooperation and regulatory frameworks required to lessen the adverse impacts of e-waste on the environment and public health. Ultimately, this study can guide optimal methods for reducing electronic waste and promoting a circular economy to decision-makers in government, business, and consumer sectors.

This research inquiry is motivated by the desire to fill significant gaps in the existing literature on the relationship between globalization, digitalization, and electronic waste (e-waste) generation at both global and regional levels, an area that has received limited empirical attention. Previous research (e.g., Boubellouta & Kusch-Brandt, 2022; Yilmaz & Koyuncu, 2023) largely overlooks regional heterogeneity and does not account for the multidimensional role of digitalization (particularly mobile phones, landlines, and internet access). In addition, these studies predominantly employed a quadratic specification when examining the non-linear link between economic growth and e-waste, which may not adequately capture the dynamic nature of this relationship. To address these limitations, the present study pursues these primary objectives with the main objective of addressing the influence of globalization on electronic waste generation at the global and regional levels. Secondly, it investigates the potential influence of digital technology and its components, as well as their differential influences, on strengthening e-waste generation. Thirdly, it examines the potential non-linear link between economic growth and e-waste generation using a dynamic threshold model, and lastly, it tests for the existence of the EKC hypothesis in the relationship between e-waste and economic growth. The results will provide useful guidelines to policymakers, utilizing this measurement, regarding how the degree of digitalization can raise the amount of e-waste generation globally and across regions.

As far as the authors are aware, no research has explicitly addressed the set of countries and global economies under discussion. This study investigates the e-waste data from the Global E-waste Statistics Partnership to close this significant knowledge gap. By addressing the gaps in the body of existing knowledge, the current study makes four distinct contributions to empirical research. First, it examines the e-waste effect of globalization and digitalization based on e-waste generation globally and across the regions to determine if regional differences really matter in the globalization-digitalization-e-waste nexus. Regional disaggregation is essential in this study because the influence of digitalization and globalization on e-waste generation varies significantly across regions. Each region demonstrates unique trajectories in policy enforcement, waste management systems, technology adoption, and economic growth, which collectively shape the scale and nature of e-waste produced. Developed economies, for instance, often experience higher e-waste levels driven by rapid technological advancement and consumption patterns, whereas developing regions struggle with rising imports of second-hand electronics and inadequate recycling infrastructure. This study captures these heterogeneities and provides a more detailed understanding of how regional characteristics mediate the globalization–digitalization–e-waste relationship. This approach not only improves the reliability of the empirical results but also ensures that the policy implications are tailored to the realities of each region. Furthermore, the limited attention given to regional variations in previous studies underscores the need for such disaggregation to reveal hidden dynamics that global-level analyses may overlook. Thus, this strengthens the robustness and policy relevance of the study by aligning the analysis with the diverse economic and environmental realities of different world regions.

Secondly, to handle endogeneity issues, enable complex data structures, and increase the accuracy of dynamic panel data models through more precise parameter estimates, the current study employs methods not previously used in e-waste research. This will enable the current study to provide more effective and objective results on the subject matter. More precisely, these results will provide policymakers with solid and precise suggestions, as every study that has tackled this particular issue globally overlooked the aforementioned problems. In addition, the study further tests for the existence of an environmental Kuznets curve (EKC) at the global and regional levels using a dynamic panel threshold approach. The term included in the existing research is a quadratic term, which might not be sufficient to adequately highlight the dynamic effect. Utilizing the dynamic panel threshold approach also effectively addresses potential endogeneity issues that static models might not handle. This method captures the asymmetric effects of explanatory variables based on whether they are above or below specific threshold levels. Additionally, it accounts for temporal dependencies by incorporating lagged variables, offering a more precise depiction of the interactions among the variables. Techniques such as the generalized method of moments (GMM) employed in dynamic panel threshold models provide more efficient and unbiased estimates compared to traditional methods. Lastly, the present study examines the effects of digitalization on e-waste by using the three basic ICT indicators: fixed telephone, internet users, and mobile phone subscribers, following previous studies (Noah & David, 2024; Škare et al., 2024). Therefore, a thorough and objective assessment of digitalization would be necessary to comprehend its contribution to the production of e-waste. Furthermore, the study examines the individual effect of these ICT indicators on e-waste to clarify the mixed reactions from the prior studies due to the use of different indicators. The rest of the study is presented in Sections 2 to 5, where Section 2 presents related literature; the approach used is described in Section 3, the findings and discussions are provided in Section 4, and the study is concluded in Section 5.

2. Review of Literature and Hypothesis Development

The word "e-waste," or "electronic waste," refers to obsolete and abandoned electronic and electrical equipment (EEE), which is commonly disposed of illegally in developing countries and contains dangerous materials (Nwagwu & Okuneye, 2016). Mukherjee et al. (2023) stated that the makeup of e-waste provides a clear understanding of its detrimental consequences as well as the significance of its recovery. Important metals can be found in e-waste since it typically contains valuable metals and high-value objects like copper, silver, gold, platinum, etc. Thus, if handled scientifically and managed sustainably, e-waste can play a significant part in the circular economy. However, incorrect disposal without treatment will negatively influence the environment and public health. When waste is deposited, a variety of hazardous substances (such as lead, nickel, zinc, arsenic, mercury, cadmium, etc.) seep into subterranean aquifers, rendering the groundwater unsuitable for both agricultural and human use. Workers may have negative health impacts from improper handling and disposal of such e-waste (Mukherjee et al., 2023).

Of all the theories highlighting the relationship between environmental degradation and economic growth, the strongest empirical backing in the literature is the environmental Kuznets curve (EKC) hypothesis. The idea that there is a connection between environmental indicators and economic growth is credited to the research done in 1991 by Grossman and Krueger, which showed an inverted U-curve relationship between the two. Known by many as the Kuznets Curve hypothesis, the Kuznets hypothesis gained traction and was widely applied in a number of macroeconomic fields, such as health economics (Costa-Font et al., 2018; Gangadharan & Valenzuela, 2001), environmental economics (Grossman & Krueger, 1991; Orubu, 2020), and other macroeconomic areas (Obukohwo & Hilda, 2023).

The IPAT model, put forth by Ehrlich and Holdren in 1971, is another popular model for examining the factors that propel environmental degradation. According to the IPAT model, the size of people (P), their level of wealth (A), which is typically measured in terms of GDP per capita, and their level of technology (T) all influence the socioeconomic impact on environmental degradation (I). Furthermore, in 1997, Dietz and Rosa developed the stochastic version of IPAT, known as STIRPAT (Stochastic Impacts via Regression on Population, Affluence, and Technology), to get around the restrictions of the IPAT model and conduct empirical hypothesis tests. One of the most popular models in the literature for analysing how population, wealth, and technology affect the environment is the STIRPAT model (Boubellouta & Kusch-Brandt, 2022; Yilmaz & Koyuncu, 2023).

