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Complexity of E-Waste and its Management Challenges in Developing Countries – A Review

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Abstract

The production of electrical and electronic equipment (EEE) that include computers, mobile phones, modems, printers, refrigerators, and air conditioning units has been growing rapidly stimulated by technological advances, increased product affordability, and short product lifespans. However, this growth has not been matched by recognition of the dangers to health and the environment from disposal of the waste EEE (e-waste) especially in developing countries. Globally, the annual generation of e-waste is in the range 20 - 50 million metric tons, which, following the current trend can increase to over 120 million metric tons by year 2050. This paper reviews the nature, complexity and health and environmental impacts of the e-waste, its global scale, and the alternative technologies for its management. However, the focus is on developing countries, which import disproportionately large quantities of used and obsolete EEE for reuse and recycling but lack effective legislation, skills and infrastructure for management of the waste. As a result, e-waste handlers and recyclers use crude methods for recycling oblivious of the inherent dangers of heavy metals and organic substances in the waste. While the exporting of EEE to developing countries for reuse extends their useful life, informal recycling and final disposal through open dumping, burning and burial poses danger to human health and the environment. Electronic products contain many materials requiring special end-of-life handling; mainly, lead, mercury, arsenic, chromium, cadmium, and plastics that are capable of releasing, dioxins and furans among other compounds. Consequently, successful management of the e-waste in the developing countries will require institution of guiding framework for end of life management such as the extended producer responsibility, and product take back. Ultimately, the key to successful e-waste management is the development of formal recycling facilities. Centralized collection points where economies of scale will attract investment for facilities for dismantling and disassembling of component for recycling and for disposal of toxic components are recommended.

Keywords: E-waste; Developing countries; Recycling; Health; Environment

Introduction

The global market for electrical and electronic equipment (EEE) continues to grow exponentially. The rapid growth growth can be attributed to the fast changes in technology [1,2], changes in the consumption patterns, changes in production media, increasing affordability from falling prices, economic developments, and short product lifespan because of technological innovations [3]. The lifestyle of the society revolves around technology, which is constantly propelled by the need for the latest and most high-tech products. However, the rapid growth in EEE is contributing to mass generation of e-waste [1,4] making it one of the fastest growing hazardous waste stream [5]. About 44.7 and 50 metric tons of e-waste was generated in 2016 and 2018, respectively, while 53 metric tons was anticipated in 2021 at an annual growth rate of 4-5% [6,7]. Moreover, the drastic advancement in technology characterized by changes in components necessitates a dynamic approach in e-waste management [8-10].

Developing countries bear an added burden of e-waste from the purchase of bulk second hand electronic gadgets [11]. Because of the inability of the citizen to purchase brand new gadgets, they are left with little choice than to purchase second hand products with shorter lifespan which soon end up as wastes [12]. Additionally, because developed countries have not been very keen on repairing WEEEs [13], many developing countries have been attracted to import their obsolete gadgets in the name of second hand equipment [14].

Generally, electronic products contain many materials requiring special end-of-life (EoL) handling, the most prominent being lead, mercury, arsenic, chromium, cadmium, and plastics that are capable of releasing, among other compounds, dioxins and furans [15-17]. Unlike for municipal wastes, these components are hazardous and, therefore, require specialized skills in handling, recycling and disposing [3,18,19].

The management of e-waste is governed by many factors that include the associated potential hazards, available recycling technology, and the applicable regulations [6,20,21]. Developed countries have generally devised fairly complex, high-cost systems to handle e-waste, following concerns for environmental conservation [6]. However, in developing countries, dismantling of electronic equipment is usually carried out in the informal sector where hazardous byproducts directly interact with human thereby posing danger to health [21,22].

The impacts of e-waste on the human health and environment in both the short and long term cannot be ignored [23]. In most developing countries with limited infrastructure and resources to handle e-waste, most of the waste ends up in open dump sites where the surrounding population is largely unaware of its dangers [1,21]. Solution to the challenges of e-waste require technical considerations. However, in most cases, legal framework, collection, logistics, and other services need to be implemented before a technical solution can be applied [20,24].

This review paper seeks to provide an overview of the challenges facing the management of e-waste in developing countries. It reviews the composition, variability, generation trends, and the health and environmental risks of e-waste at the global scale and in developing countries. The Paper reviews the challenges experienced by developing countries with the added burden of second hand gadgets with short lifespan, weak or none existence regulatory framework and poor management infrastructure. Finally, the Paper proposes strategies and measures for successful interventions in management of the waste.

Classification of E-waste

The composition of e-waste greatly depends on technical specification factors such as the type of electronic device, models, manufacturer, date of manufacture, and the age of the scrap [22,25]. Thus, e-waste recycling and disposal methods ought to advance with the dynamics of the waste [9,26]. Despite the potentially toxic materials associated with e-waste, it may contains components considered valuables and a resource [21,22]. Thus, a clear understanding of actual composition is essential for the development of environmental conservation, recovery and recycling [27]. Table 1 presents the EU classification of waste electrical and electronic equipment (WEEE).

Figure 1 depicts the typical proportions of the different categories of e-waste.

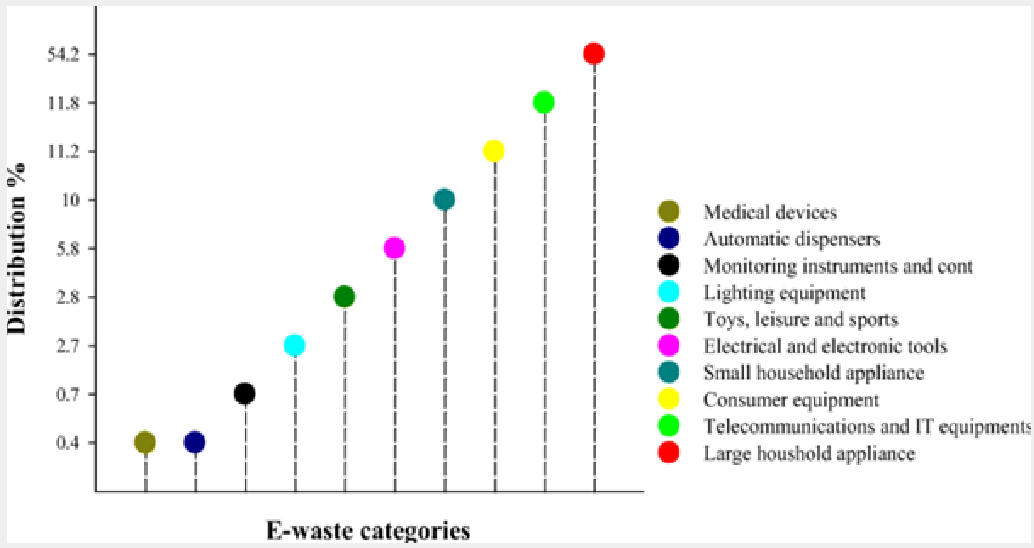

Figure 1: E-waste categories and its contribution at global level [28].

