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Electronic Waste, an Environmental Problem Exported to Developing Countries: The GOOD, the BAD and the UGLY

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Abstract: Electronic waste (e-waste) is a rapidly developing environmental problem particularly for the most developed countries. There are technological solutions for processing it, but these are costly, and the cheaper option for most developed countries has been to export most of the waste to less developed countries. There are various laws and policies for regulating the processing of e-waste at different governance scales such as the international Basel Convention, the regional Bamoko Convention, and various national laws. However, many of the regulations are not fully implemented and there is substantial financial pressure to maintain the jobs created for processing e-waste. Mexico, Brazil, Ghana Nigeria, India, and China have been selected for a more detailed study of the transboundary movements of e-waste. This includes a systematic review of existing literature, the application of the Driver, Pressure, State, Impact, Response (DPSIR) framework for analysing complex problems associated with social ecological systems, and the application of the Life Cycle Assessment (LCA) for evaluating the environmental impact of electronic devices from their manufacture through to their final disposal. Japan, Italy, Switzerland, and Norway have been selected for the LCA to show how e-waste is diverted to developing countries, as there is not sufficient data available for the assessment from the selected developing countries. GOOD, BAD and UGLY outcomes have been identified from this study: the GOOD is the creation of jobs and the use of e-waste as a source of raw materials; the BAD is the exacerbation of the already poor environmental conditions in developing countries; the UGLY is the negative impact on the health of workers processing e-waste due to a wide range of toxic components in this waste. There are a number of management options that are available to reduce the impact of the BAD and the UGLY, such as adopting the concept of a circular economy, urban mining, reducing loopholes and improving existing policies and regulations, as well as reducing the disparity in income between the top and bottom of the management hierarchy for e-waste disposal. The overarching message is a request for developed countries to help developing countries in the fight against e-waste, rather than exporting their environmental problems to these poorer regions.

Keywords: e-waste; DPSIR; environment; formal and informal activities; LCA

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1. Introduction

The world currently has a variety of environmental problems resulting from manufacturing activities, including plastic pollution and electronic waste (e-waste). Plastic pollution can be traced back to the beginning of the commercial production of plastics in the 1950s [1], but more recently, e-waste is considered an emerging environmental problem [2]. The sources of the majority of these can be traced to major developed countries, although there is an increasing contribution from rapidly developing countries like China and India.

The Basel Convention was formulated to ensure that environmental problems are not exported across boundaries [3–5]. Developed countries have state-of-the-art facilities, finances and technology to handle waste [6]. However, much of the e-waste is not recycled but exported to developing countries [7], which are already struggling with economic problems such as poverty. Although developing countries are paid for receiving this waste, the Pollution Haven Hypothesis (PHH) suggests that pollution-intensive economic activities are located, or relocated, to jurisdictions with the weakest environmental regulations, particularly, the developing countries [8]. Many studies [9,10] have highlighted the relationship between PHH and the Environmental Kuznets Curve (EKC). The EKC proposes that a nation's concentrations of pollution increase with development and industrialization up to a limit, from which point it decreases as the nation makes use of its rising economic affluence to reduce pollution concentrations [11]. This implies that the cleaner environment in developed nations is achieved to the detriment of a dirtier environment in developing nations. Hence, the EKC mirrors the PHH, whereby the rise in environmental degradation in pre-industrial economies is related to the introduction of waste from post-industrial economies.

The electronics industry is one of the fastest growing as well as the largest manufacturing industry in the world today [12,13]. E-waste accumulates nearly three times faster than other waste [14]. For example, between 20 and 50 million tonnes Waste Electronic and Electrical Equipment (WEEE i.e e-waste) are generated each year [15]. In 2019, 53.6 million metric tonnes of e-waste was produced [6]. In 2014, the United States was the greatest producer of e-waste (7.1 million tonnes) and China the second (6 million tonnes) [16].

Many factors contribute to this surge in e-waste. These include the short lifecycle of equipment, low recycling [17], and the continuous upgrading of electronic equipment [18] as affluent societies demand the latest technology. E-waste has been described as one of most difficult classes of waste to manage due to a constant change in its features and specificities [19]. Developed countries understand that recycling expired electronic equipment, contributes to saving the environment from hazardous chemicals [20], but for example in 2014, only 15% of the generated e-waste was officially discarded through countrywide take-back arrangements [15]. United Nations Environmental Programme (UNEP) suggests that only 10% of the produced e-waste in the world today is recycled in developed countries, the remaining 90% is sent to developing countries across the globe. Additionally, obsolete or used Electronic and Electrical Equipment (EEE) are often earmarked as donations destined to developing countries that cannot afford new electronic equipment, but need to keep up with the world of increasing technology [21]. Indeed, most of the waste is sent to the least developed and the most heavily indebted countries [22], such as Ghana, Nigeria, Chile, Uruguay, Vietnam, Colombia, Peru and Ecuador. These countries lack the fully developed infrastructure and recycling management systems for dealing with e-waste [23]. As a culture of consumerism proliferates, the amount of WEEE that is sent to these countries is expected to increase [24,25]. In addition, regulations are not very stringent in the receiving countries, thus making them the easy dumping sites for e-waste [15]. Formal e-waste recycling, which requires state-of-the-art facilities to safely extract salvageable materials, is expensive to install [26]. Developing countries adopt informal recycling practices that are rudimentary for extracting the resources in e-waste, thus exposing the workers to the hazardous content of e-waste [13].

The inappropriate handling of WEEE is unsafe for both human health and the environment, discharging heavy metals and persistent organics [27–29]. Overall, 70% of reported toxic and hazardous chemicals in the environment today come from e-waste [30]. They include heavy metals such as lead, mercury, cadmium and beryllium, as well as polluting PVC plastic, such as brominated flame retardants that can harm human health and the environment. Persistent organic pollutants (POPs) are an important component of e-waste; they can bioaccumulate and biomagnify through the food web [31].