Based on the environmental indicators that were employed, the studies that examined the EKC hypothesis on land pollution (solid waste, municipal waste, among others), water pollution (wastewater, water footprint, etc.), and air-related emissions (air pollution or greenhouse gas emissions) can be grouped. We particularly concentrated on the empirical studies investigating the Waste

Kuznets Curve (WKC), a waste-related Kuznets hypothesis, since e-waste is a kind of solid waste. We focus on e-waste studies because they are still few in comparison to other solid waste indicators, even though some studies use solid waste as an indicator of environmental degradation, which includes various types of solid waste, such as municipal solid waste (MSW), harmful waste, packaging waste, medical waste, and plastic waste (Arbulú et al., 2015; Cheng et al., 2020; Gui et al., 2019; Kim et al., 2018; Omotayo, 2024; Wang et al., 2022; Zambrano-Monserrate et al., 2021).

2.1 Electronic waste and digitalization

For the past 20 years, digitalization has been acknowledged as one of the major forces behind economic expansion. Without a doubt, the path of economic development has been propelled by digitalization (Adebowale & Chuks, 2020; Noah & David, 2025). But this rapid economic expansion is also linked to the disruption of the entire ecosystem. Digitalization, which has made it possible for people to connect safely across geographical boundaries, can contribute significantly to the civilization of environmental quality by advancing a conservation agenda that will protect human life (Li et al., 2024). For more than two decades, systematic research has focused on the topic of how digitization affects the environment (Charfeddine & Umlai, 2023; Matthews & Matthews, 2003). Because of how quickly technology and society are changing, the relationship between digitization and environmental sustainability is still a challenging and ambiguous research topic. There are discussions on the beneficial and negative effects of digitalization on the environment (Brenner & Hartl, 2021; Charfeddine & Umlai, 2023). On the other hand, some researchers contend that the production and use of digital technologies consume more resources and energy and produce more waste (Ben-Lahouel et al., 2024; Li et al., 2024), while others found an inverted U-shaped, non-linear relationship (Chen et al., 2020; Li et al., 2021; Truong, 2022). Some studies argue that digitalization has the potential to support environmental sustainability (Hao & Zhang, 2023; Škare et al., 2024).

Despite the numerous studies on the environmental impact of various indicators of environmental degradation, there are very few studies on the e-waste effect of digitalization. Among the recent studies is the work of Osibanjo and Nnorom (2007), which reported that the rapid growth in ICT in developing countries has led to increasingly large quantities of e-waste being generated annually. Omobowale (2013) also confirmed that while imported used ICT helps to meet the needs of modern consumers and their progress, it also contributes to the generation of e-waste in Nigeria. According to Petridis et al. (2017), increased internet usage was linked to increased use of mobile phones and other technological devices, which is linked to increased generation of e-waste. The empirical results reported by Zhang and Meng (2019) documented the existence of the EKC and showed that, in general, internet penetration lowers the real income threshold over which pollution starts to decline. According to Pont et al. (2019), every flashy disclosure of a new smartphone or fashionable digital device is just a pretext for the production of tons more electronic waste (e-waste), also known as electronic scrap, which is frequently dumped into regular trash instead of being appropriately sorted into containers that make it easier to recover valuable metals and toxic materials.

In addition, Vishwakarma et al. (2022) also stated that the rapid advancement of technology, combined with the need for a high quality of life, has led to the widespread manufacturing of electronic devices, which in turn has created large amounts of waste. As a consequence, the ICT sector produces a significant amount of e-waste. Conversely, Boubellouta and Kusch-Brandt (2020) confirmed a negative correlation between e-waste and ICT exports, indicating that a 1 percent rise in ICT exports is correlated with a 0.0268 percent fall in e-waste creation. This is also supported by Kalia et al. (2022), who reported that GDP per capita, literacy rate, urban population, and internet penetration have no direct impact on the amount of e-waste generated. However, increased internet penetration in developing nations affects e-waste, as well as higher internet penetration when e-waste policies are in place.

Although several studies have examined the environmental impacts of digitalization, limited attention has been given to its implications for electronic waste (e-waste). Among the few that exist (Omobowale, 2013; Osibanjo & Nnorom, 2007; Vishwakarma et al., 2022), most have focused either on specific countries or on individual indicators of digital technologies (Kalia et al., 2022; Petridis et al., 2017; Pont et al., 2019; Zhang & Meng, 2019). Others, such as Boubellouta and Kusch-Brandt (2020), employed ICT exports as a proxy for digitalization, which primarily reflects digital flow rather than accumulated stock. Relying on a single indicator, however, may not fully capture the comprehensive effects of digitalization on e-waste generation. Moreover, these studies failed to capture the implications of globalization on the digitalization-e-waste nexus. The present study, therefore, addresses these critical gaps by adopting a multidimensional approach that integrates globalization and multiple digitalization indicators to provide a more robust and holistic understanding of the digitalization–e-waste nexus.

2.2 E-waste and globalization

Globalization may theoretically affect the environment in both beneficial and detrimental ways. Many theories and arguments have been put out to explain the beneficial and adverse effects of globalization on the environment. These include the pollution haven hypothesis, the global environmental governance failure hypothesis, the global environmental awareness hypothesis, and the markets for the global environment hypothesis (Nguyen & Le, 2020; Rudolph & Figge, 2017). According to theories that highlight the detrimental influence of globalization on the environment, environmental degradation may get worse as a result of globalization. It can drive industrialization in both wealthy and underdeveloped nations by raising human demands. The increased reliance on coal and other fossil fuels causes greenhouse gas emissions to rise and contributes to global warming, encouraging the movement of companies that produce a lot of pollution to nations with laxer environmental laws (Gao et al., 2024; Shahbaz et al., 2018). Conversely, theories endorsing globalization's beneficial effects on the environment contend that it can contribute to an improvement in environmental quality. It can encourage changes to environmental policies and improve the efficiency of government agencies. The spread of environmental technology and environmental awareness can both rise as a result of globalization. It can inspire environmentally-friendly business practices and green innovation. Globalization can also boost competitiveness and efficiency, which lowers the amount of input and waste material needed for each unit of output (Feng et al., 2024; Md. Qamruzzaman, 2022; Rahman, 2020).

Numerous studies have been conducted on e-waste management (Kumar, 2019; Maphosa & Maphosa, 2020; Wang et al., 2022), and e-waste recycling and circular economy (Gaur et al., 2023; Ichikowitz & Hattingh, 2020; Islam et al., 2021). To our knowledge, none of the prior studies have empirically considered the link between globalization and e-waste at global and regional levels despite the increasing interrelatedness between the variables. Yilmaz and Koyuncu's (2023) study is the sole deviation from the norm. It employed the panel quantile regression technique to examine the effects of globalization, both in its entirety and in its component aspects, on the recycling rates of e-waste across thirty European nations between 2008 and 2018. The findings show that the three sub-dimensions of globalization as a whole and overall have a beneficial effect on the rate of recycling e-waste, which supports the circular economy. Lundgren (2012) supports this as well, arguing that because globalization is contributing more to the development of e-waste, the future of e-waste management depends not just on the efficiency of local government agencies but also on worldwide participation.