Contaminants in E-waste Components

E-waste contains numerous contaminants that include heavy metals, metalloids, halogenated hydrocarbons, persistent organic compounds and other substances that are of health and environmental concern [29-31]. The heavy metals and metalloids include: arsenic, cadmium, barium cobalt, copper, antimony, indium, lead, beryllium, lithium, chromium VI, mercury, nickel, thallium, tin, rare earth elements (yttrium, euro- pium), zinc sulfide [32,33].

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Table 1: Categories of e-waste according to EU directive on WEEE [12].

No.	Category	Label	Examples
1	Large household appliances	Large HH	Refrigerators, Freezers, washing machines, Dish washing machines, Cooking equipment, Microwaves, Electric heating appliances, etc.
2	Small household appliances	Small HH	Vacuum cleaners, Carpet sweepers, Water dispensers, Toasters, Fryers, etc.
3	IT and telecommunications equipment	ICT	Printers, Personal computers (CPU, mouse, screen and keyboard included), Laptop computer, Networking equipment, Scanners, Mobile phones, Television sets, etc.
4	Consumer Equipment	CE	Equipment for turning, milling, sanding, grinding, sawing, cutting, shearing, drilling, punching, folding, etc.
5	Lighting Equipment	Lighting	Fluorescent tubes, Compact fluorescent lamps, High intensity discharge lamps, etc.
6	Electrical and electronic tools	E&E tools	Drills, electric saws, sewing machines, lawn mowers, large stationary tools, machines
7	Toys, leisure and sports equipment	Toys	Electric trains or car racing sets, Hand-held video game, Video games, Computers for biking, diving, running, rowing, etc.
8	Medical devices	Medical equipment	Scanners, Operating equipment, Radiotherapy equipment, Cardiology, Dialysis, Pulmonary ventilators, etc.
9	Monitoring and control instruments	M&C	Smoke detectors, Heating regulators, Thermostats, Measuring, weighing, or adjusting appliances for household or as laboratory equipment, etc.
10	Automatic dispensers	Dispensers	Automatic dispensers for hot or cold drink, Automatic dispensers for solid products, Automatic dispensers for money etc.

The common practice of e-waste disposal through burning emits variants of polycyclic aromatic hydrocarbons (PAHs) such as benzo [b] fluoranthene, benzo [k] fluoranthene, benzo [a] pyrene, dibenzo [a,h] anthracene, dibenzo [a,l] pyrene, indeno [1,2,3-cd pyrene, etc., polyhalogenated dibenzodio- xins (PHDDs; for instance, polychlorinated dibenzodi- oxins, PCDDs), polyhalogenated dibenzofurans (PHD- Fs) and polychlorinated dibenzofurans, PCDFs), which are known for their toxicity and carcinogenic properties [34]. E-waste also contains some components such as lithium batteries, fire retardants, LCD monitors and chip glass, which are distinct from other forms of wastes and makes it complex and unique [3,35-37]. Similarly, Cathode Ray Tubes (CRT) commonly found in televisions and computer monitors contain toxic substances such as mercury, phosphorous, cadmium, barium and lead, which on improper storage may leak into the surrounding environment [18,37]. Consequently, storage of e-waste containing the CRT should be monitored for possible leakage using sensor mechanisms [19]. In practice, the CRT are fitted with leaded glass meant to provide protection against X-rays produced in the picture projection process [38]. The glass can contain lead in the range 1.6-3.2kg [39], which is potentially harmful on release to the environment [40,41]. The toxicity characteristics of the CRT has led to a ban of its disposal in landfils such as the U.S, Japan, EU states and many other developed nations.

E-waste also comprises plastics and other components, which contain flame retarding substaces in the form of polybrominated diethyl ethers (PBDE) [38,42,43]. The PBDE have no chemical bond with the plastics; therefore, they can easily escape into the environment from the surfaces [44,45]. The lipophilic characteristic of the PBDE can make it bioaccumulate in organisms and undergo bio-magnifications in food chains [46-48]. On the other hand, circuit boards found in most electronic devices may contain arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), and other toxic chemicals [29,49]. Typical printed circuit boards treated with lead solder in electronic devices contain approximately 50g of tin-lead solder per square meter of circuit board [50,51].

Obsolete electronic products such as computers, refrigerators, and air conditioning units contain ozone depleting substances such as chlorofluorocarbons (CFC), halon, carbon tetrachloride (CCl_4), methyl chloroform (CH_3CCl_3), hydrobromofluorocarbons (HBFC), hydrochlorofluorocarbons (HCFC), methyl bromide (CH_3Br) and bromochloromethane (CH_2BrCl) [52]. These substances may escape to the environment from improperly disposed items in dumping sites [3,18,21].

Given the diverse composition of e-waste, its associated environmental impact and ozone depletion potential depends on its composition, duration of exposure; for example, in the dumpsites, and the concentration of contaminants found in the equipment [49,53]. The method of disposal also determines the potential damage to the environment [54]. For example, the concentration of heavy metals such as copper, cadmium, nickel, lead and zinc [55], in the ecosystem are of significance [29,56,57].

On a positive note, e-waste from IT and telecommunication sources contains larger quantities of precious metals than household appliances [39,58]. For example, mobile phones

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contain up to 40 base metal elements including copper and tin; special metals such as lithium (Li) cobalt (Co), indium (In), and antimony (Sb); and precious metals such as silver (Ag), gold (Au), and palladium (Pd) [59-61]. Consequently, to minimize loss of such valuable materials, special attention should be paid in the handling of such waste [21,62]. In effect, the effort put in mining ores for minerals such as gold and palladium can be complemented by strategic recycling of the e-waste (Chancerel, 2009) [39].