This study focuses on six countries that are among the top 10 e-waste dumping sites in the world. The aim of the analysis is to compare and contrast the common drivers of e-waste in these countries, common activities, existing pressures, environmental state changes, impacts on human welfare, as well as possible responses as management measures for the problem. This study will summarize the contribution of existing laws both national and international towards the management of e-waste, and synthesize knowledge about e-waste as a pressure on the environment to ensure that the research results are useful to the end-users, such as environmental managers. The knowledge from social, economic and environmental aspects, is analysed for relevant management options for the e-waste industry, including a contribution to the circular economy. The current Circular Economy Action Plan provides measures throughout the life cycle of products such as electrical equipment so as to streamline and improve economies with minimal environmental impacts [32]. The results of the analysis should be useful to raise societal awareness of e-waste. It may also promote the dialogue between the users of the research and public administration to bridge the existing science–policy gap [33].

2. Site Selection and Data Analysis

The sites for this study and the reasons for their selection are considered in Section 2.1. The search methods for locating existing data for each of the selected sites are summarised in Section 2.2. Although there are many different frameworks that have been developed for the analysis of complex social ecological systems [34], the Driver-Pressure-State-Impact-Response (DPSIR) framework [35] is described in Section 2.3 for analysing the data on e-waste. Finally, Life Cycle Assessment (LCA) for e-waste is considered in Section 2.4; this constitutes an organized method to evaluate and quantify a product's impact on the environment throughout all states of the product's existence, from creation to final disposal [36].

2.1. Study Sites

The issue of e-waste as an existing environmental problem across three major continents (Asia, Africa and Latin America) is analysed, particularly for the locations most vulnerable to e-waste dumping (Figure 1). Two countries have been then selected from each of the continents: Mexico and Brazil in Latin America, Ghana and Nigeria in Africa, and India and China in Asia. These choices are based on a combination of factors, including the total amount of e-waste that is exported to each country as well as the amount of e-waste generated internally. There is specific focus on some cities that receive exceptional quantities of e-waste, such as Agbogbloshie in Ghana which has been described as the most polluted e-waste site on earth [37], and Guiyu in China which is considered the electronic graveyard of the world [38] because of its informal e-waste recycling.

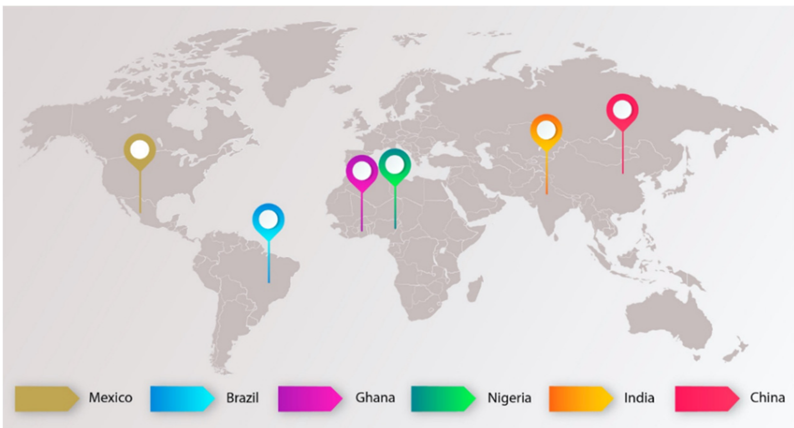

Figure 1. Study sites.

2.2. Data Sources and Collection

A structured keyword search (Table 1) was conducted to obtain information relevant to e-waste, using web-based databases such as Web of Knowledge (International Scientific Indexing (ISI) Web of Science), Science Direct (Scopus), Google General and Scholar. The searches were not restricted to a specific time period and, in the case of Google, the data included peer-reviewed publications and grey literature. For example, when the ISI Web of Science database was searched (using name of country and e-waste as keywords), this returned 1388 results: Mexico (3), Brazil (5), Ghana (81), Nigeria (61), India (1023) and China (177). In addition, when other search keywords were used in combination such as: name of the country, e-waste, and health, this returned 767 results: Mexico (3), Brazil (5), Ghana (51), Nigeria (34), India (58) and China (349). Duplicated information was removed, yielding 500 results for analysis. Again, based on factors such as the title of the article and abstract, the data size was narrowed to 151 results. The final information that constitutes the basis of the study was obtained following a systematic approach to extract information about e-waste relative to the drivers, activities, pressures, state changes, impacts, humans, and welfare issues [39]. The described existence and absence of several activities/pressures/state changes/impact (on welfare) in the studied regions were extracted and, if data existed, were analysed with both qualitative and quantitative specifics presented for each result unit [40].

Table 1. Examples of search results obtained using "country and e-waste as keywords".

Search Keywords	Country	Web of Science	Google Scholar	Total
"Mexico, e-waste"	Mexico	11	5770	5781
"Brazil, e-waste"	Brazil	35	7290	7325
"Ghana, e-waste"	Ghana	81	4740	4821
"Nigeria, e-waste"	Nigeria	61	6090	6151
"India, e-waste"	India	1023	18,000	19,023
"China, e-waste"	China	177	31,000	31,177
Total		**1388**	**72,890**	**74,278**

2.3. Analytical Framework

The DPSIR analysis framework has been key in providing management measures for major environmental problems [41] and has been adopted by many international organizations such as the Organization of Economic Cooperation and Development (OECD), the European Environment Agency (EEA) and the United Nations Environment Programme (UNEP) [39,42,43].

For this study the enlarged DPSIR {D(A)PSI(W)(M)} is used to analyse the data for e-waste [39]. It identifies the DRIVERS of an environmental problem, the specific human ACTIVITIES that cause the problem, the resulting PRESSURES causing changes in the STATE of the environment, as well as delivery of ecosystem-services that ultimately IMPACTS on human welfare [35,39]. Ecosystem services (ES) are the benefits that societies obtain from the environment and include provisioning services (food, water), regulating services (climate, floods) that affect cultural services (recreational, aesthetic, spiritual), and supporting services such as (soil formation, nutrient cycling) [44,45]. Compromising the flow of ES may impact human welfare [46] and can result in loss of life (cancer as a result of lead in e-waste) and many health-related problems. RESPONSES as management measures then become necessary to manage the activities, state changes and the impact. The responses include policy actions, social constructs, conflict management, public information, education, awareness raising, governance, technology and infrastructure [39].

2.4. Life Cycle Assessment (LCA)

LCA provides a continuous and organized way to effectively assess and recognize environmental inventory, environmental impact and improvement opportunities linked with the overall stages of a system boundary [47]. LCA has since been employed to examine the environmental impact of e-waste treatment on the environment [48,49]. Data on LCA in the chosen developing countries were generally lacking, with the exception of China. Hence, articles on LCA from Japan, Italy, Switzerland and Norway were reviewed to identify environmental impacts associated with e-waste management. These highlight the diversion of environmental problems from developed to developing countries.

