Journal of Global Information Management
Volume 32 • Issue 1

E-Waste:
A Global Problem, Its Impacts, and Solutions

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ABSTRACT

E-waste is a major global problem linked to the use, and discard of, electronic and electric devices. While the volume of these obsolete devices continues to increase and accumulate, the means and approaches currently used to reuse, dispose of, recycle, and address this continues to vary widely in terms of availability, effectiveness, and value. The issues relating to e-waste management include those emanating from managerial, environmental, labor, and health perspectives. This article aims to present an overview of the key considerations related to the e-waste dilemma, and also proposes issues, challenges, and solutions to addressing the problem. A focus on the factors and variables affecting e-waste management, together with a global framework of e-waste management methods and strategies, are then followed by recommendations and viable areas for future research.

KEYWORDS

cultural differences, electrical and electronic equipment, e-waste, environmental impacts, global regulations, impacts of technology, recycling, resource recovery, sustainability, waste management

INTRODUCTION

The growth of computer and electronic technology use has been linked to increased productivity, the growth of global business, and a positive impact in terms of how we work and live our lives. In addition, the increasing pace of new developments as they relate to technology enhancements has been dramatic, as well as the availability and accessibility of these to many sectors of the population. Unlike the earlier models of computing, where an organization would share the use of a mainframe computer, the prevalence of computing power and technology on desktops through distributed networked systems have truly increased our capabilities and global reach (Srivastav et al., 2023).

One of the results of this astronomical growth in technology (and electrical device) use, especially for desktops, laptops, tablets, mobile phones, and personal (PC) computers is the fact that these abandoned, used, and obsolete items have created an enormous problem with e-waste. Whether it be

DOI: 10.4018/JGIM.337134
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computing, networking, or other communications equipment, the problem of e-waste disposal has become a critical issue and one that is global in scope (Srivastav et al., 2023).

Combined with this are the types of waste which come from obsolete electrical devices appliances (refrigerators, microwaves, washing machines, etc.), medical equipment, industrial devices, and household small electronics. It could be said that within the broader category of "e-waste" electronic and electrical items have been discarded because they are obsolete, no longer work, are an outdated model, or are unrepairable (Srivastav et al., 2023)

While the basic underlying concept of e-waste management is straightforward, in that it is concerned with how e-waste is collected, processed, and then recycled and disposed of, the myriad of issues which results from this can be complex - involving technical, scientific, legal, regulatory, environmental, health, and societal issues.

The purpose of this paper is to examine and analyze the critical issues which relate to the management of e-waste, from which a framework or structure for research is proposed based on a global perspective.

In short, given the extensive and growing use of electronic technologies and electric devices, this is a critical area to examine, both in relation to the volume, and scope of the e-waste generated, and the different issues and considerations which come into play.

DEFINITION AND ORIGINS OF THE PROBLEM

E-waste, also known more technically as WEEE (Waste Electrical and Electronic Equipment) or EEE (electrical and electronic equipment) for short, can be defined as "any discarded product that has a battery and/or plug, contains hazardous substances, and can pose a severe risk to human health and the environment (Forti et al., 2020). Another definition states that "e-waste encompasses a broad and growing range of electronic devices ranging from large household devices and consumer electronics to computers and devices which have been discarded by their users" (Shahabuddin et al., 2022; Puckett et al., 2002). Simply put, it is waste that emanates from discarded, used, and otherwise unwanted electronic and electrical devices. There are a wide range of items which can fit into this category, and a rough categorization can be made using the categories ICT (Information and Communications Technologies) and computer equipment and hardware, household appliances, consumer equipment, and electronic accessories/components. Examples of these kinds of devices are found in Table 1.

While the problem of e-waste may not receive as much attention as other issues such as climate change and global warming, for instance, the impacts of the increasing amount of e-waste generated has far-reaching and profound implications regarding health, environmental impacts, and the economies of many countries in the world. Part of the problem is that while there is an increasing number of users of electronic and electrical devices, together with advances in technology leading to upgrades and enhancements, at the same time there is wide variance worldwide in terms of proper and effective management and disposal strategies and policies, and there does not appear to be a clear and consistent global strategy for managing this problem. According to Forti (2020), 53.6 metric tons of e-waste were generated worldwide in 2019, and the amount is expected to increase to 74 metric tons (or 38%) by the year 2030. Roughly one third of this is generated in Asia, the second third about equally divided between Europe and North America, and the last third comprising the rest of the world. To provide some perspective as to the scope of the problem and how various parts of the world contribute, North America contributes per year approximately 13.3 kg of e-waste per person, while in Europe the average is roughly 16.2 kg or e-waste per person (Forti et al., 2020; Hinchcliffe et al., 2020). In general, it could be noted that while North and South America generate a moderate to high amount of e-waste, a small amount is properly recycled, and while Asia generates roughly twice as much, it recycles roughly the same % as in the Americas. Europe stands out as generating a-moderate amount but recycling a large proportion of what is created may account for the greater per capita e-waste. Other regions of the world generate smaller amounts, but also recycle only a