However, the study conducted by Yilmaz and Koyuncu (2023) did not only focus on a regional context within developed economies but was also primarily Eurocentric in nature, thereby overlooking the experiences of developing countries. Additionally, their analysis utilized a quadratic model to explore the non-linear relationship between economic growth and e-waste generation, which may not effectively capture the complex and evolving dynamics of this interaction. In addition, the study has largely neglected the role of digitalization in shaping the globalization–e-waste nexus. To bridge these gaps, the present research adopts a comprehensive multidimensional framework that incorporates both globalization and multiple digitalization indicators, thereby offering a more robust and inclusive understanding of the interconnections between globalization, digital transformation, and e-waste generation. Therefore, the empirical review's findings have shown that the environmental impacts of globalization and digitalization are inconclusive, while some studies have suggested a positive impact, and others have reported a negative impact. Therefore, based on the evidence from the related existing literature, the hypotheses on the link between e-waste and ICT are stated as follows:

H_1: *Digitalization significantly promotes e-waste generation globally and across various regions.*

H_2: *Globalization significantly promotes e-waste generation globally and across various regions.*

H_3: *There is a non-linear relationship between economic growth and e-waste generation globally and across various regions.*

3. Methodology

3.1 Theoretical framework

The main objective of this study is to evaluate the consequences of globalization and digitalization on e-waste globally and regionally. To achieve this, the study model is constructed using the environmental Kuznets curve (EKC) hypothesis, which was put forth by Grossman & Krueger in 1991. This hypothesis describes the phenomenon wherein, in the early stages of economic development, environmental degradation increases in tandem with economic growth, but after reaching a certain point, or turning point, environmental quality improves as economic growth continues. Equation (1) expresses the EKC hypothesis in its fundamental form:

$$END = (GDP, GDP^2) \tag{1}$$

where: *END* is environmental degradation, *GDP* and GDP^2 are the economic growth and its quadratic term respectively.

In addition to the theoretical justification, incorporating GDP per capita and its squared term in Equation (1) is crucial to reflect the possible non-linear relationship between economic growth and environmental degradation (e-waste generation). At the early stages of economic expansion, rising income levels are typically accompanied by increased environmental pressure. However, once income surpasses a particular threshold, countries tend to invest in improved environmental management practices, resulting in a gradual reduction in environmental degradation (Boubellouta & Kusch-Brandt, 2020; Yilmaz & Koyuncu, 2023). Ehrlich and Holdren (1971) proposed the Environmental Impacts of Population, Affluence, and Technology (IPAT) as a way to measure environmental deterioration. It contains additional important variables in addition to the economic development and its quadratic term, provided by the EKC hypothesis. The dynamic IPAT framework's fundamental form can be expressed as follows:

$$I = (P, A, T) \tag{2}$$

where: *I* is environmental impacts, *P* is population, *A* is affluence, and *T* is technology.

Since *I* and *A* also imply environmental degradation and economic growth respectively, substituting the additional variables suggested by IPAT in Equation (1) can be expressed as follows:

$$END = (GDP, GDP^2, PPT, TGY) \tag{3}$$

where: *PPT* is population and *TGY* is the technology to capture digitalization, other variables remain as defined in Equation (1).

The inclusion of population growth and technology in Equation (3) is also supported by the previous studies like Boubellouta and Kusch-Brandt (2022), Kalia et al. (2022), and Zhang and Meng (2019), among others. It was reported that population growth increases the number of consumers, leading to higher demand for electronic devices and, consequently, greater volumes of discarded products. Technological advancement accelerates product innovation and reduces the lifespan of electronic goods through rapid obsolescence, encouraging frequent replacement and contributing to e-waste accumulation. In the relevant previous studies, such as Boubellouta and Kusch-Brandt (2022), Yilmaz and Koyuncu (2023), energy consumption was used to measure technology; the present study deviates from these studies by proxying technology with digitalization. This study further deviates from Boubellouta and Kusch-Brandt (2020), who used ICT exports as a proxy for ICT development by using ICT indicators (Internet access subscriptions, mobile and fixed phone) as suggested by recent studies (Li et al., 2024; Noah & David, 2025; Saba & David, 2023). As stated earlier, employing a single indicator of digitalization or measures like ICT exports as a proxy for digitalization, not only primarily measures digital flows rather than the accumulated stock of digital development, but also may not fully capture the broader and more complex influence of digitalization on e-waste generation (Noah & David, 2024a).

In addition to the variables of interest (globalization and digitalization), urbanization has been shown in prior research to increase the generation of e-waste, and this has been routinely included as a control variable. Inclusion of urbanization is justified by its strong influence on the demand, use, and disposal of electronic products. Urbanization fosters higher levels of digitalization, industrialization, and consumerism concentrated in cities, which intensifies electronic consumption and waste generation. Therefore, it is essential for understanding the socioeconomic and structural factors driving global and regional e-waste production (Boubellouta & Kusch-Brandt, 2022; Kalia et al., 2022; Zhang & Meng, 2019). Using e-waste generation (*EWG*) for environmental degradation, GDP per capita and its quadratic term (*GDP* and GDP^2) for economic growth, *MOT, TLN,* and *ITA* for mobile line, fixed telephone and internet access to capture digitalization, *GLN* for globalization, *PPT* for population growth, and *UBI* for urbanization measure by the urban population, Equation (3) can therefore, be re-written in a panel econometrics format as follows:

$$EWG_{it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 GDP_{it}^2 + \alpha_3 PPT_{it} + \alpha_4 UBI_{it} + \alpha_5 GLN_{it} + \alpha_6 MOT_{it} + \alpha_7 TLN_{it} + \alpha_8 ITA_{it} + \varepsilon_{it} \quad (4)$$

Furthermore, we develop a dynamic threshold model to investigate the non-linear correlation between the generation of e-waste and economic growth on a global and regional scale. This gives room for this study to examine the presence of an inverted U-curve in income level rise and e-waste generation. In this context, the threshold represents a specific level of economic growth (per capita income) beyond which the relationship between growth and e-waste generation changes direction or intensity. Economically, this implies that at lower income levels, increases in economic growth may initially lead to higher e-waste generation due to greater technological adoption and usage, but after surpassing a certain level, further growth may reduce e-waste through improved recycling systems, technological efficiency, and environmental awareness. This enables the study to detect the existence of an inverted U-shaped relationship, consistent with the EKC hypothesis, while capturing the dynamic adjustments that a simple quadratic specification may fail to reveal.