3. Results

The results are the outcome of the application of the DPSIR framework as an analytical tool to the issue of e-waste in the present study.

3.1. Drivers

The drivers of the e-waste problems are wide and varied and include source of income, livelihood, employment, valuable material, and technological advancement.

3.1.1. Source of Income and Livelihoods

The e-waste sector is an important source of income and livelihoods for the social actors involved. The global annual worth of the e-waste sector is estimated at USD 62.5 billion [50] employing 18 million people worldwide in 2010 [51]. The value of the industry is approximately USD 105–268 million annually in Ghana [37] supporting between 20,300 [52] and 200,000 workers [53] in the informal sector. According to the International Labour Organization [54], about 132,000 informal e-waste workers (collectors and refurbishers) seek their sources of livelihood from the e-waste industry in Nigeria. In addition, between 400,000 and 1,000,000 people benefit from the e-waste sector as their source of income in Brazil [55,56]. In India, the e-waste industry is estimated to be worth about USD 3 billion annually [57] involving nearly 25,000 informal workers in Delhi alone [58] and more than 30,000 in Seelampur [59] resulting in 450,000 direct jobs and 180,000 indirect jobs nationwide (Press Trust of India) [60]. Cordova-Pizarro et al. [61] estimated the value of printed circuit boards of mobile phones in e-waste to be USD 11.277 and USD 12.444 million per year in Mexico. The e-waste industry employs an estimated workforce of about 700,000 people [62] in China and this is expected to increase to 23.8 billion by 2030 [63].

3.1.2. Source of Valuable Material

Embedded in e-waste are scarce and valuable resources such as europium and terbium [64]. These rare earth metals continue to diminish in the natural environment, while cheap and abundant raw materials are readily available in e-waste. The resource content of discarded e-waste also contains valuable metals such as gold, silver, copper and platinum [30] and are 40–50 times richer than natural deposits [65]. This increasing value of the e-waste industry is one of the main drivers of the e-waste problem. For example, the increasing demand for cheaper and low-cost raw materials accounts for the surge in illegal importation of e-waste into China [66].

3.1.3. Technological Advancement

Rapid technological advancement in the 21st century, coupled with a growing middle class, has played an important role as a major driver for e-waste generation [67]. There is a relationship between the consumption of electrical and electronic equipment and the generation of electronic waste. For example, e-waste generation is high in the US, China, Japan, Australia and countries in Europe where the consumption of electrical equipment is high making up about 8% of the solid waste streams in these countries [27,68,69]. In addition, support for technological progress in developing countries has led to the generation of significant quantities of e-waste. This usually occurs when end of life or waste electrical and electronic equipment (WEEE) are sent to developing countries as donations [70,71].

3.2. Activities

The e-waste industry is characterized by both formal and informal activities, and the latter are unregulated [72]. These activities are summarized in Figure 2 and include migration, scavenging, sorting, open dismantling, refurbishing, open burning, acid bathing or open pit acid leaching, open dumping, selling of e-waste, and child labour [73].

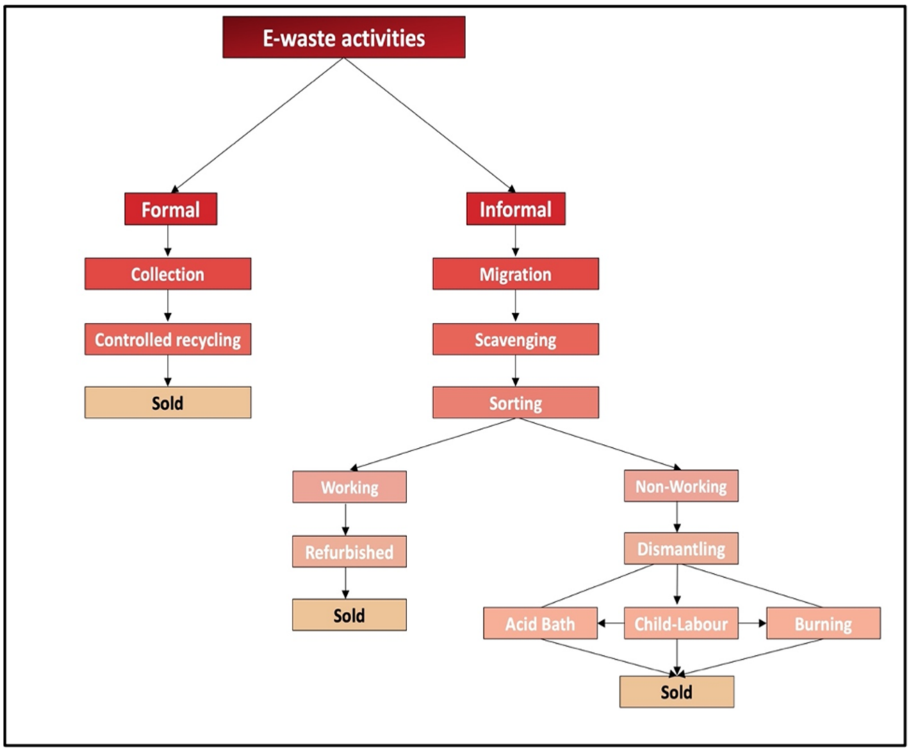

Figure 2. Activities within the e-waste sector.

3.2.1. Formal Activities

Formal e-waste activities are authorized and have been officially documented by governments [74]. These activities include the formal collection of e-waste from private companies or government agencies, involving controlled dismantling and recycling that consider aspects of human and environmental needs requiring the use of sophisticated machines and procedures. In the formal e-waste sector, e-waste generated in private and formal institutions tend to favour formal collection and processing of e-waste [75]. Formal e-waste activities are expensive and capital intensive, thus leading to a lower number of formal recycling units in the e-waste sector [26]. Research shows that less than 20% of the generated e-waste across the globe is formally handled [6]. This activity is still in the developmental stages, and accounts for 2% of the activities in China. There are only 109 formal collection and recycling systems in China [76], 1 in Ghana [37] and 150–312 in India [51,77]. Furthermore, Nigeria has about four formally known e-waste recycling centres: Hinckley Recycling with a capacity of 20,000 tonnes of e-waste per annum, the Lagos Waste Management Administration (LAWMA), the Lagos State Environmental Protection Agency (LASEPA), and E-terra Technologies Ltd.; indeed, Lagos is in the process of establishing a circular system for electronic waste worth USD 15 million [73]. In Mexico, companies that are involved in the formal recycling of e-waste include Recicladora Electrónica, Recall International, Secretaría del Medio Ambiente del Distrito Federal (SEDEMA) and Recicla Electrónicos México (REMSA) [78]. Most formal e-waste recycling centres in the study regions are not evenly distributed thus affecting recycling efficiency.