Table 1. E-waste device categories

Category	Device/Appliance
Computer	PC (laptop, desktop) Printer Monitor Mouse and peripherals Keyboard Scanner
Networking / Office	Copier Modem Router Fax machine
Mobile phones and related devices	Cell phone Telephone
Household appliances	Refrigerator Washing Machine Air conditioner Water heater
Home electronics	Television
Other	Medical equipment/devices Industrial equipment/devices Toys, leisure and sports equipment

small portion of it. Given the large amounts of-waste generated annually, roughly 70-80% of this is shipped from developed nations to lower-income ones, which then is recycled there "informally" using various means, often improper and unsafe, or alternately, dumped into landfills (Shahabuddin et al., 2022; Gollakota et al., 2020; Pascale, et al., 2018; Balde et al., 2017). See Table 2 for a breakdown of e-waste generation and recycling.

Unlike other forms of garbage and waste, whether it be household garbage, paper, or cans/bottles, e-waste is comprised of multiple elements, often embedded within each other, which may include various metals, plastic, glass, and other liquid and solid materials. Layered within the outer casings of these devices can be toxic chemicals and substances, which can be released when recycled or disposed of. Therefore, the task of disposal and recycling is a complicated, time-consuming, and potentially hazardous task (Rautela et al., 2021). Additionally, because of the potential health and environmental problems caused by -e-waste processing and disposal, it is typically done in countries and regions far removed from where they were originally used, including China, India, Pakistan, as well as other

Table 2. E-waste generation in 2019

Region	E-waste Generated (Total Volume in Mega Tonnes (MT))	E-waste Generated (Per Person)	E-waste Recycled (Volume/% of Total in Mega Tonnes (MT)
North and South America	13.1 Mt	13.3 kg	1.2 Mt (9.4%)
Europe	12.0 Mt	16.2 kg	5.1 Mt (42.5%)
Africa	2.9 Mt	2.5 kg	0.03 Mt (0.9%)
Asia	24.9 Mt	5.6 kg	2.9 Mt (11.7%)
Oceania	0.7 Mt	16.1 kg	0.06 (8.8%)

Source: Forti et al., 2020

areas of Asia and Africa. The approaches to handling and processing e-waste in these countries can pose many problems, including the impact of toxic processing and disposal sites contaminating the water, air, soil, in that area and the surrounding regions. The people working on e-waste are often subjected to health hazards, inadequate protection, and unsafe working conditions (Rautela et al., 2021).

Other related issues include the transport, storage, and harmful effects on anyone coming into direct, or even indirect contact with e-waste. There are also policy and government-related issues in the countries which generate and in many cases export e-waste, and also in those countries that process these obsolete or unwanted electronic devices.

Because this is such a broad topic, encompassing a broad range of issues and considerations, the focus of this paper will be on defining and explaining in detail the problem of e-waste, discussing the various impacts of the problem, and presenting several solutions which have been proposed, suggested, and implemented. From here, a research framework is presented examining the components underlying e-waste research, and also viable areas for future research in this area.

IMPACTS OF THE PROBLEM

The impacts of the e-waste problem are numerous and complex, and currently there are multiple perspectives from which to evaluate them.

Many countries and regions in the world do not have clear and effective legislation, laws, regulations, or guidelines to direct how e-waste is handled. Instead, in many cases the management of e-waste is performed in an ad-hoc manner, delegated to local authorities, or implemented using unregulated and unsafe informal methods (Rautela et al., 2021)

As mentioned, before processing and recycling can even start, often there is the need to transport this waste to countries which can process it, most of which are located in Asia, Africa, or South America. Of the over 50 metric tons of e-waste which was generated in 2019, roughly 10% crossed country borders to be processed, and of this only 35% was managed in a controlled, regulated manner. While there are a wide variety of hazards associated with e-waste and the potentially dangerous materials contained within them (lithium ion batteries, for example), risks occur especially when being stored and transported within confined spaces, such as ship containers, for example (Balde et al., 2022; Rautela et al., 2021; Fiore et al., 2019; Elia, 2018). There are also risks to the personnel handling e-waste products, such as the case of transformers which can expose workers to toxic levels of PBCs due to a leak in transformer oils during transport (Naik et al., 2022; Balde et al., 2022; Budnik et al., 2014).