Health and Environmental Impacts of E-waste

The impact on health from exposure to chemicals in e-waste especially during recycling is of increasing concern particularly in the era of drastic technological advancements [1,3,22]. Exposure to toxic substances in e-waste can nearly affect every system in the human body [21,55]. Electronic waste materials comprise diverse and complex toxic components such as cadmium, mercury, lead, polybrominated flame retardants, barium, and lithium [49,56]. The toxicity is not limited only to the metals parts but also to the plastic components such as plastic casings and cables made of polyvinyl chloride (PVC) [63,64]. Most e-waste contains persistent bioaccumulative toxins (PBT) that pose health and environmental risks [65]. Human handling of e-waste through various processes of management including incineration, disposal in in non-sanitary landfills or melting down processes are common pathways for exposure to the toxins [9,30,66]. For example, e-waste disposal in non-sanitary landfills can lead to discharge of toxic leachate into groundwater and expose land and aquatic animals to related health risks. The pathway for e-waste ingestion by both domestic and wild animals is either through direct consumption of polluted water or indirect intake through plants [53,67].

Table 2: E-waste components, sources and health impacts.

E-waste Component	Uses in E- Appliances	Adverse Health Effects
Lead	Lead is used in glass panels and gaskets in computer monitors and in solder on printed circuit boards and other components. CRTs can contain up to 1.5-8 pounds of lead	Lead causes damage to the central and peripheral nervous systems, blood systems, kidney and reproductive system in humans. It also affects the endocrine system and impedes brain development among children. Lead tends to accumulate in the environment and has high acute and chronic effects on plants, animals and microorganisms [16,70]
Cadmium	Used on surface mounted chip resistors, infrared detectors and semiconductor chips. It is also very common in nickel-cadmium rechargeable batteries which can contain between 6-18% cadmium	Cadmium can leach into the soil, harming microorganisms and disrupting the soil ecosystem; when inhaled, cadmium can cause severe damage to the lungs and kidney. It can also contribute to low cognitive and learning ability and neuromotor skills in children [16,71,72].
Mercury	Mercury is used in florescent tubes, thermostats, sensors, relays, switches, medical equipment, lamps, mobile phones and in batteries.	Mercury can lead to damage of central nervous system including; sensory impairment, dermatitis, memory loss, and muscle weakness. Environmental effects in animals include death, reduced fertility, and slower growth and development [16,72].
Sulfur	Used in lead acid batteries	Causes damages to vital organs such as liver, kidney and heart and eye and throat irritation; in the environment, it increases the problem of acid rain (Sankahla et al. 2016).
Hexavalent Chromium/ Chromium VI	Chromium VI is used as corrosion protector of untreated and galvanized steel plates and as a decorative or hardener for steel housings.	Can be carcinogenic on inhalation; chromium VI can cause damage to DNA and is extremely toxic in the environment. Long term effects are skin sensitization and kidney damage (Metcalf & Eddy, 2003).
Brominated flame retarders (BFR)	Used as flame retardant in plastic housing in most electronic equipment. Examples include; PBBs, PBDE, DecaBDE, OctaBDE, PentaBDE	Can be persistent in the atmosphere and also bio-accumulative; can lead to impairment of the nervous system, thyroid and liver problems (Sankahla et al., 2016).
Beryllium oxide	Used as a filler in thermal interface materials such as thermal grease and as heat sinks for CPU and power transistors, and in magnetrons, X-ray-transparent ceramic windows, heat transfer fins in vacuum tubes, and in gas lasers	Long exposure is associated with lung cancer. It can also lead to chronic and acute beryllium disease [72].
Polyvinyl chloride (PVC)	Commonly used for insulation on electrical cables	The manufacturing of PVC involves release of toxic and hazardous raw material such as dioxins. Some components of PVC such as chlorine, can be bio accumulative and can cause long term pollution to the air, soil and water, leading to health problems in humans and animals [21,72].
Perfluorooct-anoic acid (PFOA)	Used as an antistatic additive in industrial applications and in electronics and non-stick cookware (PTFE).	Increased maternal PFOA levels is associated with an increased risk of spontaneous abortion (miscarriage) and stillbirth [73]

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Possible landfill leachate leakages can result in groundwater pollution, affecting local aquifers and indirectly entering the food chain [68]. The toxic substances from e-waste are known for adverse effects on human health including birth defects, and damage to the brain, heart, liver, kidney and skeletal system [69]. Furthermore, the toxins can significantly affect the nervous and reproductive systems in the human body [8,23]. Likewise, incineration or burning of e-waste either as a disposal method or for recovery of valuable minerals is associated with emission of fumes, gases and particulate matter into the air [23]. When computer monitors and other electronics are burned, they release carcinogenic dioxins into the air [3]. Such emissions lead to air pollution, which may end up in precipitation and thereby pollute land and water bodies [3]. Table 2 presents the various e-waste components, their source appliances and their health impacts.

The Global Scale of E-waste

E-waste is a global, regional and domestic problem, which is one of the fastest growing waste worldwide [22,23,50]. Its exponential growth relates to multiple factors that includes consumer demand and high obsolescence rate leading to frequent and, in some cases, unnecessary purchase of the EEE [29,74]. The recent surge in e-waste volumes is also attributed to the quick drop of acceptable consumer life span of EEE over the years [22]; for example, from 4 to 2 years as of 2003 [75].

While the global population is nearly 7.9 billion, there are estimated 7.1 billion mobile phones [76]. Currently, the global e-waste generated annually is estimated to be between 20 to 50 million metric tons, which, following the current trend can potentially double to over 120 million tons by 2050 [74]. In 2012 alone, China reportedly generated 11.1 million tons of e-waste while the US generated 10 million tons. The generation translates to an average of 5 and 29.5 kg/capita for China and the U.S, respectively [22,77]. E-waste, in the US, presently constitutes 2-3% of the municipal solid waste stream; it is considered responsible for nearly 70% of the country's toxic waste [78]. The associated dangers of PC waste relate to an average computer screen containing at least two to four kg of lead [79,80]. However, considering newer EoL disposition options that are now available, the general out look of the current situation may need to be reconsidered.