3.2.2. Informal Activities

Informal activities within the e-waste industry have the tendency to impact the environment negatively as well as having adverse impacts on human health [38]. Informal activities are unregulated, labour demanding and involve the use of simple, rudimentary equipment to dismantle e-waste [79,80]. In some countries, for example China, the informal sector dominates WEEE management, even though specific regulations are in force [81]. Informal activities are lucrative when compared to the formal activities, thus leading to a larger informal e-waste sector accounting for about 98% of the e-waste activities in developing economies such as China [75]. Informal activities within the e-waste industry in India are as nearly as large as those in China, covering 95% of the activities [82]. Additionally, to some extent, a larger section of the e-waste sector in Ghana, Nigeria, Mexico and Brazil are also characterized by informal activities.

Migration is a prominent activity among e-waste workers and it is particularly noticeable in Guiyu in China and Agbogbloshie in Ghana where most of the informal actors are migrants [83,84]. For example, in Guiyu nearly 70% of e-waste workers, are migrants from surrounding cities such as Hunan and Anhui [62], similar to those found in Agbogbloshie in Ghana where the majority of the workers (80%) migrated from the northern part of Ghana and some neighbouring countries [85]. Similar observations have been made in Nigeria where migrant workers from Northern Nigeria are involved in e-waste activities [86]. In addition, migrants in Mexico engage in informal e-waste activities as their alternative sources of income [87]. Streicher-Porte et al. [88] have also reported the activity of migration among Indian e-waste workers where migrant workers came from neighbouring Bangladesh, as well as other regions within India, such as West Bengal, Bilhar and Uttar Pradesh.

Within the informal e-waste industry, resources must be scavenged for, before being sorted into functional and non-functional components. Functional components are refurbished and resold, creating value for money augmenting the circular economy. Non-functional components are dismantled. Covered copper wires are burnt in the open to retrieve materials, mother boards of computers are leached (acid bath) to obtain resources.

Such activities usually involve child labour [89–93]. In India, approximately 35,000 to 500,000 child workers less than 16 years of age are active in different phases of e-waste activities [94,95]. Cordova-Pizarro et al. [61] also confirmed the existence of the activity of child labour among Mexican e-waste workers whose ages ranged between 8 and 15 years. It has also been reported that, children engaged in e-waste activities in Ghana [85,96], Nigeria [96] and Guiyu in China [97], are often tasked to dismantle e-waste or burn it to retrieve valuable materials. Child labour within the e-waste sector is prominent during the weekend and school vacations [98], where children work alongside their families who reside alongside e-waste dumps [99,100]. Obaje [96] notes potential unknown health consequences on children.

3.3. Pressures

The pressures from e-waste are from the volume generated (Table 2). They are partly determined by factors such as the size of the economy, recycling capacities, laws in each country, or global location. The projected total pressure emanating from the global generation of e-waste is expected to reach 82.34 million tonnes by the end of the year 2030, an increment of 37.64 million tonnes from the 2016 pressure of 44.7 million tonnes [6,51]. The Asian Region produces the largest amount of e-waste worldwide, accounting for 41% e-waste produced in 2016 (18.2 million tonnes) [51]. China generates most of the e-waste in Asia and globally. India is the second largest producer of e-waste in Asia and the fourth largest producer globally, producing an estimated pressure of 5.73 million tonnes per year in 2020 [94].

Table 2. Estimated pressures within the E-Waste sector by country.

Country	Pressure	Year	Reference(s)
Ghana	280,000 tonnes	2009	[101]
Nigeria	277,000 tonnes	2016	[54]
India	5.73 million tonnes	2020	[94]
China	7.94 million tonnes	2016	[50]
Brazil	1.65 million tonnes	2016	[50]
Mexico	1.1 million tonnes	2015	[50]
Global	59.08 million tonnes increasing to 82.34 million tonnes	2019–2030	[6,51]

The contribution of the African continent to the total pressure of e-waste exerted on the environment is only 5% of the global pressure representing 2.2 million tonnes [51]. Ghana and Nigeria are major destinations of shipped e-waste from Europe and the US. Ghana has the most polluted e-waste processing site in the world [37], producing a pressure of about 280,000 metric tonnes of e-waste in 2009 [101]. The majority of e-waste sources in Nigeria are shipped from Europe and the USA [102], producing 277,000 tonnes of e-waste in 2016 [54]. In Latin America, Brazil produces the greatest pressure, estimated at 1.65 million tonnes in 2016 [50]. Mexico produces pressures of about 358,000 tonnes of e-waste annually and contributed an estimated 257,000 tonnes of e-waste in 2006 which increased to over 390,000 tonnes in 2018 [103].

3.4. State Changes

Studies have highlighted the environmental effects of e-waste processing on the environment especially informal e-waste recycling. Toxic substances such as cadmium, lead, copper, mercury and polychlorinated biphenyl have been identified in the air, soil and water adjacent to informal e-waste recycle sites. For example, cadmium and lead levels exceed the WHO guidelines in the Li River in China [104], as well as high concentrations of copper, cadmium, lead, iron, chromium, and nickel in the Odaw River in Agbogbloshie e-waste site in Ghana [105]. Similar findings in Ghana also show traces of aluminium, copper, and iron in various environmental compartments, with lead levels four times higher than allowable by the United States Environmental Protection Agency (USEPA) for ambient air quality [106]. The Alaba market in Lagos has copper, lead, zinc concentrations as much as 100 times higher than non-e-waste recycling sites [54]. Higher ground water pollution and additional pollution and environment effects are observed in areas demarcated for informal e-waste activities in India [107]. Air pollution from the burning of e-waste materials release greenhouse gases as well as contaminants such as dioxins and furans into the environment [54,108].