In fact, there are regulations on the export of e-waste from developed nations to low-income countries, in particular the Basel Convention on the Control of Transboundary Movement of Wastes and their Disposal (2001). However, a number of countries, including the United States, did not ratify the convention, and hence were not obligated to follow its rules and guidelines, and continue to export waste in whatever manner they saw fit.

Moreover, a common way to get around proper recycling methods, is to designate certain e-waste as “functional second-hand/not for recycling”, making it exempt from the regulations. However, in the end the e-waste itself must still be disposed of or processed, and so it doesn’t alleviate the problem, but only temporarily masks it from scrutiny, and in many cases ends up in the same place and is managed the same was as those not so designated.

The process of recycling e-waste is different from other kinds of waste, since there are many toxic chemicals and substances which can be found in electronic and electric devices. In order to safely recycle these, any toxic chemicals and substances need to be separated from its surrounding and protective materials, then removed and discarded, while any useful material (metals, plastics) and valuable elements (rare earth elements) should be retained for further recovery processing (Xavier et al., 2023). Ideally, here should be guidelines and safeguards in place to control and prevent exposure to these toxins, but often especially in informal recycling firms and settings, these safeguards are overlooked and not implemented whether for expediency, or to reduce costs (Lin et al., 2022; Rautela, et al., 2021). Please see Table 3 for an illustration of the various e-waste components of a computer and its peripherals, and both the processing and hazards which arise as a result of its recycling (Wath, Dutt, & Chakrabarti, 2011).

The list of chemicals and toxins which are found in electronic and electrical devices are extensive and pose a significant hazard to those who work with e-waste without adequate protection. Some of the most hazardous to health include both inorganic (mercury, lead, cadmium, etc.) and organic chemicals (PVC, PCBs). While some of these normally do not pose any risk enclosed within the designed devices and used in normal ways, after they are discarded and recycled, they can be toxic once removed and exposed. Here is where the hazard occurs, since without proper precautions, workers engaged in recycling can be exposed to these kinds of substances (Lin et al., 2022). The most common hazardous components of e-waste are listed in Table 4.

Whether because of age, upgrades, or because the devices no longer work, obsolete technological and electrical devices pose a major problem in terms of collection, transport and disposal/recycling. As in the case of appliances such as refrigerators and air conditioners, the presence of environmentally

Table 3. E-waste processing: A computer and its components/peripherals

e-Waste Source	e-Waste Component	Processing/Recycling	Potential Hazards and Exposure
Laptop or Desktop Computer	Circuit Boards	Remove computer chips (de-soldering), burning and/or acid baths	Air pollution, also cadmium, mercury, beryllium
Memory and other computer chips	Computer chips (on circuit board)	Chemical stripping using acid, burning	Lead, tin
Computer Monitor/screen	CRT (cathode ray tube) Flat screen monitors (prior to 2009)	Break/remove yoke, dumped/landfilled	Air and water pollution: Lead, Barium, Mercury
Cables and wiring	Computer wires	Burning and stripping	Air, water, and soil pollution
System case, keyboards, monitors, printers	Plastic components	Shredding, melting	Air pollution

Table 4. Selected list of hazardous substances found in e-waste

Hazardous Substance	Found in Components	Means of exposure	Health Impacts and Effects
Lead (Pb)	Circuit boards Glass panels	Air, water, soil	Blood, nervous systems, kidneys Child brain development
Mercury (Hg)	Circuit boards Switches and relays CRT monitors	Air, water, soil	Brain, skin, respiratory, heart, liver, kidney Children’s development
Cadmium (Cd)	Semiconductors Batteries	Air, water, soil	Liver, kidney, neurological damage, bone disease, lung cancer
Barium (Ba)	CRT components	Air, water	Muscle, heart, blood pressure, liver.
Beryllium (Be)	Motherboards	Air, water	Lung (Pneumonia), skin
BFR Brominated flame retardants	Electronic equipment housings Circuit boards	Air, water, soil	Thyroid, nervous system
PVC Polyvinyl chloride	Cabling Computer unit housings	Air, water, soil	Immune system.
PCBs Polychlorinated biphenyls	Batteries	Air, water, soil	Cancer, immune system, nervous system, female reproduction.
Hexavalent Chromium (Chromium VI)	Computer unit housing components	Air, water, soil	Cancer, respiratory, female reproduction.

unsafe and potentially hazardous chemicals and toxins (such as freon) makes the process difficult (Lin et al., 2022).