In 2009, discarded TVs, computers, peripherals such as printers, scanners, fax machines, and mouse, keyboards, and cell phones in the US totaled 2.37 million tons [81]. While by 2019, the world generated a staggering 53.6 million metric tons of e-waste, which was 9.2 million metric tons higher than that generated in 2014, the projected generation by 2030 will be 74.7 million metric tons [82]. The global quantity of e-waste in 2019 was mainly comprised of small equipment (17.4 million metric tons), large equipment (13.1 million metric tons), and temperature exchange equipment (10.8 million metric tons) [83]. Screens and monitors, small IT and telecommunication equipment, and lamps represented a smaller share of the e-waste [84]. On average, the total weight of global EEE consumption, excluding photovoltaic panels, increases annually by 2.5 million metric tons. The fate of 82.6% (53.6 million metric tons) of e-waste generated by 2019 was uncertain as it was not formally collected and managed in an environmental sound manner [83]. The global e-waste generation trend is graphically summarized in Figure 2.

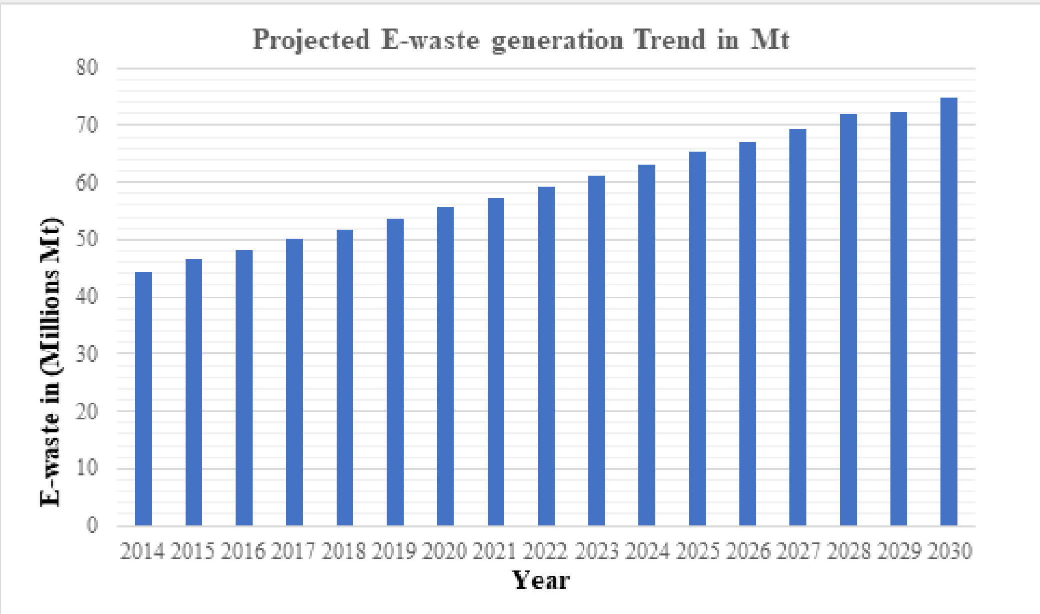

Figure 2: Annual generated and projected Global E-waste [82].

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Out of 20 to 50 million tons of global e-waste generated annually, it is estimated that 75 to 80% is shipped to countries in Asia and Africa for "recycling" and disposal [74]. Loopholes in current e-waste regulations allow for the export of e-waste from developed to developing countries under the guise of "donation" and "recycling" purposes. Although most e-waste challenges are more prevalent in the developing countries that accept shipments of e-waste for processing, toxic waste knows no borders [21]. The more electronics that get discarded, the greater the environmental and health dangers for everyone globally [1,21,22]. An estimated, 50 tons of mercury and 71 kilotons of BFR plastics are found in globally undocumented flows of e-waste annually, which is largely released into the environment and impacts the ecosystem [43,85]. Improper management of e-waste also contributes to global warming [3,86]. By 2019, discarded fridges and air-conditioners that were unmanaged in an environmentally sound manner released an estimate of 98 metric tons CO_2 equivalents into the environment, which was approximately 0.3% of global energy-related emissions [83].

On a positive note, e-waste can be viewed as a resource, as it contains various precious metals potentially available for recycling and use as secondary raw materials in the manufacturing industry [87]. By 2019, the value of raw materials in the global e-waste was estimated to be approximately $57 billion U.SD [21,83]. Cell phones and similar electronic items were estimated to contain large amounts of precious metals such as gold and silver [88,89]. In the U.S, phones dumped annually were estimated to contain over $60 million worth of gold and silver [53]. Harvesting this valuable resource can potentially minimize CO_2 emissions relating to mining of the earth's crust for fresh minerals [6,77]. In many developing countries such as Kenya, Nigeria and Pakistan, imported e-waste has created a growing informal economy through employment along the waste handling and management chain [89].

Challenges in Management of E-waste in Developing Countries

The greatest challenges facing the management of e-waste in developing nations is the lack of legislation and appropriate infrastructure in e-waste management [21]. Most developing countries lack guiding legal frameworks for EEE EoL management [90], product take back, and implementation of extended producer responsibility (EPR) [12]. Furthermore, most of the countries have shown little to no commitment in effective management of e-waste stream [53,91]. Such inaction is partially attributed to inadequate awareness of the potential impacts of the e-waste stream [62], inefficient enforcement by responsible regulatory bodies [92], limited recycling technologies, and inadequate infrastructure for disposal of the waste [12]. For example, most citizens in developing nations are ignorant of the regulations regarding e-waste management, which however, are not enforced [93]. As successful e-waste management must involve all stakeholders, such lack of awareness has hampered the contribution of the citizens in proper management of the waste [83,94]. Moreover, most developing countries have shown more interest in addressing the more basic problem of domestic waste despite the growing toxic impacts associated with special waste streams such as the e-waste [21,22].

Although there have been some efforts in recycling of e-waste, developing nations have faced the challenge of limited technologies, and the tools and equipment required for e-waste recycling [22,53]. Most commonly, recycling efforts are implemented in an informal set up involving dismantling of the electronic gadgets and scavenging for precious components [52,95]. The process involves the use of crude tools and equipment in an open set up where associated toxic fumes that endanger the workers and the environment are emitted [21,94]. The sites are often characterized by open burning to expose the targeted components [53]. The workers also lack safety protection gear and they are exposed to the life threatening toxins [22,54]. Successful handling of e-waste demands the use of highly trained personnel [12], and the use of specialized equipment [18], which, however, are lacking in most developing countries [19].