An LCA review of the e-waste in selected developed countries, Japan, Norway, Switzerland and Italy, provides a snapshot (Table 3) of the environmental effects associated with e-waste, such as the transportation, landfilling and incineration of discarded e-waste. The results show the transportation of e-waste across boundaries is associated with some environmental effects [109,110] and accounts for about 10% of the total environmental effects along the entire process in Norway [111]. Additionally, in Switzerland, the greatest environmental impacts of e-waste are within landfill, whilst in both Italy and Switzerland they are related to incineration [110,112]. Recycling provides some environmental benefits [110] so some of the developed countries, that lack recycling facilities, are diverting environmental impacts associated with e-waste to developing countries.

Table 3. A snapshot of the diverted environmental degradation from the developed to developing countries.

Norway	**Component of the LCA and Associated Findings**	[111]
Type of e-waste	Refrigerators, LCD Screens and Mobile Telephones	
What was done	The study calculated the life cycle environmental impacts of specific e-waste products along the parts of the value chain	
Transport	Transport accounts for about 10% of the total environmental effects along the entire process	
Land filling	Information on how landfilling would affect the environment was not available	
Incineration	The study did not comment on how incineration of e-waste would affect the environment	
Recycling	Valuable and rare earth metals recovery have both environmental and financial benefits while inefficient recycling of refrigerants negates the total global warming potential benefit	
Recommendation/ conclusion	Communication targeting the positive benefits of recycling rather than focusing much on the negative outcome of not recycling could be beneficial	
Japan	**Component of the LCA and Associated Findings**	[109]
Type of e-waste	Washing Machines, Refrigerators, Air Conditioners, Televisions	
What was done	The study provided an LCA based quantitative assessment of climate co-benefits from WEEE recycling in Japan	
Transport	Long distance transportation was noted to be the critical phase that emitted the most greenhouse gases	
Land filling	Only glass was sent to landfill with no information on the environmental effects	
Incineration	Insufficient data	
Recycling	Increasing greenhouse gas emission was observed in the following order: refrigerators > air conditioners > washing machines >televisions	
Recommendation/ conclusion	The study concludes that proper recycling will reduce both the consumption of virgin materials and the emission of greenhouse gases	
Switzerland	**Component of the LCA and Associated Findings**	[112]
Type of e-waste	WEEE	
What was done	The study carried a combined material flow analysis and life cycle assessment for WEEE collection and recovery systems	
Transport	Insufficient data	
Land filling	The greatest environmental impacts were noted during the landfilling scenario	
Incineration	Freshwater Aquatic Ecotoxicity Potential and the Global Warming Potential were the noted total environmental impacts	
Recycling	Recycling with reference to plastics has minimal environmental impacts	
Recommendation/ conclusion	The study recommends research to be directed towards the recovery of geochemically rare metals	
Italy	**Component of the LCA and Associated Findings**	[110]
Type of e-waste	Cooling Equipment, Large Household Appliances, Televisions and Screens	
What was done	Material flow analysis and life cycle assessment of a full-scale e-waste management facility	
Transport	The transport component of LCA is associated with some environmental impacts	
Land filling	Insufficient data	
Incineration	Polyurethane and rubber incineration had critical environmental impacts	
Recycling	Recycling of the metal components of e-waste provided good environmental benefits	
Recommendation/ conclusion	The main environmental impacts were the potential for aquatic eco-toxicity	

3.5. Impact on Human Welfare

A wide range of negative impacts on human welfare (Table 4) have been linked to e-waste in many informal e-waste recycling sites such as Agbogbloshie in Ghana, Lagos in Nigeria, Guiyu in China, Delhi in India, Santo Andre in Brazil, and Renovación in Mexico. These impacts on human welfare include health-related impacts, physical injuries, excessive noise, chronic diseases and stress. Social impacts such exploitation of children and migrants have also been noted.

Separate but similar studies have found higher concentrations of heavy metals (cobalt, chromium, copper, iron, selenium, and zinc) in blood [113], PAH metabolites in urine [114], and polychlorinated biphenyls in breast milk [115] in e-waste workers. Some neurodevelopmental disorders and/or foetal perturbations have also been linked to exposure of pregnant women or children to e-waste [116]. For example, pregnancy-related issues such as spontaneous abortions, stillbirths, and premature births, and reduced birthweights and birth lengths have been linked to e-waste exposure in e-waste operating sites [91,117,118]. Reduced vital capacity in school children in the city of Guiyu in China as a result of blood chromium concentrations as well as reduction in weight, height, and body-mass index [119] have been reported. Some studies also suggest that the observed DNA damage among e-waste workers is the result of exposure to e-waste with increased frequencies of micro-nucleated binucleated cells in peripheral blood [120–123]. Lead, one of the most common chemicals in e-waste, is associated with delayed puberty in girls while, lower sperm count and quality is linked to polychlorinated biphenyls tetrachlorodibenzodioxin (TCDD) and perfluroalkyls in e-waste [124–126].

In developing countries, such as Nigeria and Ghana, the unstable electricity supply for both domestic and industrial usage is a problem. In such situations, e-waste workers such as refurbishers, resort to the use of power supply generators to carry out their activities. According to Manhart et al. [86], the use of power supply generators is associated with excessive noise pollution with unknown consequences on workers.

Another important impact of e-waste processing (especially informal) on human welfare among e-waste workers is the high prevalence of physical injuries. For example, 59% with cuts in Nigeria [89]; itchy eyes, skin irritations, burns and stress Ghana [126]; breathing problems and skin irritation in India [127]; 68.7% with accidents in Brasil [128], as well as soreness in the body especially in the arms, back, legs and shoulders in Chile and Brasil [128,129].

Table 4. Reported related health issues among e-waste workers in the study regions.

Health Impact	Country	Reference
Stress	Ghana	[126]
Physical injury	Brazil, Ghana, Nigeria, India	[89,90,128]
Excessive noise	Ghana, China	[130,131]
Pregnancy-related issues	China, Ghana	[132–136]
DNA damage	China, Nigeria	[137–140]
Skin problems	India, Brazil, Nigeria	[89,90,127,129]
Respiratory problems	Ghana, India, Nigeria, China	[89,90,113,141]
Hearing problems	Ghana, China, Nigeria, India	[130,142–145]

4. Responses and Management Measures

Several management measures for e-waste pollution are ongoing, including a call for the adoption of circular economy principles, extended producer responsibility (EPR), recycling, urban mining and data gathering. Potential interventions for managing e-waste are proposed together with the identification of gaps in these interventions.