Many countries around the world participate in one or more steps of the e-waste process whether as producer, consumer, or disposer. Designers of electronic items are generally located in more developed regions (North America, Europe), but outsource their manufacturing to Asia, including China, India, as well as other developing and third world countries. Consumers include those in a wide variety of nations, with volumes varying by region and country. Disposers are found mainly in developing and third world countries including those in Asia and Africa. For instance, the United States is a major consumer and designer, of electronic items. While there are a number of US tech firms which manufacture these kinds of devices, much of the manufacturing and production is done overseas, a substantial portion is exported to other countries for recycling or disposal. China, on the other hand, can lay claim to the fact that it is a major consumer and producer of electronic devices and is also involved with e-waste disposal and recycling (Murthy & Ramakrisha, 2022).

SOLUTIONS TO THE PROBLEM (BENEFITS AND OPPORTUNITIES)

As discussed in previous sections, there are a number of impacts and consequences due to the volume of, and continuing increases in, e-waste generation throughout the world. The goal of this section is to examine the current and proposed solutions to the problem, with regards to proper management, collection, followed by recycling, and disposal of e-waste.

Improved and Evolving Management Practices. There can be management and production-oriented practices which can help to reduce the generation of e-waste, encourage effective re-use, and manage properly the task of collection and proper recycling.

By effectively managing inventory levels both before and during the production process, it may be possible to reduce waste and eliminate the need to store and dispose of excessive raw materials used in the production of electronic and electric devices. This can be accomplished by improved efficiency when ordering material, and ensuring that only the quantity needed is maintained by using an inventory control system (Singh, Chauhan, & Sarkar, 2022; Chowdury & Patel, 2017; Rao, 2014)

There may be ways to enhance the production process, through a review of policies and procedures, making efforts to reduce waste due to accidents, spillage, or equipment failures. Another option is to consider replacing non-degradable components with more environmentally-friendly substitutes, such as paper-based materials when manufacturing printed circuit boards (Sudheshwar et al., 2023). Other methods include ensuring that less, rather than more, toxic chemicals are used; separating the toxic from the non-toxic waste streams during processing and recycling; and the reuse of recycled materials in the production of new product unit components (Pan, Wong & Li, 2022; Chowdhury & Patel, 2017; Rao, 2014).

Finally, there are solutions inherent in the product design process. Products and devices can be designed to use more renewable, and fewer hazardous materials. First, effective design may seek to minimize the requirements for and quantities of hazardous materials. Materials and energy from more natural sources may also prove to be possible, as well as greater emphasis on repair and re-use. Currently, in the case of computers, for example, there is a market for refurbished devices, which offer performance but at a lower price than new items (Shields, 2019; Bakhiyi et al., 2018; Jing, Jia, and Bo, 2021; Rao, 2014).

Attention to design, particularly to encourage longer usage lives, is also an important aspect to consider, since electronic products can become obsolete due to technical obsolescence (less performance since the product lacks the latest features) or economic obsolescence (newer models offer more at a lower price). The increased growth in technological advances therefore contribute to more e-waste being generated (Shittu, Williams, & Shaw, 2021). There are also regulations which have been introduced in various countries which cite guidelines for placing electronic items back into use, whether directly, or after repair, refurbishing, repurposing, or remanufacturing (Anandh et al., 2021).