Although most developing countries are signatories to various international conventions on the safeguarding of the environment, many still lack adequate regulatory framework to deal with e-waste within their respective borders [21,53,96]. Other developing countries have either developed or borrowed policies and legal framework regarding e-waste management, without the policies being contextualized, implemented and practiced [21,93]. In such cases, the policies have been viewed as mere efforts to comply with certain international requirements without commitment to safeguard the environment [23], and protect health [97]. Moreover, the regulatory bodies are always faced with budget constrains curtailing adequate implementation as there are many competing basic needs [21]. Most developing countries have also violated e-gadgets import policies resulting in open borders for bulk second hand electronic gadgets, which soon end up as e-wastes [11]. Such setback is aggravated by citizens' inability to purchase brand new gadgets leaving them with little choice than to purchase second hand products with shorter lifespan [12].

Unlike the developed countries that have well-planned and constructed waste disposal infrastructure and systems, most developing countries lack such facilities [9,11]. While developed world widely use infrastructure such as sanitary landfills and incinerators for disposal of e-waste, the developing countries apply open dumping, open burning, and burial as alternatives [53,98]. As a result, numerous cases of land, water and air pollution characterized by negative environmental and health impacts have been reported [21,53]. Open burning is often associated with toxic emissions to the air damaging the atmosphere and inflicting adverse effects on human health [97,99]. The cost of developing

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efficient containment infrastructure has always been a challenge to most developing countries. Nevertheless, despite the numerous challenges with the management of e-waste, there exists several opportunities such as employment creation, revenue generation and production of bi-products [100].

Techniques of E-waste Management in Developing Countries

Informal recycling

Informal recycling is a common and growing method of e-waste management in developing countries owing to its limited need for technology and infrastructure [1,25,91]. The practice is common in developing countries that have high demand for second-hand electronic equipment and the practice of selling e-waste to informal collectors [101,102]. However, the method is characterized by numerous environmental and health risks that limits its acceptance Deepali et al. (2005).

The informal recycling procedures involves breaking down of electronic equipment to separate reusable components and recovering valuable metals such as plastic, iron, aluminum, copper using crude techniques [103]. Usually, untrained workers carry out risky procedures without personal protective equipment [104]. The manual dismantling of gadgets usually involves using tools such as hammers, chisels, screw drivers and bare hands; removal of components from printed circuit boards by heating over coal-fired grills; stripping of metals in open-pit acid baths to recover gold and other metals chipping; melting plastics; burning cables to recover copper; burning unwanted materials in the open air; and disposing unsalvageable materials in fields and riverbanks [105,106]. Thus, the workers are exposed to harmful substances such as heavy metals, inorganic acid, and polycyclic aromatic hydrocarbons [29,35,99,101].

Unlike other solid wastes, composition of e-waste is diverse and complex with the hazardous components existing even at microscopic levels [9,16]. Harmful e-waste substances at both micro and macro levels can leach into the surrounding soil, water and air and adversely affect human health and the ecology [21,53]. The impacts can be extreme in developing countries where people engaged in informal recycling of e-waste live in proximity to dump sites or landfills of untreated e-waste and work without protection or safeguards [6,95]. Most workers engaged in these recycling operations are the urban poor, who are unaware of the hazards associated with their work (Asha, 2003).

Successful e-waste management by recycling demands transition from informal to formal sector with a well-organized structure employing appropriate technology and adequate safety measures [104,107]. Additionally, it requires formulation and strengthening of policies for improved recycling rates, working conditions, and efficiency [21,108].

Open dumping, open burning and burial

Most developing countries practice open dumping, burning and burial as methods of dealing with their e-waste [53,97]. Often, the waste is disposed as mixed waste together with municipal solid waste posing serious health and environmental risks of toxic leachates and emissions [109]. Open dumping and burning exposes the general public to long term effects of highly toxic e-waste related mixtures (EWMs), through inhalation, contact with soil and dust [66,110], or oral intake of contaminated food and drinking water [53]. The extent of exposure may vary form one developing country to another [21].

Open dumping in developing countries is also characterized by large quantities of e-waste discarded openly along riverbanks [53] where e-waste is manually disassembled, working pieces repaired and marketed and junks burned openly [111]. Villagers living along rivers where piles of e-waste are disposed and burned often use the river water directly for drinking, cooking and washing [112]. Uncontrolled open burning of e-plastics, can generate polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF), which are persistent organic pollutants. These dioxins and furans can enter the body via inhalation, ingestion and skin absorption [105]. Exposure to PCDD/PCDF at elevated levels can lead to chloracne; a severe skin disease, darkening of the skin, and altered liver function [113].

Reuse/Repair

Repair and reuse of EEE involves rectification of a number of faults within the gadgets and returning them to useful service [114,115]. Accordingly, the end of life (EoL) of the product is extended, thereby lowering the rate of disposal as a waste [21,116]. Objectively, a product reuse focuses on extension of the product life [117,118], thus diverting its route from disposal facilities such as landfills [119]. Reuse largely takes the form of repair [54,58] reconditioning and remanufacturing [114]. Although recycling is the most recommended method of e-waste management [120], the decision on the most preferred method of managing WEEE should be guided by the most ecological and economic option available [114,121]. The consumer decision during the use phase of a product whether to repair, pass to a second user or dispose, affect product life spans and subsequently the rate of e-waste generation [53,122].

There is a growing trend in repair of EEE in developing countries. The repair may be viewed as a way of extending theproducts life [123], thereby reducing the quantity of WEEE generated in the short-term [114]. In the the EU and other WEEE regulations, the hierarchy for e-waste loop management considers avoidance [127], re-use of components or parts [25], materials or energy recovery [125], and finally appropriate disposal (Herrmann et al. 2002). While most developed countries have not been very keen on repairing WEEE [13], many developing countries have been attracted to import their obsolete gadgets often dumped to them as second hand equipment [14].