4.1. E-Waste Recycling Practices

E-waste recycling is one of the sustainable solutions for dealing with the high tonnage of e-waste in the environment, both in developed and developing countries. Sustainable e-waste recycling is critical in achieving a progressive circular economy [146]. Recycling practices in the developed countries are dominated by formal activities under controlled conditions that protect the environment and human health. In developing countries, on the other hand, the majority of the recycling practices are informal [75], exposing workers to e-waste hazards, as well as exposing the environment to e-waste contaminants. Though formal e-waste recycling practices are beneficial to the environment and human health, they are not widely praticed especially in developing countries.

4.2. Adopting a Circular Economy

A well-developed circular economy has the potential to generate jobs worldwide, possibly up to 6 million [147]. The focus of a circular economy as opposed to the linear economy seeks to prevent waste generation in a product's life cycle, such electrical gadgets, by restraining the consumption and waste of resources [148]. A generalized concept of a circular economy for all types of environmental problems is ineffective, since environmental problems differ in scope, definition, origin and with different stakeholders. The current economy thrives on material consumption, so adapting to use a recycled resource input can slow this growth [149]. For example, only about 12% of the resource input in the EU economy is said to have been recycled [150], so recycling must increase to make the circular economy sustainable. In the context of e-waste, a well-developed circular economy will involve designing electrical equipment that lasts longer to reduce consumption, reusing through refurbishing and recycling non-functional electrical gadgets. Reuse and recycling are a larger component of the informal e-waste activities. Hence, achieving a universal circular economy should involve the informal e-waste sector as a major stakeholder. Providing informal e-waste workers with better options to recycle e-waste will help to reduce the environmental effects associated with informal e-waste activities.

4.3. Urban Mining

Urban mining is a discourse that supports the circular economy principles. It becomes beneficial as a way of reducing the pressure on raw materials and as a solution in times of material scarcity and unavailability. According to Araújo et al. [151] and Georgiadis and Besiou [152], the electronic industry accounts for 10–20% of the current environmental problems associated with the removal of non-renewable natural resources. Urban mining is a state-of-the-art technology used to recover valuable materials from e-waste. Urban mining of e-waste for valuable material such as gold is 13% cheaper than resorting to virgin mining of ores [153]. The value of raw materials in nonfunctional mobile phones reached EUR 9.4 billion in 2016 [50]. From environmental as well as sustainability points of view, urban mining of e-waste has the advantages of reducing the global carbon footprints through less energy consumption [78], as well as reduction in natural resource extraction and waste generation [51]. Nonetheless, the application of urban mining is currently limited and can only be used to extract specific, high value resources, such as gold in e-waste. The lack of its wide application leads to the potential loss of valuable resources from e-waste and an inefficient circular economy.

4.4. Research and Data Gathering

Research is needed to provide up-to-date information on the amount of Electrical and Electronic Equipment (EEE) that is generated every year including: what quantity becomes obsolete, what quantity is recycled in developed countries, what quantity is exported to developing countries and what quantity is recycled formally and informally in developing countries. Sufficient information documenting formal recycling of e-waste in Africa is lacking. This is exemplified in Nigeria that currently has no institutional or non-governmental entity for documenting and updating information about e-waste to augment policy decisions [154].

Data on the impacts of e-waste on human welfare are also lacking for some of the countries presented in Table 4. This makes the management of the issue challenging; for example, data on physical injury associated with e-waste are absent in Mexico and China, while data on excessive noise, pregnancy-related issues and DNA damage are only shown for Ghana and China. There is also lack of data on issues relating to skin problems in Mexico and China, respiratory problems in Mexico and Brazil and hearing problems in Mexico and Brazil. Considering that the search language in this current study is only applied in English, this may explain the conspicuous lack of data for Brazil and Mexico. Nonetheless, Balde et al. [50] observed that though some statistics are available, the lack of data for e-waste is a persistent issue.

4.5. Policies and Regulations

As many as 78 countries across the globe have instituted some policies, laws or regulations to manage the issue of e-waste [6]; of these, 25 countries are signatories to the Bamako Convention in Africa [155]. All the countries in the studied regions are signatories to one or more of the International Labour Standards (International Labour Organization), international laws and conventions (Basel convention and the Rotterdam convention) as well as national laws that seek to prevent the exportation of environmental problems to developing countries. Table 5 summarises and gives examples of some of the laws and regulations aiming at managing the exportation of e-waste to developing countries.

The Basel Convention is one of the international conventions seeking a global cooperation to reduce the exportation of e-waste to developing countries. It recognizes e-waste as one of the high-priority waste streams [156] with about 186 parties as signatories [157]. Additionally, the Organization for Economic Co-operation and Development (OECD) recognizes the Extended Producer Responsibility (EPR) as a policy option for producers to bear the cost of managing waste associated with their products such as electrical equipment. This policy requires product producers to prevent waste generation through better product designs that are environmentally friendly [158]. The 1991 Bamako convention is a regional treaty within the African continent to ban the import of hazardous wastes into Africa, as well as controlling and managing transboundary movement of this waste within Africa [159,160]. In Latin America, Mexico and Brazil are signatories, respectively, to the Agreement on Environmental Cooperation of North America (ACAAN) and the Mercosur Policy Agreement from 2006 [6,161].

Indeed, at national, regional and international levels, each country has policies, laws and regulations that contain measures to manage the proliferation of e-waste. However, the situation continues to persist due to poor implementation, enforcement and the existence of loopholes within the legislation. For example, according to Awasthi et al. [157], the development of the Basel convention is one of the top-down management measures that did not take account the private sector, and hence lacks scientific data and technical ability to deal with the issue of e-waste. Again, this convention did not prohibit the trade of hazardous waste to less developed countries, thereby creating a loophole for the exportation of e-waste [162]. Additionally, the EPR is not mandatory for producers, which does not encourage global cooperation to end e-waste. Additionally, existing laws, policies and regulation are not enforced, coupled with corruption at the various national levels. In Europe, Estonia, Croatia and Bulgaria are the only two countries to achieve the legally binding rate of collecting 65% of the produced e-waste [6,163], a situation justifying enforcement as the key solution to the e-waste problem. The EU is also making e-waste processing mandatory and setting stringent recycling goals to help mitigate the problem [164].