As previously mentioned, every previous study on the topic only takes into account a quadratic term for economic growth, which might not be the most effective way to show the dynamic effect. The dynamic threshold proposed by Seo et al. (2019) and Seo and Shin (2016) is utilized in this study to confirm the presence of this link at the global and regional levels. These authors suggest estimating the threshold using a GMM estimator. The use of a dynamic panel threshold approach helps to effectively address endogeneity problems that are often not captured by static models. This technique also identifies the asymmetric effects of explanatory variables depending on whether they lie above or below certain threshold values. Moreover, by incorporating lagged variables, it accounts for time-dependent relationships, thereby providing a clearer and more accurate representation of how the variables interact over time. Overall, this approach yields more consistent, efficient, and unbiased parameter estimates than conventional estimation methods. We then develop Equation (5) in light of this.

$$EWG_{it} = \beta_i + \theta X'_{it} + k(q_{it} - \gamma)1\{q_{it} > \gamma\} + \mu_{it} \quad (5)$$

where: χ' is the explanatory variables, which also include lagged dependent variables to capture the dynamic threshold influence of the model, and q is the threshold variable (economic growth), and γ is the value of the threshold.

3.2 Measurement of variables and data sources

The study data were obtained from various reputable secondary sources for 174 countries globally from 2013 to 2022. The data for the explained variable (e-waste) was sourced from the Global E-waste Statistics Partnership report (Baldé et al., 2024). Data related to GDP per capita, population, and urbanization were obtained from the World Development Indicators (WDI) of the World Bank. Data on globalization was sourced from the KOF Globalization Index, and ICT development indicators (Internet access subscriptions, mobile and fixed telephone) were obtained from the International Telecommunication Union. In addition, the explained variable is quantified by the amount of e-waste produced (kilograms per capita), which is computed by dividing the total amount of e-waste produced by the population of each nation. Economic growth is measured by the GDP per capita (US$); population growth (%) and urbanization (%) are measures of population growth and urbanization respectively; and ICT indicators (percentage of the population with internet access, penetration of connected mobile lines, and penetration of connected fixed and CDMA lines) are indicators of ICT development. Table 1 contains all the information about the study's variables.

3.3 Analytical techniques

To estimate the models, the study uses Seo and Shin's (2016) dynamic panel threshold model. The method tackles the inherent endogeneity and simultaneity that cannot be ruled out in the relationship between globalization, digitalization, and e-waste. It is based on the GMM principles. Simultaneously, the approach provides the EKC-suggested threshold level between e-waste and economic growth. Dynamic panel threshold modelling offers several advantages, particularly in econometric and statistical analyses. It allows for the modeling of nonlinear relationships between variables, which can be crucial in understanding complex relationships between economic growth, globalization, digitalization, and e-waste. By incorporating lagged dependent variables and endogenous covariates, it also addresses potential endogeneity issues that static models might not handle effectively. This approach can further capture the asymmetric effects of explanatory variables, depending on whether they are above or below certain threshold levels. The dynamic models account for temporal dependencies by including lagged variables, providing a more accurate representation of economic relationships. Seo et al. (2019)'s STATA command is employed to determine the threshold value.

4. Presentation of Results and Discussion

The descriptive statistics results are shown in Table 1. The mean, maximum, and minimum values for the examined variables at the global and four regional levels are included in these statistics. The details of the variables show that Africa has the lowest average e-waste generated, with 2.643kg, followed by Asia and America, while Europe has the highest, with a value of 15.475kg, which is almost double the global average of 8.342kg. Europe also has the highest e-waste generated, with a value of 28.500kg, followed by Asia, America, and Africa with 23.600kg, 22.100kg, and 12.600kg respectively. Africa has the minimum e-waste generated with a value of 0.200kg, followed by Asia, America, and Europe. This can be related to the level of the economy; the greater the anticipated rate of e-waste generation, and vice versa. This further indicates a wide income gap among the selected countries. This is also supported by the average GDP per capita for these regional levels. The average GDP per capita for Europe is US$30,851.98, while the average GDP per capita for Africa is US$2,741.82, far below the average global GDP per capita of

US$14,982.93. This also applies to almost all the remaining variables except for population growth. Africa has the highest average value of 2.293%, followed by Asia, America, and Europe with 1.534%, 0.956%, and 0.245% respectively.

Table 1: Descriptive Analysis

Variables	Statistic	EWG	GDP	PPT	UBI	GLN	MOT	TLN	ITA
Global	Mean	8.343	14982.93	1.329	58.239	62.792	109.972	16.825	51.147
	Maximum	28.500	123678.7	11.790	100.000	91.000	420.850	61.703	104.430
	Minimum	0.200	216.97	-6.850	11.480	35.000	13.490	0.006	0.600
Africa	Mean	2.643	2741.82	2.293	45.282	52.135	87.217	3.766	24.219
	Maximum	12.600	17253.51	3.870	89.740	72.047	185.560	35.386	84.120
	Minimum	0.200	216.97	-0.080	11.480	34.564	23.520	0.006	0.600
America	Mean	9.031	13188.88	0.956	62.067	61.828	116.403	19.639	59.128
	Maximum	22.100	65120.39	2.880	95.430	84.479	201.930	53.772	104.430
	Minimum	1.700	1794.790	-0.590	18.460	44.565	48.900	3.433	15.500
Asia	Mean	7.506	14756.27	1.534	57.129	59.252	116.652	14.975	50.300
	Maximum	23.600	97630.83	11.790	100.000	89.187	420.850	60.566	99.700
	Minimum	0.300	500.52	-6.850	12.980	36.161	13.490	0.162	1.800
Europe	Mean	15.475	30851.98	0.245	71.505	80.710	121.478	32.122	76.993
	Maximum	28.500	123678.7	3.930	98.040	91.141	164.390	61.703	99.500
	Minimum	1.800	2124.660	-1.760	42.490	64.527	90.860	4.872	37.440
Sources		GEM	WDI	WDI	WDI	KOF	ITU	ITU	ITU

Note: EWG = e-waste generated in kg, GLN = globalization, GDP = GDP per capita, UBI = urbanization, PPT = population growth, TLN = fixed telephone, MOT = mobile phone, and ITA = internet access subscriptions. ITU = the International Telecommunication Union, GEM = the Global E-waste Monitor Statistics Partnership, WDI = the World Bank's World Development Indicators, and KOF = the KOF Globalization Index.
Source: Authors' computation.

The correlation matrix is presented in Table 2. The correlation matrix reveals a robust positive correlation between e-waste and globalization. Similarly, strong positive correlations are observed between e-waste and digitalization (mobile phones, fixed telephones, and internet access). This is 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 imperative to note that the substantial positive correlation observed between e-waste, globalization, and digitalization points to a possible linkage between the variables 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.

Table 2: Correlation Matrix

Variables	EWG	GDP	PPT	UBI	GLN	MOT	TLN	ITA
EWG	1.000							

GDP	0.854***	1.000						
	(0.000)	---						
PPT	-0.310***	-0.104***	1.000					
	(0.000)	(0.000)	---					
UBI	0.679***	0.594***	-0.115***	1.000				
	(0.000)	(0.000)	(0.000)	---				
GLN	0.769	0.634	-0.359	0.650	1.000			
	(0.000)	(0.000)	(0.000)	(0.000)	---			
MOT	0.494***	0.433***	-0.178***	0.514***	0.439	1.000		
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	---		
TLN	0.797***	0.645***	-0.443***	0.547***	0.669	0.407***	1.000	
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	---	
ITA	0.854***	0.703***	-0.364***	0.684***	0.774	0.566***	0.707***	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	---

Note: EWG = e-waste generated in kg, *GLN* = globalization, *PPT* = population growth, *GDP* = GDP per capita, *BI* = urbanization, *ITA* = internet access subscriptions, *TLN* = fixed telephone, and *MOT* = mobile phone.