Reverse Supply Chain. While there is overall familiarity with the concept of the supply chain, which describes the processes beginning with raw materials and producing them as marketable products, another concept has been discussed in relation to e-waste. This is the reverse supply chain, which looks at the process from product acquisition to inspection/disposition, to disposal or refurbishment and re-distribution of obsolete items. There are many aspects which come into play for a reverse supply chain, and this is the subject of valuable research relating to e-waste (Doan et al., 2019; Deng, 2022)

One area which appears to be lacking in many nations is an awareness and attention to the problems of, and proper solutions for alleviating, the challenges posed by e-waste. There are countries which implemented awareness campaigns, and which have led to calls for citizens to cooperate and do their part to recycle obsolete devices in the proper way, and for producers and local municipalities to institute programs to manage this problem. This has been more successful in some countries than others. Often, there is a need for regulations and laws to be instituted to support the request for cooperation, as well as funds allocated to initiate the program, such as paying for collection services to pick up e-waste devices, such as which is done for household recycling (Sipka et al., 2021; Shields, 2019).

On the part of producers, the concept of EPR (Extended Producer Responsibility) provides a proactive means for receiving back obsolete devices for recycling and processing, which are sometimes referred to as "Take Back Programs." Other variations include the ability for consumers to return used devices through their retailers, drop them off to producer-arranged locations, and the like; and in some countries a fee is paid by the consumer at the time of purchase to help cover the costs of recycling and disposal (Halim & Suharyanti, 2019). Because some countries have little in the way of awareness campaigns or organized programs, few means are available for effectively managing the e-waste being generated. In these cases, old devices are stored until some means of disposal becomes available, or alternately, sold to "waste collectors" who go around collecting these in the community (LeClerc & Badani, 2021).

E-Waste Generation and Disposal Reporting. One area which deserves additional attention is the effective and consistent reporting on the types and amounts of e-waste that is generated, recycled, and disposed of. Since there are no established guidelines for this, the varying measures and approaches often result in underestimation or misreporting (Shittu, Williams, & Shaw, 2021).

Waste disposal and collection. Another important aspect of the solution to the e-waste problem is to examine the methods of waste disposal and collection. After an electronic or electric device reached the end of its useful life, no longer works properly, cannot be repaired, or for some other reason is no longer needed and desired, the important consideration is what to do with this unwanted device.

This can be a more involved issue than it appears, and can vary by country, culture, awareness, or because of policies which have been instituted and promoted in the past or currently. In some countries including those in Europe and North America, these devices are regarded more as "waste" and the primary question is how to get rid of them (Veenstra et al., 2010). In other nations, including China and others in Asia, many consider these obsolete or used devices to have value, and the goal is to get the most value out of the resource (Hicks et al., 2005). In fact, attitudes towards fees can be related to the mindset of a particular nation, region, or community. For some, in nations where e-waste is thought of as having of little value, there may be a willingness to pay a fee for disposal, or to personally deliver the devices to a collection site. On the other hand, where they are considered to have some value, users will not part with them unless they are paid a disposal fee (Veenstra et al., 2010; Hicks et al., 2005).

Awareness is a positive factor, since if there are policies or campaigns in place which have been instituted to collect e-waste, citizens are more likely to follow the prescribed procedures for collection and recycling. In some countries, the recycling of cans, bottles, and paper may be a good precedent and example, from which to bring about an e-waste collection program. Switzerland is a country where there is not only an organized and established program in place which is promoted and made aware to citizens (Baxter & Gram-Hassan, 2016). On the other hand, there are nations where there is little awareness or attention given to policies and procedures regarding e-waste, and therefore the actions taken are largely ad-hoc, informal, or non-existent (Mozo-Reyes et al., 2016).

Producer versus Consumer Responsibility. As mentioned earlier, EPR (Extended Producer Responsibility), is where producers of electric and electronic devices take on the responsibility for reducing the impacts of e-waste while at the same time endeavoring to promote the profitability of the firms participating and involved in the initiative. The goal is first to enhance and promote the usage and lifespan of products either through repairing non-operating devices, and/or re-use them in another capacity. Where this cannot be accomplished, the next option would be to disassemble the devices and re-use the components in some other capacity, or for production of new devices. Finally, in the case where none of these options are possible, the goal should be to dispose of the devices (LeClerc & Badami, 2021; Khan et al., 2014; Afroz et al., 2013.)

This contrasts with what is known as ECR (Extended Consumer Responsibility) where accountability for the management of e-waste rests with consumers, rather than producers. Under ECR, consumers are encouraged to turn in their devices and "reuse and recycle" (Masud et al., 2022; Lepawski, 2012; Kang & Schoenung, 2006).

It should be mentioned that one approach to e-waste, is the "out of sight, out of mind" approach where consumers simply put their unused devices in storage and in effect, forget about them. This is often done as a matter of convenience, and also when it is perceived that – they have some inherent value and should be saved for "sale" to the highest bidder (Sengupta et al., 2022; Andeobu et al., 2021a).