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Repairing/reusing instruments can be a good measure for sustainable waste management because it lowers the manufacturing volume of WEEE thereby reducing the amount of e-waste [2,21]. A large volume of WEEE such as mobile phones has also created an opportunity for repair and reuse, although it is not realized well in many countries [126]. However, changes in product designs, technology, and wireless services often pose difficulties in the repair or upgrade of the equipment [127].

Sustainable E-waste Disposal Methods for Developing Countries

Bioremediation

Bioremediation employs the use of living organisms such as microbes and plants in the removal of contaminants, pollutants, and toxins from soil, water, and other environments with the aim of restoration them to their original form [128-130]. The process is considered an eco-friendly bio-hydrometallurgy technique potentially for mobilization of metals from e-waste [121,132]. Bioremediation microbes include bacteria, fungi consortium organisms, and algae [140,143]. Cynogenic and chemolithotrophic bacteria are some of the most commonly used bacterial agents for the bioleaching process [133,134]. Cynogenic bacteria such as Chromobacterium violaceum, Bacillus megaterium and Pseudomonas sp. can extract the metals by releasing cyanide (Natarajan et al. 2015), whereas chemolithotrophic bacteria such as Acidothiobacllus ferrooxidans, Leptospirillum ferrooxidans release Fe3+ [135], which serves as an oxidizing agent for releasing metals from e-waste into solution [136].

The bioleaching mechanisms involving the use of microorganisms is referred to as a direct method while that involving the use of metabolic compounds is referred to as an indirect method [137,138]. The equations 1 and 2 below summarize the bioleaching by byproducts of iron-sulfur-oxidizing bacteria while equations 3 and 4 summarize biocyanidation bioleaching process.

$$Fe^{2+} + O_2 + 4H^+ \rightarrow e^{3+} + H_2O \qquad (1)$$

$$2Fe^{3+} + Cu \rightarrow 2Fe^{2+} + Cu^{2+} \qquad (2)$$

$$HCN \rightarrow CN^- + H^+ \qquad (3)$$

$$M + CN^- + O_2 + H_2O \rightarrow M\left(CN\right)^2 + H_2O \qquad (4)$$

Bioremediation can improve extraction efficiency where thermal or physicochemical methods are at times less effective [128]. The efficacy of bioremediation is dependent on enzymatic attack on pollutants and quick conversion to harmless products [139,140]. The optimal action of such microorganisms relies on prevailing environmental conditions that permit microbial growth and activity that stimulates degradation process for the target pollutants [128,141]. The microbial resistance and tolerance to the pollutants, particularly heavy metals, is critical to the success of bioremediation processes [142]. The action of the microorganisms can sometimes be affected by the toxicity of the e-waste [89], which can be overcome by a two-step bioleaching process using resistant bacteria [134].

The action process of microbes in handling pollutants such as heavy metals include removal of the toxins from the environment [144], degradation to less toxic forms and transformation to complete benign forms usable in their metabolic processes [145]. Brandl et al. [146], observed effective in-situ bioremediation of aluminum, nickel, zinc and lead from the leachates of electronic scraps by using bacteria-Thiobacillus thiooxidans, T. ferrooxidans and fungi- Aspergillus niger, Penicillium simplicissimum.

Incineration

Incineration utilizes controlled complete combustion process to burn the waste material in a specially designed incinerators at temperatures in the range 900-1000ºC [147]. Incineration presents a faster and easier method to separate and recycle metals while the gases and liquids formed from the process may provide required energy to self-sustain the process thus reducing external energy requirements [2,148]. The process of incineration also results in conversion of some environmentally hazardous organic substances into less hazardous compounds [21,89,147].

Unfortunately, e-waste incineration plants can contribute significantly to the annual emissions of toxic substances such as cadmium and mercury (Sharma et al. 2012). Combustion at high temperature, above 1200ºC, is usually associated with reduction of CO formation and removal of maximum PBDD/F in the forms of HBr or Br_2, which can significantly lower toxicity [149,150]. However, such high temperatures favor formation of NOx above the standard emission level of 500mg/Nm^3 [151].

Where combustion is carried out at low temperature in the 600-800ºC range, copper can act as a catalyst leading to emission of highly toxic substances such as polybrominated dibenzo-dioxins (PBDD), polybrominated dibenzo-furans (PBDF), polychlorinated dibenzo-dioxins (PCDD), polychlorinated dibenzofurans (PCDF), fly ash, carbon oxides, hydrogen bromide, methane, ethylene, benzene, toluene, phenol, benzofuran, styrene, PAH and bromophenols [152,153]. Solid residues of incineration referred to as "bottom ash" usually comprise higher levels of heavy metals such as Cu, Pb, and Cd which can further complicate their safe disposal [154].

Studies suggest that pollutants such as mercury, benzene, toluene, ethylbenzene, and xylenes can be removed through iron oxide nanoparticles adsorbents [155,156] but their inclusion in pyrolysis and other recycling processes is yet to be seen. National research Council [147] presented a typical waste incineration process that also suits e-waste as illustrated in Figure 3.

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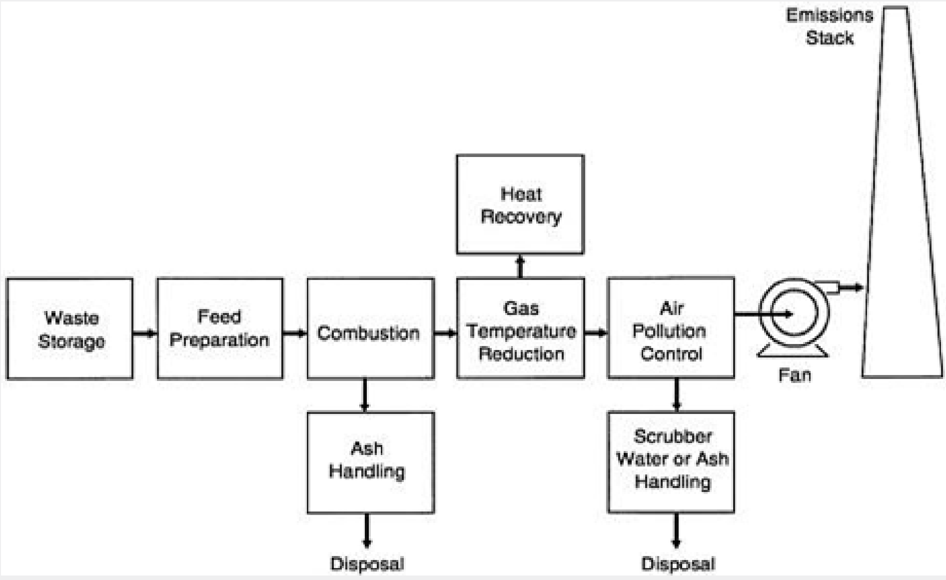

Figure 3: Typical waste-incineration facility schematic [147].