Source: Authors' computation.

Furthermore, before estimating the models to achieve the study's objectives, several pre-estimation and diagnostic tests were conducted to ensure the validity and reliability of the empirical analysis. These include tests for unit root, cointegration, multicollinearity, serial correlation, and heteroscedasticity. Assessing the stationarity properties of panel data is particularly important, as non-stationary series can lead to spurious or biased econometric results. To determine the order of integration of the variables, a series of panel unit root tests was performed. Table 3 presents the outcomes of the Augmented Dickey-Fuller (ADF) and Variance Inflation Factor (VIF) tests, which assess stationarity and multicollinearity respectively. The null hypothesis of the ADF test posits the presence of a unit root, indicating non-stationarity. However, the results reveal that all variables are stationary at the level (integrated of order zero). Additionally, the VIF values confirm the absence of multicollinearity among the explanatory variables, consistent with the findings from the correlation matrix.

Table 3: Unit Root and Multicollinearity Tests

Variables	Augmented Dickey-Fuller test statistic			VIF
	t-statistic	p-value	Remark	Mean VIF: 2.30
EWG	-7.0454***	0.0000	I(0)	-
GDP	-7.2853***	0.0000	I(0)	2.26
PPT	-6.1542***	0.0000	I(0)	1.03
UBI	-6.0452***	0.0000	I(0)	2.17
GLN	-6.4592***	0.0000	I(0)	2.92
TLN	-7.8656***	0.0000	I(0)	2.33
MOT	-9.2038***	0.0000	I(0)	1.55
ITA	-7.8903***	0.0000	I(0)	3.87

Note: VIF is the Variance Inflation Factor
Source: Authors' computation.

After conducting the unit root tests, a cointegration analysis was performed to evaluate the existence of long-term relationships among the variables. Although all variables were found to be stationary at level [I(0)], the cointegration test was further employed to strengthen the evidence of a long-run relationship within the model. Table 4 presents the results of the Johansen and Kao-Engle Granger cointegration tests, which were selected for their capacity to handle a larger number of regressors than the more restrictive Pedroni and Westerlund approaches. The findings reveal statistically significant results at the 1% level across all test statistics, confirming that the variables are cointegrated and exhibit a stable long-run equilibrium relationship.

Table 4: Cointegration Test

Johansen cointegration test					Kao cointegration test		
Hypothesized		Trace				Statistic	p-value
No. of CE(s)	Eigenvalue	Statistic	Critical Value	p-value	Modified Dickey-Fuller	2.2217**	0.0132
None *	0.1325	980.3367	159.5297	0.0001	Dickey-Fuller	-0.6575	0.2554
At most 1 *	0.1212	811.6741	125.6154	0.0001	Augmented Dickey-Fuller	-4.6954***	0.0000
At most 2 *	0.1128	658.3246	95.75366	0.0001	Unadjusted Modified Dickey-Fuller	3.8494***	0.0001
At most 3 *	0.1029	516.2970	69.81889	0.0001	Unadjusted Dickey-Fuller	0.7320	0.2321
At most 4 *	0.0954	387.3021	47.85613	0.0001			
At most 5 *	0.0812	268.2369	29.79707	0.0001			
At most 6 *	0.0768	167.7079	15.49471	0.0001			
At most 7 *	0.0596	72.87836	3.841466	0.0000			
Trace test indicates 8 cointegrating eqn(s) at the 0.05 level							

Source: Authors' computation.

Table 5 reports the outcomes of the cross-sectional dependency tests, employing the Pesaran, Friedman, and Frees approaches. The potential presence of cross-sectional dependence is particularly relevant given the strong economic interconnections among countries. Failing to account for such dependence may result in biased or inconsistent estimates (Appiah et al., 2022; Noah & David, 2024b). The null hypothesis for these tests states that there is no cross-sectional dependence among the variables. At the 1% level of significance, the results confirm the absence of cross-sectional dependence, indicating that the variables are largely independent across countries in the sample.

Table 5: Cross-sectional Dependency Test

Model	Pesaran		Friedman		Frees	
	Statistic	p-value	Statistic	p-value	Statistic	p-value
Global	-0.5110	0.6095	3.3461	1.0000	42.1130	0.9027
Africa	-0.2180	0.8277	5.0780	1.0000	8.5290	0.7678
Europe	3.2560	0.0011	16.1250	0.9996	8.5820	0.7678
America	-1.1380	0.2552	2.7270	1.0000	7.6990	0.7678
Asia	-0.325	0.7450	1.5580	1.0000	17.6870	0.7678

Source: Authors' computation.

Table 6 presents the results of the autocorrelation and heteroscedasticity tests. The null hypotheses for these tests assume the presence of autocorrelation and heteroscedasticity in the model. The findings confirm the existence of both issues, indicating that the use of panel OLS would yield biased and inconsistent estimates. Consequently, the study adopts the panel threshold analysis as a more suitable approach. This method not only effectively addresses the problems of autocorrelation and heteroscedasticity but also accounts for potential endogeneity, thereby ensuring more reliable and robust results aligned with the objectives of the study.

Table 6: Auto-correlation and Heteroscedasticity Tests

Model	Auto-correlation LM test		Breusch-Pagan Heteroscedasticity test	
	IS-statistic	p-value	X^2-statistic	p-value
Global	59.2500***	0.0000	465.1800***	0.0000
Africa	27.4800***	0.0040	59.3700***	0.0000
Europe	25.2500***	0.0080	27.8100***	0.0000
America	19.8300**	0.0480	26.5300***	0.0000
Asia	32.3300***	0.0010	145.5800***	0.0000

Source: Authors' computation.

4.1 Empirical result

Proceeding to the estimation of the models, Table 7 presents the findings on the e-waste effects of globalization and digitalization at the regional and global levels. The estimation results are based on the dynamic panel threshold. This is used to examine the non-linear link between economic growth and e-waste generation globally and at the four regional levels. Before presenting the results, the linearity test is examined. Under the null hypothesis that there is no threshold, the test verifies the threshold relationship, which is based on the bootstrap method, between economic growth and the generation of e-waste at the global and four regional levels. The p-values significant at the 1% and 5% significance levels indicate a nonlinear association (see Ajide & Ojeyinka, 2022; Bolarinwa et al., 2021). This provides a strong foundation for policy deliberations and conclusions.