Government and local policies and legislation. Another solution can come from global organizations, individual governments, and state/regional and local authorities, instituting recommendations, policies, laws, and regulations which are centered upon the effective management of e-waste. Because this is a global problem and one which spans multiple continents, nations, and regions, the solution is complex and varies widely from one area or country to another. The range of policies and laws is large and involved and requires a detailed study to provide a fair and complete review.

One of the broadest sets of recommendations concerning e-waste is the Basel Convention, an international United Nations treaty designed to regulate the transport of hazardous waste between nations and reduce the export of e-waste from developed to less developed countries. The notion of "hazardous waste" is extended to e-waste and therefore is one of the more important global regulations that cover e-waste transport and export. It was signed in 1989, and took effect in 1992, and is overseen by the consumer watchdog group, the Basel Action Network (BAN). (UNEP, 2011). Other important policies include the WEEE Directive and the RoHS Directive developed by the European Union, the Bamako Convention, and legislation created to address e-waste in China, India, Japan (Home Appliance Recycling Law), and South Korea's Waste Management Act (Shittu, Williams, & Shaw, 2021).

There can be local laws and regulations which require that e-waste devices be disposed of or collected in a certain manner, and what incentives or penalties can apply based on compliance or refusal to cooperate with these. In addition, there need to be programs in place to support these laws and policies. For example, if you require that e-waste not be thrown in the trash but collected and recycled in a certain manner, then there needs to be drop-off locations or collection methods.

Landfilling. One relatively simple, yet ineffective solution, is landfilling, where trenches are dug and e-waste is buried, then covered again by soil. Depending on the facility, some secure landfills have plastic or clay liners, or leachate collection basins, which direct the flow of leachate to wastewater treatment plants. This is not an ideal solution, since soil contamination, and in the case of improperly constructed landfills, water and environmental contamination, can occur. This could be deemed a disposal method which contributes to land and soil pollution and poses health hazards to those living in the area (Yaashikaa et al., 2022; Pramila, Fulekar, & Bhawana, 2012).

Incineration. Incineration uses high heat both to reduce the volume of the e-waste materials, and generate power using the energy found in the e-waste materials. Of course, this process requires special incinerators, designed to break down various forms of e-waste. A downside to incineration is air pollution and the impact of this on the population and the environment (Yaashikaa et al., 2022; Pramila, Fulenar, & Bhawana, 2012).

Formal recycling. Formal recycling is performed in a regulated and controlled manner, often in specially designated facilities set up to handle the various types of e-waste. Because e-waste is composed of heterogeneous parts, including metals, plastics, and glass, together with potentially toxic chemicals and substances, one of its most critical functions is the separation of these components, and the recovery of useful resources (metals, minerals, rare earth elements). Some of the tasks involved include sorting (taking a mixed waste stream and separating into separate component materials), thermal treatments (using heat and combustion to alter or transform), biological treatments, and reprocessing (add value to materials to make it more useful as a resource). These are general concepts about the various kinds of recovery solutions and treatments based on the kinds of material being processed (Rodriguez et al., 2020; Metropolitan Waste and Resource Group, 2018).

The extraction of useful materials requires some or all of the following processes, including the removal of dangerous components which propose a hazard (such as batteries or mercury lamps), processing by shredding and crushing, sorting from items in the waste stream into those possessing a specific resource, and focused processing to obtain the desired resources (through a chemical, physical, or thermal process). One of the thermal processes commonly used is pyrolysis, which is a form of decomposition using thermal means (Andooz et al., 2022; Rodriguez et al., 2020; Lin et al., 2019).

Often, the recycling is tied into some form of collection program, where users of unwanted devices bring these to a collection facility. Some countries have policies which are tied into these recycling programs, so that there is an organized system for handling the waste beginning with receiving, and then processing. In the EU, for example, there is the WEEE Directive, which is the European Union's legislation designed to ensure compliance with the EPR (Extended Producer Responsibility) model for handling e-waste by producers and importers. This legislation had multiple iterations, and varies in its implementation by country. However, it is notable that in the EU, there is a solid framework for the management of e-waste, including the mechanisms and procedures for the recycling process in particular (Andersen, 2021; Cole et al., 2019).

Notably, the countries with the highest rates of e-waste recycling (around 49%) are Sweden, Switzerland, and Norway, which also have organized systems for managing e-waste (Balde et al., 2017).