Landfilling

Landfilling is one of the most popular methods for e-waste disposal in the world [6]. The technology involves placing of the waste in excavated ground and covering by a thick layer of soil. Modern techniques such secure landfill are provided with layers of impervious liners made up of plastic materials or geo-synthetic clay that collect leachate for treatment [157].

The degradation processes of e-waste in landfills are very complicated and run over a wide time span [158]. The largest concentration of lead in leachate comes from the CRT funnel at an average of 75.3mg/L [159]. Another source of lead is the lead-bearing solder on wiring boards [160]. Crushed e-waste in Japan landfills have reported high concentrations of lead [161,162]. Ferronato & Torretta [53] found landfill sites contribute considerable toxic contamination attributed to medium and long-term leakage of cadmium and mercury into the soil. These metals are often emitted through diffusion or combustion of landfill gas [21,71]. Cadmium from one mobile phone battery can pollute over 600m^3 of water [163].

The environmental risks from landfilling of e-waste are exacerbated by the presence of organic acids from anaerobic digestion of other wastes that increase leaching of metals [157]. The environmental concerns around landfilling for e-waste indicates its unsuitability for treatment of volatile and biologically non-biodegradable components such as Cd, Hg, CFC and persistent polychlorobiphenyls (PCB). Although e-waste represents less than 2% of landfill mass, it contributes over 70% of the hazardous heavy metals [164].

Formal recycling

Recycling is the preferable method of e-waste management. The technique involves dismantling of the electronic equipment and recovery of various components [35,165]. Recycling of WEEE can broadly be divided into three major steps; namely:

a) Disassembly involving dismantling and careful sorting, targeting on singling out hazardous or valuable components,

b) Upgrading using mechanical/physical processing,

c) Mechanical processing to upgrade and refine desirable materials targeting return of recovered materials to their life cycle [165,166].

Some of the e-waste components considered as recyclable include PCB, plastic, CRT, ferrous and non-ferrous metals, keyboards, laptops, modems, telephone boards, hard drives, mobiles phones, fax machines, printers, CPUs, memory chips, connecting wires and cables [70]. However, electronic devices contain up to 60 different elements with a mixed combination of valuable and hazardous components [35]. Therefore, the process of recycling must take care of the variability of the waste, and thus consider categorization of the waste for efficient process. Figure 4 represents a recommended categorization of WEEE (He et al. 2006).

The fraction of e-waste that is considered valuable for retrieval include gold and silver, which are of great economic value [58]. These precious metals are rare, though naturally occurring, highly ductile and possess high melting point [58,167]. Other retrievable special metals include nickel and its alloys, cobalt based alloys,

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and titanium and its base alloys [168]. A single personal computer can contain significant recoverable value from gold plated connectors, components, pins and transistors [103]. Thus, there is a justification of recovery of metals and valuable elements from e-waste [64].

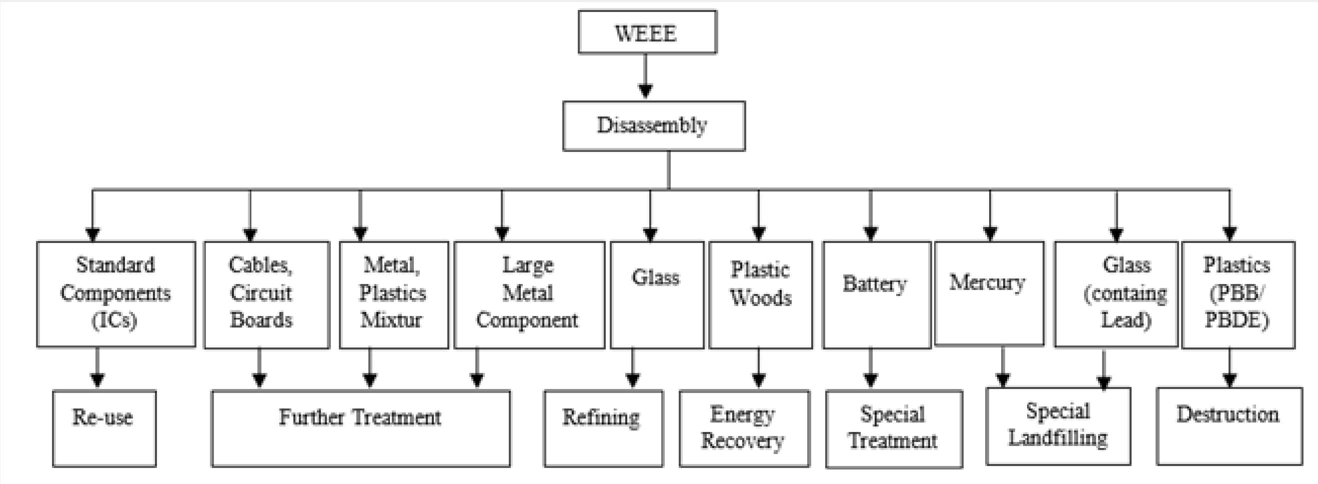

Figure 4: Recycling process developed by Ragn-Sells Elektronikatervinning AB (He et al. 2006).

Recycling of electronics can reduce the environmental impact associated with primary production of the metals [54] including energy intensive stages such as mining and smelting that significantly contribute to emissions of greenhouses gasses [58].

Positively, there has been calls advocating the upgrade of skills and technique for e-waste recycling (Maes & Preston–Whyte, 2022) to minimize associated hazards [1]. Formal recycling of e-wastes demands various facilities and proper licensing to support risk assessment and establish industry specific guidelines including permissible workplace emission levels and occupational exposure limits [21]. The extent of exposure for workers and the environment varies depending on the recycling set up, the safety protection and the technology applied [169]. Some of the primary risk associated with dismantling stage includes accidental releases and spillages of hazardous substances [105].