Table 7 presents some significant findings at the global and regional levels based on the analysis of our primary variables of interest. The results in the below-threshold region (lower region) show that globalization positively affects e-waste generation globally and at regional levels, excluding Europe. Therefore, the influence of globalization on the generation of e-waste globally and at regional levels, except for Europe, is significant. The insignificant effect of globalization in Europe contradicts the study by Yilmaz and Koyuncu (2023). This may be related to the differences in the methodologies and measurements adopted in measuring e-waste. In addition, in the above-threshold region (upper region), globalization positively affects e-waste generation in Africa, America, and Europe, and negatively affects e-waste generation globally and in Europe. This supports the report of Yilmaz and Koyuncu (2023) that globalization reduces e-waste. The findings further reveal that digitalization positively affects the generation of e-waste globally, in Africa and Asia, and it negatively affects e-waste generation in America and Europe in the below-threshold region. Specifically, mobile phones positively impact e-waste generation globally and across the regions but negatively affect e-waste in Europe. Fixed telephones also negatively impact e-waste generation globally and in America, and positively impact e-waste generation in Africa, but do not influence e-waste generation in Asia and Europe.

Table 7: Model Estimation Results

Variables	Global	Africa	America	Asia	Europe
Panel A: Lower Region					
Lag of EWG	0.5576***	0.7264***	0.7589***	0.5487***	0.8576***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
GDP	0.0001***	0.0001***	0.0001***	0.0001***	-0.0002**
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0288)
PPT	0.0046**	0.0053***	0.2817***	0.0212***	0.0543
	(0.0130)	(0.0000)	(0.0000)	(0.0021)	(0.9182)
UBI	0.0784***	-0.0002	0.1847***	0.2705***	-0.1999***
	(0.0000)	(0.9862)	(0.0021)	(0.0000)	(0.0006)
GLN	0.0448***	0.0688***	0.0981***	0.0331***	-0.0507
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.3151)
MOT	0.0170***	0.0084***	0.0043**	0.0041***	-0.0068**
	(0.0000)	(0.0000)	(0.0271)	(0.0000)	(0.0139)
TLN	-0.0372***	0.0283***	-0.0276**	0.0020	-0.0072
	(0.0000)	(0.0075)	(0.0231)	(0.3270)	(0.5380)
ITA	0.0339***	0.0192***	-0.0126**	-0.0028*	0.0223***
	(0.0000)	(0.0000)	(0.0190)	(0.0719)	(0.0018)
Constant	4.6539***	-0.5588	-3.2486***	1.1179*	-10.0702**
	(0.0000)	(0.1624)	(0.0000)	(0.0971)	(0.0319)
Panel B: Upper Region					
Lag of EWG	0.0349	-0.0741	-0.0423	0.0594***	-0.0084
	(0.2142)	(0.2491)	(0.2701)	(0.0096)	(0.9255)
GDP	-0.0001***	-0.0001***	-0.0001***	-0.0001***	0.0001
	(0.0001)	(0.0001)	(0.0001)	(0.0000)	(0.6497)
PPT	-0.0459**	-0.0139***	-0.2696**	0.0094	-0.0339
	(0.030)	(0.000)	(0.036)	(0.968)	(0.791)
UBI	0.0146***	0.0009	-0.0347***	0.0362***	-0.0099
	(0.0055)	(0.7724)	(0.0000)	(0.0000)	(0.7638)

Variables	Global	Africa	America	Asia	Europe
GLN	-0.0605***	0.0282***	0.1158***	-0.0365***	0.1109**
	(0.0000)	(0.0007)	(0.0000)	(0.0090)	(0.0325)
MOT	-0.0164***	-0.0062***	-0.0092***	-0.0090***	0.0153***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
TLN	0.0679***	0.1280***	0.0100	-0.1638***	0.0008
	(0.0000)	(0.0002)	(0.4663)	(0.0000)	(0.9520)
ITA	-0.0343***	-0.0078***	0.0091	0.0096***	-0.0018
	(0.0000)	(0.0035)	(0.2020)	(0.0067)	(0.8732)
Threshold value	0.6309***	1.8727***	0.7742***	2.3600***	0.6492***
	(0.0000)	(0.0000)	(0.0069)	(0.0000)	(0.0000)
Turning point value	36206.520	10959.340	36206.520	36206.520	27239.350
Linearity test	57.34**	50.51***	51.43**	51.59**	88.45***
	(0.017)	(0.000)	(0.033)	(0.030)	(0.000)
No of bootstrap	300	300	300	300	300
Number of countries	174	46	33	55	40

Notes: EWG = e-waste generated in kg, *PPT* = population growth, *GDP* = GDP per capita, *UBI* = urbanization, *GLN* = globalization, *ITA* = internet access subscriptions, *TLN* = fixed telephone, *MOT* = mobile phone, and the lag of *EWG* is the lag of e-waste generated.

Source: Authors' computation.

Internet access promotes e-waste generation globally, in Africa, and Europe, while it reduces e-waste generation in America and Asia. In the case of the above-threshold region, digitalization negatively affects e-waste generation globally, in Africa, and Asia, and positively affects e-waste generation in Europe, but does not influence e-waste generation in America. Specifically, mobile phones negatively impact e-waste generation globally and across the regions, but positively affect e-waste in Europe. Fixed telephones also positively impact e-waste generation globally and in Africa, and negatively impact e-waste generation in Asia, but do not influence e-waste generation in America and Europe. Internet access promotes e-waste generation globally, in Africa, and Europe, while it reduces e-waste generation in America and Asia. The positive influence of digital devices on e-waste generation is supported in the studies by Petridis et al. (2017), Pont et al. (2019), and Vishwakarma et al. (2022), while this is in contrast with Boubellouta and Kusch-Brandt (2020) and Zhang and Meng (2019).

Apart from the variables of interest, in the below-threshold region, the findings further reveal that the coefficients of the lagged values of e-waste are positive and significant at 1% significance level globally and across the four regional levels. This implies that the past value of e-waste generated affects the present value. However, the past value of e-waste generated does not influence the present value globally and across the four regional levels (except Asia) in the above-threshold region. This implies that, although only in the below-threshold region globally and in other regions, the previous value of e-waste generated affects the present value in the above and below-threshold region of Asia. With the exception of Europe, where it is statistically significant and negative, the below-threshold region's global and regional coefficients of economic growth are both positive. The global and regional coefficients of economic growth in the above-threshold region are negative and statistically significant, excluding Europe, where they are positive but not statistically significant. This also supports the relevant theories and actual findings. Similarly, the population growth coefficient is also positive and statistically significant globally and across all the regions except Europe. In the above-threshold region, the coefficients of population growth are negative and statistically significant globally, in Africa and America, while it is statistically insignificant in Europe and Asia. The positive effect of population growth in the below-threshold region is supported by studies like Kalia et al. (2022) and Zhang and Meng (2019), while the negative impact is in line with the findings of Boubellouta and Kusch-Brandt (2021) and Yilmaz and Koyuncu (2023). Also, the urbanization coefficients are statistically significant and positive globally, in America and in Asia, negative and statistically significant in Europe, but statistically insignificant in Africa in the below-threshold region. In the above-threshold region, the coefficients of urbanization are also positive and statistically significant globally and in Asia, negative and statistically significant in America, but statistically insignificant in Europe and Africa. The positive influence of urbanization on e-waste is supported by the findings of Chatti and Majeed (2022) and Zhang and Meng (2019) but contradicts the findings of Boubellouta and Kusch-Brandt (2021) and Kalia et al. (2022)