Informal recycling. Informal recycling is the processing of e-waste using manual and simplistic, processes which are neither regulated nor controlled, and this occurs primarily in Asia (most activity in China, India, Thailand, and Vietnam), South America (Brazil, Chile, in particular), and Africa (Ghana, Nigeria, and South Africa). The term informal means that the recyclers can be small businesses (some family owned and run), where the operators frequently live at the recycling sites, or have individuals working at large waste dump sites (Andeobu et al., 2021b). Often, there is little or no attention given to the health and safety of workers, and the facilities are more primitive and expose workers to the dangers of toxic chemicals and hazardous processing methods. Some of the methods used include basic shredding and cutting of e-waste parts, burning items in open fires, and use of chemical solvents. Children are often engaged in this kind of labor, which can be hazardous. Some of these processes are performed in the workers' homes further exposing them to risk and poisoning (Andeobu et al., 2021a, 2021b).

Based on environmental, safety, and health risks, the least desirable approaches are landfilling and incineration. The superior approach is recycling, with formal recycling more desirable than informal recycling, due to the risks involved with the latter.

Other Recycling Methods. While the methods discussed already focus on what can be done to process the collected e-waste, there are other approaches which are used to "clean up" and "restore" soil and groundwater which has been contaminated by the toxic substances found in e-waste. These methods suggest more "natural" approaches to managing the problem of neutralizing areas poisoned and damaged by e-waste recycling processes.

Bioremediation uses natural processes to restore an environment (soil, air, water) to its original, cleaner state. Bioremediation can include adding various microorganisms to the soil or groundwater to achieve this effect; using enzymes to accomplish this; or adding nutrients to the soil and/or water to stimulate this effect by microorganisms already present in the environment (Dasila et al., 2023; Sharma et al., 2023; Pramila et al., 2012; Bollag & Bollag, 1995).

Phytoremediation uses plants to remove pollutants and restore an area to a cleaner, more pristine state. These methods have been shown in studies to improve the state of soils by using plants such as rice, alfalfa, ryegrass, and fescue grass together with specific types of bacteria (Pramila et al., 2012; Brandl et al., 2000) in areas having been contaminated with PCBs and other toxic compounds (Gunarathne et al., 2020; Xiezhi, 2008).

E-waste extraction. While most of the discussion concerning solutions centers around reducing the hazards of, and the volume of, e-waste, another concerns the extraction of valuable metals, minerals, and other substances from the e-waste. Often categorized under the term "urban mining" the recovery or extraction of materials can yield valuable resources from e-waste. The e-waste generated in just one year, 2019, can yield as much as 57 billion dollars of secondary raw materials (Forti et al., 2020). These include rare earth metals (REMs) such as gold, silver, and copper, and various other materials which are valuable, and can also be useful in manufacturing and production of various goods. While the extraction of these valuable resources is a positive, there are also issues with removing them from several types of e-waste, and whether the extraction and removal is worthwhile with regard to return vs. the costs and efforts involved in the extraction process (Dutta et al., 2023; Chakraborty et al., 2022; Islam et. al, 2020).

Bioleaching is a method which has received more attention recently, since it denotes a means for recovering both valuable (and toxic) metals and mineral resources from e-waste, using microorganisms, which shows promise of being an effective alternative for resource recovery (Yaashika et al., 2022; Arya & Kumar, 2020).

See Table 5 for a list of recoverable resources from e-waste.

E-WASTE PERSPECTIVES IN SELECTED COUNTRIES

Asia and Oceania

Asia and Oceania play a key role in the global e-waste situation. Overall, Asia generates a large amount of e-waste, among the main world regions. In addition, a large amount of the actual production and manufacturing of EEE (Electrical and Electronics Equipment) devices occurs in Asia. Finally, much of the world's e-waste processing and recycling also occurs in Asia (Andeobu et al., 2021a).