Table 5. Existing laws and policies for the management of e-waste.

Regulations/Policies	Ghana	Reference
International Labour Standards (examples)	ILO Convention on the Safety of Chemicals at the Workplace.	[52]
International Conventions (examples)	The Basel Convention,1998; Rotterdam Convention, 2001; Stockholm Convention on Persistent Organic Pollutant; the Vienna Convention on Protection of the Ozone Layer.	[52]
Regional Conventions and initiative (examples)	The Bamako Convention.	[37]
National laws (examples)	The Environmental Protection Agency Act, 1994 (Act 490).	[52]
Regulations/Policies	**Nigeria**	**Reference**
International Labour Standards (examples)	The Transition from the Informal to the Formal Economy Recommendation, 2015 (No. 204), the Chemicals Convention (No. 170) and Recommendation (No. 177), 1990; the Employment Relationship Recommendation, 2006 (No. 198); the Promotion of Cooperatives Recommendation, 2002 (No. 193); the Labour Inspection Convention, 1947 (No. 81); the Occupational Safety and Health Convention (No. 155).	[54]
International Conventions (examples)	Basel Convention—signed in 1990 and subsequently ratified and accepted it in 1991, 1998; Rotterdam Convention, 2001; Stockholm Convention on Persistent Organic Pollutants.	[54]
Regional Conventions and initiative (examples)	The Bamako Convention—signed but not ratified.	[54]
National laws (examples)	Harmful Waste (Special Criminal Provisions) Act Cap HI, 1988 and updated in 2004; the National Environmental (Sanitation and Waste Control) Regulation 2009; the National Environmental (Electrical/Electronic Sector) Regulations 2011.	[165] [54]
Regulations/Policies	**India**	**Reference**
International Labour Standards (examples)	Minimum Age Convention, 1973 (No. 138) Worst Forms of Child Labour Convention, 1999 (No. 182); Forced Labour Convention, 1930 (No. 29); the Equal Remuneration Convention, 1951 (No. 100); the Abolition of Forced Labour Convention, 1957 (No. 105), and the Discrimination (Employment and Occupation) Convention, 1958 (No. 111).	[51]
International Conventions (examples)	Basel Convention—signed on 15 March 1990 and ratified it in 1992, 1998 Rotterdam Convention 2001; the Stockholm Convention on Persistent Organic Pollutants.	[51]
Regional Conventions and initiative (examples)	Insufficient information.	[51]
National laws (examples)	The E-Waste (Management and Handling) Rules 2011 by the Ministry of Environment, Forests and Climate Change.	
Regulations/Policies	**China**	**Reference**
International Labour Standards (examples)	Non existing sector-wide labour regulation aiming at e-waste.	[166]
International Conventions (examples)	The Basel Convention ratified in Basel Ban Amendment in 1999; Rotterdam Convention; Stockholm Convention on Persistent Organic Pollutants.	[76,167,168]
Regional Conventions and initiative (examples)	Insufficient information.	

Table 5. *Cont.*

Regulations/Policies	China	Reference
National laws (examples)	Notification on Importation of the Seventh Category Waste, (MEP) effective 1 February 2000; the circular on Strengthening Environmental Management of Waste Electrical and Electronic Equipment (MEP); the Technical Policy on Pollution Prevention and Control of WEEE (MEP); Circular Economy Law (NPC, 2009); Regulation on Management of the Recycling and Disposal of Waste Electrical and Electronic Equipment (NDRC; NPC, 2009; MIIT and others; Administrative Measure on Pollution Prevention of Waste Electrical and Electronic Equipment (MEP); Administration of the Recovery and Disposal of Waste Electrical and Electronic Products ('China WEEE directive', State Council, 2009.	[162,168]
Regulations/Policies	**Mexico**	**Reference**
International Labour Standards (examples)	Insufficient information.	
International Conventions (examples)	Basel Convention, Rotterdam Convention 2001; the Stockholm Convention, and the Montreal Protocol.	[2]
Regional Conventions and initiative (examples)	Regional Platform on Electronic Waste in Latin America and the Caribbean (RELAC); Agreement on Environmental Cooperation of North America (ACAAN).	[2]
National laws (examples)	NOM-161-SEMARNAT-2011 General Law for the Prevention and Management of Solid Waste; Regulations of the General Law for the Prevention and Management of Solid Waste.	[2,169]
Regulations/Policies	**Brazil**	**Reference**
International Labour Standards (examples)	Insufficient information.	
International Conventions (examples)	The Basel Convention ratified on 1 October 1992.	[162]
Regional Conventions and initiative (examples)	The Mercosur Policy Agreement from 2006.	[161]
National laws (examples)	National Solid Waste Policy of 2010 (Law 12.305), Decree 875 (19 July 1993), Decree 4.581 (27 January 2003), and Resolution CONAMA 452 (2 July 2012) (Ministério do Meio Ambiente, 2015).	[162]

5. Discussion

5.1. Exporting Environmental Problems

The snapshot of the LCA produces an image of some of the environmental consequences that are associated with the management of e-waste. Transportation is an important component of exporting e-waste to developing countries. For example, a total of about 6072 km or 3279 nautical miles have to be traversed in order to get e-waste across from Norway to Ghana. Yet, transportation of e-waste has been shown to contribute about 10% of the total environmental effects along the entire process in Norway and to emit greenhouse gases in Japan [109,111]. Landfilling and incineration of discarded e-waste are common activities in developing countries, producing large environmental effects with impacts on the potential aquatic ecotoxicity and for global warming in Switzerland [112]. While formal recycling has been noted to offset some of the negative environmental effects in e-waste, the literature shows that formal facilities are expensive to install in developing countries. Despite the knowledge the LCA snapshot provides, developed countries continue to export e-waste to developing countries.