Furthermore, the results also confirm that 63.09%, 187.27%, 77.42%, 236%, and 64.92% are the threshold values at which economic growth would be negative globally, in Africa, America, Asia, and Europe respectively. After this threshold, economic growth becomes negative and significant in reducing e-waste generation globally and at regional levels. This aligns with the EKC hypothesis, which is defined by an inverse U-shaped link between GDP per capita and environmental degradation (e-waste). This is also supported by earlier studies by Boubellouta and Kusch-Brandt (2021; 2022), and Kusch and Hills (2017). Additionally, the turning point values are US$36,206.520, US$10,959.340, US$17,697.23, US$36,206.520, and US$27,239.350 for the global, Africa, America, Asia, and Europe respectively. These turning point levels are deemed reasonable and are consistent with the GDP range of the dataset. Specifically, the global turning point of US$36,206.520 per capita exceeds the global average GDP per capita of US$14,982.93 from Table 1 more than twice. This also applies to all the regional levels except Europe, where the average GDP per capita (US$30,851.98) is higher than the turning point of US$27,239.350.

To further validate the reliability of our findings, we performed a robustness analysis by re-estimating the model using the two-step System GMM approach, adding the squared term of GDP as an extra variable. Table 8 shows the results of this robustness assessment, which are largely consistent with the preliminary results obtained from the panel threshold estimation. While a few minor variations were observed, the overall pattern of the findings is consistent, thereby reinforcing the robustness and credibility of the study's empirical conclusions.

Table 8: GMM Estimations

Variables	Global	Africa	Europe	America	Asia
Lag of EWG	0.518***	0.522***	0.898***	0.474***	0.488***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
GDP	0.038	0.106***	-0.043***	0.027	0.182***
	(0.233)	(0.000)	(0.004)	(0.521)	(0.000)
GDP2	-0.019	-0.053***	-0.021***	0.014	0.091***
	(0.233)	(0.000)	(0.004)	(0.521)	(0.000)

Variables	Global	Africa	Europe	America	Asia
PPT	0.037***	0.213***	-0.028	-0.048***	0.087***
	(0.000)	(0.000)	(0.136)	(0.000)	(0.000)
UBI	0.011***	0.008***	0.001**	0.002***	0.003***
	(0.000)	(0.000)	(0.030)	(0.001)	(0.000)
GLN	-0.397***	-0.525***	0.030	-0.287***	-0.270*
	(0.000)	(0.000)	(0.484)	(0.000)	(0.058)
TLN	0.002	-0.001	0.018	-0.060***	0.059***
	(0.729)	(0.667)	(0.108)	(0.000)	(0.001)
MOT	0.028*	-0.019	-0.068***	0.060***	-0.003
	(0.098)	(0.148)	(0.000)	(0.005)	(0.915)
ITA	0.001***	0.001***	-0.001***	0.001***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Constant	0.172	0.800***	0.346***	0.679***	-0.229
	(0.276)	(0.000)	(0.002)	(0.001)	(0.376)
Wald test	7899.76 (0.0000)	30994.74 (0.0000)	43054.97 (0.0000)	18150.82 (0.0000)	14162.64 (0.0000)
AR(1)	0.1089 (0.9133)	1.1723 (0.2411)	-0.9611 (0.3365)	-0.8281 (0.4076)	-0.3074 (0.7586)
Sargan	72.5415 (0.2650)	32.9155 (0.2460)	32.1002 (0.1997)	26.3903 (0.1197)	31.5359 (0.3520)
No of instrument	28	28	28	28	28
No of Country	174	46	40	33	55

Source: Authors' computation.

4.2 Discussion and policy implications

The findings from the present study demonstrate that in the below-threshold region, globalization contributes to increase e-waste generation globally and regionally, excluding Europe. This suggests that as countries integrate more into the global economy, they face higher levels of e-waste, highlighting the need for robust e-waste management systems to handle the growing volumes. In contrast, in the above-threshold region, globalization's impact is mixed; it increases e-waste in Africa, America, and Europe but reduces it at the global level and in Europe. This indicates that different stages of globalization may have varying effects on the generation of e-waste, emphasizing the importance of tailored e-waste policies that consider the specific context of each region. Digitalization also plays a crucial role in e-waste generation. In the below-threshold region, digitalization drives e-waste generation globally, and in Africa and Asia, while reducing it in America and Europe. This suggests that the proliferation of digital technologies leads to higher e-waste in regions with rapid digital adoption, but can also result in better e-waste management practices in more developed regions. Specifically, mobile phones contribute positively to e-waste globally and regionally, except in Europe, where they have a negative impact. Fixed telephones, on the other hand, reduce e-waste globally and in America but increase it in Africa, indicating differing impacts based on regional technological infrastructure. Internet access promotes e-waste generation globally, in Africa, and Europe, but helps reduce it in America and Asia, reflecting the dual role of internet proliferation in both increasing access to digital devices and enhancing e-waste recycling practices.

In the above-threshold region, the impact of digitalization on e-waste is more complex. It reduces e-waste generation globally, in Africa, and in Asia, while increasing it in Europe and having no effect in America. This suggests that at advanced stages of digitalization, there might be better e-waste management systems in place globally, but specific regions like Europe may still struggle with e-waste due to higher consumption rates. Mobile phones have a global and regional negative impact on e-waste, except in Europe, where they contribute positively, indicating that policies targeting mobile phone recycling in Europe could be particularly beneficial. Fixed telephones show a positive impact on e-waste globally and in Africa, a negative impact in Asia, and no impact in America and Europe, suggesting a need for region-specific e-waste management strategies for older communication technologies. Internet access continues to promote e-waste globally, in Africa, and Europe, while reducing it in America and Asia, underscoring the importance of enhancing internet-based e-waste management solutions in regions where internet access is widespread.

The results further indicate that past values of e-waste generation significantly influence current values globally and regionally in the below-threshold region. This suggests that historical e-waste generation trends persist over time, necessitating long-term planning and investment in e-waste management systems. Conversely, in the above-threshold region, past e-waste values do not significantly impact current values globally and in most regions, except for Asia. This implies that for regions like Asia, historical data on e-waste can inform future management strategies, while other regions may require real-time data-driven approaches.

Economic growth has varying effects on e-waste generation. In the below-threshold region, economic growth positively promotes e-waste generation globally and regionally, while its impact in Europe is negative. This shows that the use of electronic gadgets rises with economic growth, producing an increase in e-waste. In Europe, where economic growth reduces e-waste, lessons can be learned about effective waste management practices that could be applied to other regions. In the above-threshold region, economic growth negatively impacts e-waste generation globally and across most regions, indicating that advanced economies might adopt more sustainable consumption patterns or efficient e-waste management systems.