E-waste recycling process is associated with secondary emission of organic pollutants such PAH, PCB, brominated flame retardants (BFRs) such as PBDs, and polychlorinated dibenzo-p-dioxin/ furans (PCDD/F), which can be formed during crude thermal processes of e-waste recycling [53,170]. Weathering of organic contaminants is also likely to result in the formation of metabolites that could potentially be more toxic than their parent specific guidelines including permissible workplace emission levels and occupational exposure limits [21]. The extent of exposure for workers and the environment varies depending on the recycling set up, the safety protection and the technology applied [169]. Some of the primary risk associated with dismantling stage includes accidental releases and spillages of hazardous substances [105].

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The recommended e-waste recycling chain consists of five main activities; namely: collection, evaluation, dismantling separation and recovery (Figure 5). The recycling chain often yields separate components or fractions of materials that can re-enter the market for reuse and/or as a feedstock for other processes. [22,76,172-175].

Recommendations for Management of E-waste in Developing Countries

Success in e-waste management in developing countries calls for enactment and enforcement of laws relating to procurement and disposal of EEE with a focus on capturing the emerging environmental and safety concerns. Stringent procurement and

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disposal laws can control the import e-waste and ease the burden of e-waste stocks piling in public institutions. Strengthening the legal framework is an important step towards successful e-waste management by overseeing and tracking the waste throughout the entire chain from the generation/source to the final disposal. The legal framework needs to provide for an extended producer responsibility that ensures the financing of collection and recycling of the waste. The framework should further create favorable investment conditions for investors by prompting experienced recyclers and investing in appropriate technology. As such, the common informal collection centers must be upgraded and formally recognized as part of the waste management chain and a feeder to the subsequent recycling and disposal route.

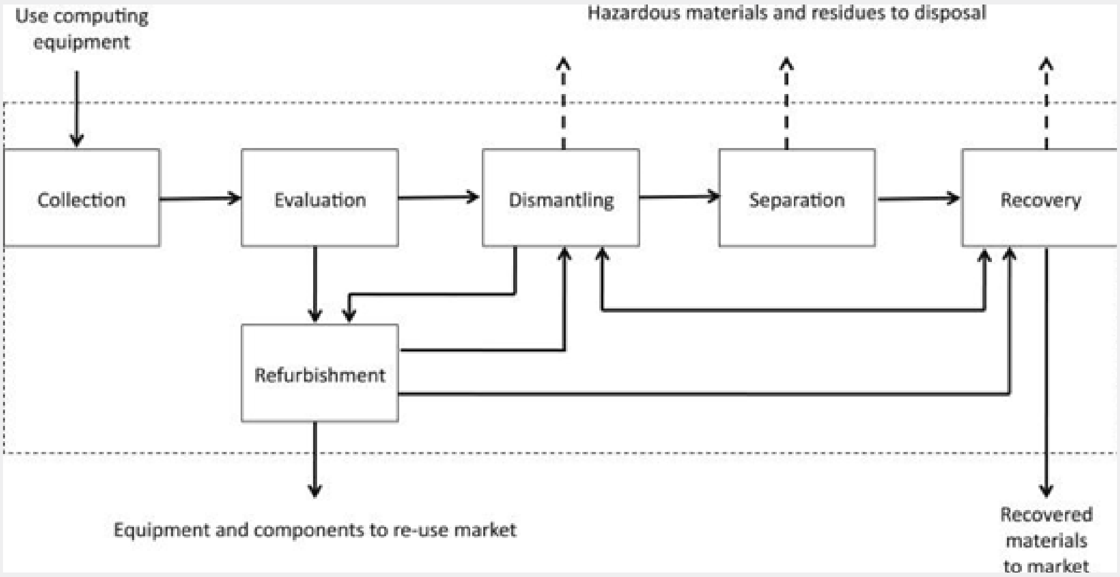

Figure 5: Desired flow diagram for e-waste within a recycling facility [22].

Sensitization and citizen education on their role in successful e-waste management can be a central step towards e-waste management. Notably, most developing countries are characterized by low citizen awareness on the hazards of e-waste and its negative impact on the environment. Mitigating this challenge, and achieving an effective e-waste management, calls for a deliberate sensitization effort. For example, the citizens should be cultured to avoid indiscriminate disposal of e-waste with municipal solid waste. They should also avoid open burning of such waste material. Similar campaigns have had great impact in improving the handling domestic waste and disposal in many countries. The education sector also needs to incorporate e-waste management in their system through early sensitization.

There is need to mount up campaigns promoting re-use and recycling of e-waste as a way of minimizing the waste volumes destined for already overstretched disposal infrastructures. It can also reduce the required size of new ones and thereby make them more affordable. A well-managed infrastructure can in turn reduce the environmental and health impacts that would otherwise occur while dealing with large waste volumes in large management plants. Additionally, re-use and recycling of valuable materials within e-waste can promote a circular economy through secondary material use.

In considering that most developing countries do not have effective recycling facilities for e-waste, an effective e-waste management strategy should consider a centralized collection point where e-waste can be dismantled/disassembled for component reuse and disposal of toxic components at designated sites. The centralized collection point should warehouse the e-waste until appropriate EoL management issues are resolved. The likely buildup of stockpiles of e-waste will be a prerequisite for economies of scale for e-waste recycling as the large volumes can attract investment in recycling plants. The collected items can also be exported as recyclable material to foreign facilities, business affiliates and/or to third party recyclers. Interest in large volumes of waste can also attract investments in landfilling and incineration for final disposal of final waste at the end of the chain. The investment in recycle and disposal technologies will alleviate dangers associated with crude methods of disposal.

To avert adverse health impacts of e-waste on handlers, developing countries must train the local manpower to ensure adequate reverse flow of components/modules and establish frameworks and the necessary logistics for the take-back of EEE and components for reuse and recycling. An effort to create a ready market for disassembled components either locally or in other countries will create stability in the sector or ensure continuity

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within the waste management chain. As a way of managing the known hazardous components of e-waste, development of a state-of-art incineration and landfill facilities is critical for handling sensitive disassembled components. Ultimately, development of formal recycling facilities holds the key to successful e-waste management.

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