5.2. Income Inequality and Social Equity

Information on incomes for various e-waste workers is limited, particularly, for their monthly earnings. In the informal sector, records are not usually kept of the workers' activities, although there are income records for the e-waste sector in Ghana, where the level of income is dependent on the position of a worker on the e-waste management hierarchy (Figure 3); workers at the base of the hierarchy earn 0–50 Cedis up to the chairman with 1300 Cedis per month. Despite the lack of detailed information on income for the other countries in this study (Table 6), there is evidence for variation in Nigeria, China, Mexico, Brazil and India. In the global context, income variation among e-waste workers has also been examined according to gender (male or female) and the amount of waste that is collected and processed per day [51]. Individuals occupying the base of the hierarchical pyramid (burners and collectors) had lower wages in Ghana, which is similar to the observations made by Oneko [170] among Indian e-waste workers. This is reflected by 80% of e-waste workers (females) occupying the base of the hierarchy in India. In comparison, 70% of the collectors are male adults in Nigeria, and young children and women in Ghana [171]. On average, workers earn between USD 91 and 1300 a month in Ghana [172,173]. E-waste workers in Nigeria earn on the average USD 5.28–670 a month [86]. Informal workers earn about USD 79 a week on the average which translates to USD 316 a month in Mexico. Additionally, e-waste workers in India (dismantlers) with reference to Seelampur make around USD 2.8–11 per day (USD 67.2–264 a month); the recommended daily minimum wage of about USD 7.8 per day was instituted by the Office of the Labour Commissioner on 23 October 2019 [174,175]. E-waste workers (Catadors) in Brazil on the other hand earn on average USD 184 in a month [55]. Women and children involved in informal e-waste recycling (dismantling) in China earn USD 1.5 per day (USD 36 per month) [72].

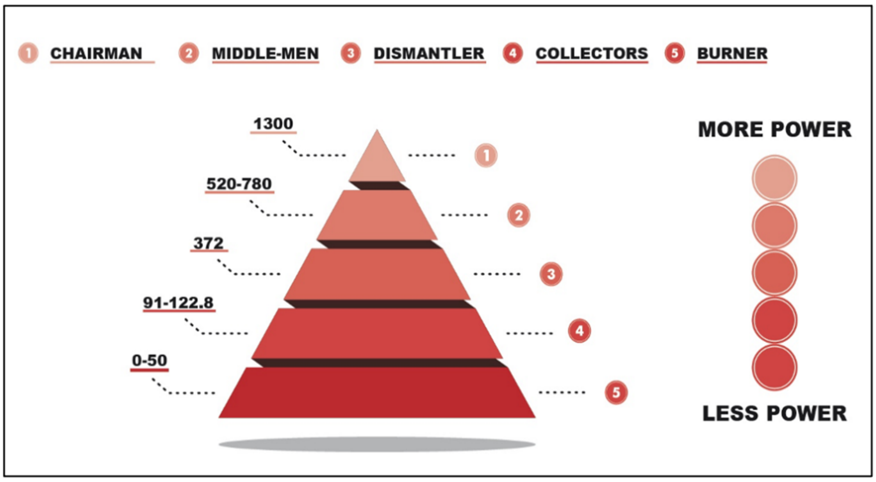

Figure 3. The e-waste management hierarchy in Ghana and monthly income in Ghana (Cedis). Adapted from ILO [51].

Table 6. Income variations among e-waste workers in US dollars per month.

Country	Average Income in US Dollars/Month	Reference(s)
Ghana	91–1300	[172,173]
Nigeria	6.7–670	[86]
India	72.8–286	[173]
China	58.5	[72]
Mexico	316	[176]
Brazil	184	[55]

5.3. Achieving Sustainable E-Waste Management

The results of this study show that there are increasing problems for human health and the environment occurring from e-waste in both developed and developing countries. Essentially, the developed countries are resolving most of these problems by exporting them to developing countries, where the need for economic activity is high and controls are relatively lax for preventing harm to human health and the environment. However, there is increasing pressure to manage e-waste sustainably for both developed and developing countries. The negative environmental impacts in the LCA start with the transportation of e-waste to developing countries which suggests that waste management facilities should be installed closer to where the waste is generated. Although the costs will be high for modern facilities, they could be established near to major cities where the waste is generated. Another important aspect of the e-waste accumulation is the relatively short period over which electronic equipment, such as washing machines, phones and computers, becomes obsolete [26]. There needs to be a requirement, including mandatory laws, to extend the life of electronic equipment including ensuring that it is fully recycled at the end of its life span. Currently, substantial quantities of e-waste end up in landfill [177]. Hence, landfill is now a source of valuable materials, with increasing scarcity of these materials from other sources. Therefore, there is an economic opportunity to recover marketable materials at local landfill sites as well as to provide quality employment opportunities and reduce the negative impact of e-waste on the environment [178]. In considering the global effort to develop a sustainable circular economy, landfill mining is an important strategy for transitioning from the current unsustainable management of e-waste [179,180]. In summary, stringent environmental policies such as penalties and sanctions in a global context are required to support sustainable management options and sustainable economic opportunities for e-waste in both developed and developing countries.

6. Conclusions

The export of e-waste to developing countries is driven by the need for novel sources of materials and for constant technological advancement. This is currently creating millions of jobs across the globe (the GOOD), contributing to the attainment of some of the 2030 Sustainable Development Goals (SDGs), such as ending poverty in developing countries. Complex human activities, both formal and informal, occur with this "driver" but flaws with management of e-waste are having negative effects on the "state change" of the environment (the BAD) culminating with negative "impacts" on human welfare (the UGLY). The BAD and the UGLY will outweigh the GOOD in the absence of sound management measures, a trend that is inconsistent with the SDGs.

There is an economic hierarchy among e-waste workers which provides the basis for managing e-waste activities in the informal sector especially in Agbogbloshie in Ghana. This study links income and power among e-waste workers in the informal sector hierarchy. Though the hierarchy has not been documented in the other regions, it is probably similar.

Finally, this study highlights that developed countries have the responsibility to share knowledge, transfer technology and invest in the state-of-the-art facilities for developing countries to handle this environmental issue. Furthermore, the application of the concept of a circular economy should be designed for specific environmental problems, rather than just for the application of a theoretical concept. Exporting environmental problems is not an acceptable solution.

Implications and Limitations of the Study

The aim of this study has been to provide evidence for the export of environmental problems from developed to developing countries. The study shows that developed countries are not assuming full responsibility for their environmental problems. This calls for an improvement in existing environmental laws, as well as enforcement of these laws at the international level to curb the further export of environmental problems.

The lack of data from Brazil and Mexico can probably be attributed to the limitations of searching for data only in English and not the languages of these two countries. Additionally, there is also lack of data on LCA for the study regions. Resources should be provided for further research on the LCA of e-waste in these developing countries.

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