In the below-threshold region, population growth positively influences e-waste globally and regionally, but is statistically insignificant in Europe. This implies that higher population growth leads to increased e-waste, underscoring the necessity of scalable e-waste management solutions in densely populated regions. In the above-threshold region, population growth negatively affects e-waste generation globally, in Africa and America, suggesting that these regions might be adopting better waste management practices as their populations grow. Similarly, urbanization also plays a critical role in e-waste generation. In the below-threshold region, urbanization positively correlates with e-waste globally, in America, and Asia, while negatively impacting e-waste in Europe and having no significant effect in Africa. This highlights the need for urban planning that incorporates e-waste management solutions, such as establishing urban recycling centres and promoting community awareness about e-waste. In the above-threshold region, urbanization continues to positively influence e-waste globally and in Asia but negatively impacts America, indicating that different urbanization patterns require tailored approaches to e-waste management. Europe and Africa show no significant impact, suggesting that other factors might be more influential in these regions.

The results further confirm specific threshold values at which economic growth negatively impacts the generation of e-waste, aligning with the EKC hypothesis. This hypothesis suggests an inverted U-shaped link between GDP per capita and environmental degradation (e-waste). Beyond the thresholds, economic growth significantly reduces e-waste generation, highlighting the need for policies that support sustainable economic development. These findings indicate that once a region surpasses its economic threshold, it can effectively manage and reduce e-waste generation. Regions like Africa and Asia with higher threshold values should prioritize economic policies that encourage investments in green technologies and e-waste recycling infrastructures. In addition, the turning point values highlight the income levels at which economic growth begins to reduce e-waste generation. These values are consistent with the GDP range of the dataset, emphasizing the realistic nature of these thresholds. This suggests that many regions are still below the threshold where economic growth can effectively reduce e-waste. For Africa, America, and Asia, where the average GDP per capita is significantly lower than the turning points, substantial economic growth is required to reach the stage where e-waste generation starts to decline. In Europe, where the average GDP per capita is already higher than the turning point, the focus should shift to maintaining sustainable economic growth and enhancing e-waste management systems. Europe can serve as a model for other regions by demonstrating how to balance economic prosperity with effective e-waste reduction strategies.

5. Conclusion and Recommendations

There is increasing urgency to leverage the role of globalization and digitization to achieve the United Nations Sustainable Development Goal 13, which emphasizes enhancing resilience and adaptation capabilities to climate-related risks, as governments at the global and regional levels strive towards attaining this goal. Our research contributes important empirical knowledge to the body of literature that has previously found the relationship between globalization, digitalization, and electronic waste to be inconclusive. This is because globalization and digitalization are complex phenomena that present difficulties for accurate monitoring and explanation. Our study has made a substantial contribution to our understanding of the consequences of globalization and digitalization on electronic waste both globally and regionally over the years 2013–2022. The auxiliary objective complements the focus of the study by examining the potential non-linear link between e-waste generation and economic growth using a dynamic threshold model. Employing the dynamic panel threshold of GMM, we document that globalization positively affects e-waste generation globally and at regional levels except for Europe.

The findings further show that digitalization positively influences e-waste generation globally, in Africa and Asia, and it negatively affects e-waste generation in America and Europe. This confirms the significant roles of globalization and digitalization in e-waste generation at global and regional levels. Specifically, mobile phones positively impact e-waste generation globally and across the regions but negatively affect e-waste in Europe. Fixed telephones also negatively impact e-waste generation globally and in America, positively impacting e-waste generation in Africa, but do not influence e-waste generation in Asia and Europe. Internet access promotes e-waste generation globally, in Africa, and in Europe, while it reduces e-waste generation in America and in Asia. Using the novel dynamic panel threshold, the study further investigates the threshold that regional and global economic growth would need to reach to lessen the generation of e-waste. Furthermore, the results also confirm the threshold values at which economic growth would be negative: 63.09% globally, 187.27% for Africa, 77.42% for America, 236% for Asia, and 64.92% for Europe. After this threshold, economic growth becomes negative and significant in reducing e-waste generation globally and at regional levels. This aligns with the EKC hypothesis, characterized by an inverted U-shaped link between GDP per capita and environmental degradation (e-waste).

The results of this study are essential for developing certain targeted policies for efficient e-waste management. The positive effect of globalization on the generation of e-waste globally and at most regional levels underscores the need for international and regional cooperation in managing e-waste. Governments should collaborate to establish stringent international e-waste regulations and develop comprehensive regional recycling programmes. The dual impact of digitalization on e-waste generation is positive globally, in Africa, and in Asia, but negative in America and in Europe. This highlights the necessity for tailored digitalization policies. In Africa and Asia, investments in digital infrastructure should be coupled with robust e-waste management systems. This includes promoting eco-friendly devices, enhancing recycling facilities, and enforcing regulations that mandate producers to manage e-waste responsibly. In America and Europe, efforts to innovate and implement sustainable digital practices should be sustained to maintain the reduction in e-waste generation.

Specifically, there is a need for targeted policies to manage mobile phone waste. Europe's practices in reducing mobile phone e-waste should be studied and potentially adopted in other regions. The negative impact of fixed telephones on e-waste globally and in America suggests effective existing management strategies. These regions should continue to support and enhance these strategies. In Africa, where fixed telephones positively impact e-waste, specific recycling programmes as well as the proper disposal of these devices should be promoted. Monitoring and maintaining effective practices in Asia and Europe, where fixed telephones do not significantly impact e-waste, is also important. Internet access increases e-waste globally, in Africa, and in Europe, indicating a need for better management practices in these regions. Policies should focus on the sustainable use of internet-connected devices, including promoting longer device lifespans and improving recycling programmes. In America and Asia, where internet access reduces e-waste, successful policies and practices should be enhanced, and potentially replicated in other regions.

Lastly, given the specific economic growth thresholds at which the impact on e-waste generation becomes negative, aligning with the EKC hypothesis. Policymakers should focus on achieving these economic growth thresholds while integrating sustainable development practices. Investments in green technologies, infrastructure, and policies promoting economic growth while minimizing environmental degradation are essential. Tailored strategies should be developed for each region based on its specific threshold value to ensure that economic growth reduces e-waste generation.

Notwithstanding its contributions, this study has its limitations that offer room for further investigations. First, due to data constraints, the study was limited to the years 2013–2022, which might not adequately account for long-term structural changes in the dynamics of e-waste, globalization, and digitization. Future research could assess more recent trends, especially in developing economies, by using higher-frequency data or extending the time horizon. Second, significant differences between nations and within regions may be obscured by the use of aggregate indicators for globalization. More detailed data could be included in future studies to take into consideration the elements of globalization as well as sectoral or nation-specific effects. Last but not least, future studies might examine the importance of institutional quality and possible variables like environmental legislation, recycling technologies, and informal waste management practices, or use spatial econometric tools to account for cross-border spillover effects of e-waste.

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