Table 5. Recoverable resources from e-waste

Resource	Sourced from E-waste Component(s)
Gold (Au)	Integrated circuits, wires used for bonding, contacts
Silver (Ag)	Switches, contacts, solders
Platinum (Pt)	Connectors and capacitors, hard disks
Copper (Cu)	Cables and wire connectors
Tin (Sn)	Solders
Antimony (Sb)	Flame retardants and used in CRT monitor glass
Cobalt (Co)	Rechargeable batteries
Indium (In)	Semiconductors, solders, flat panel monitors

China. China plays an extremely important role when relating to e-waste. It's not only a major consumer and producer (including manufacturing) of EEE products, but the country also generates a large amount of e-waste every year. It has been reported that China generated 7.2 megatons of e-waste in 2016, and is expected to increase to 27.2 Mt in 2030 and 51.6 MT in 2050 (Li and Achal, 2020; Zeng et al., 2020). Most of the e-waste is in the form of mobile phones, followed by computers, televisions, and household products (refrigerators, washer machines and air conditioners). It's also one of the major countries engaged in the recycling of e-waste. China's approach to recycling e-waste has previously been largely informal, which increases the potential for many risks to health and the environment. However, there have been recent efforts to pursue regulated, formal recycling (Kumar & Li, 2017; Lu et al., 2015; Lin & Ma, 2022; Salhofer et al., 2016).

In fact, two towns in China have gained notoriety as focal points for e-waste recycling. One is Guiyu in Guandong, China in the Southeast, the other is Taizhou in the East in Zhejiang province. These two cities form the main centers of e-waste recycling in China and are well known for pollution due to illegal e-waste processing practices. Guiyu is sometimes referred to as the "e-waste capital of the world" and employs in excess of 150,000 persons from several villages in the area (Andeobu et al., 2021a). Aside from these, there are waste processing plants in 29 mostly Central and Eastern provinces of China, with at least some using safer and more effective formal methods of processing and recycling (Song et al., 2019).

India. India is one of the largest producers of e-waste in the world, in part due to its increasing average annual growth rate, as well as a major consumer of electronic devices. Approximately 3 million tons of e-waste was produced in 2018, and this is projected to grow substantially. More than 150 million computers are projected to become obsolete and need replacement in the future and the electronics industry is expected to grow at an extremely high rate during this decade. While the government has established regulations concerning e-waste procedures, especially in line with environmental protection and goals, most of the e-waste processing is done through informal non-regulated businesses. Due to the small, unregulated businesses, many owned and run by families, the sophistication of equipment and facilities may be limited, with many of these firms employing children and women. Because income can be obtained from the sale of used devices, much of the e-waste in India is sold by individuals to kawariwalas, who go door to door buying old and obsolete devices, with the general belief is that there is value in them (Sengupta et al., 2022; Andeobu et al., 2021a; Arya & Kumar, 2020; Borthakur et al., 2017; Zeng et al., 2016; Chugh et al., 2016; Agarwal et al., 2014; Dwivedy et al., 2012; Pandey et al. 2014).

Unlike some other countries, in India the majority of obsolete, non-working, and unused devices are either stored and held, or disposed of primarily through some form of sale, rather than being thrown away. Through the government, devices can be sold through auction, or alternately, to one of the kawariwalas mentioned previously. To further illustrate this, roughly 3 out of every 4 obsolete computers in India are stored and kept (Andeobu et al., 2021a; Ragupathy & Chaturvedi, 2013; Ramachandra & Varghese, 2004), rather than their being sold or disposed of outright, often due to a lack of knowledge about the various options available, or an unwillingness to quickly part with something which is perceived to have value (Sengupta et al., 2022; Dwivedy et al., 2015).

Indonesia. There has been an increase in the use of electronic and electric devices in the country, and therefore the increase in e-waste has been substantial. Overall, this was not previously regarded as a major issue that received much attention, and e-waste recycling is mostly conducted by informal businesses and individuals, which suggests that improper and unsafe procedures are being followed. There were two sets of government regulations introduced for addressing e-waste, in 1999 and 2009. (Kurniawan et al., 2022; Mairizal et al., 2021; Arya & Kumar, 2020; Santoso et al., 2019; Andarani et al., 2014; Sembiring et al., 2010; Maherswari et al., 2019; Yoshido et al., 2016).

Malaysia. This country is expected to contribute to the increase of e-waste produced, considering that the nation was listed by the International Monetary Fund (IMF) as being the 3rd largest economy in Southeast Asia in 2019. The issue of e-waste has recently become a more major one, since in 2005 there was a law passed under the title of Environmental Quality Regulations 2005 where e-waste was listed as a specific type of waste to be addressed (Yong et al., 2019; Ismail et al., 2019).

Japan. A major user and producer of e-waste, Japan has enacted regulations and laws concerning e-waste, and has a relatively high percentage of e-waste being recycled, roughly 70%. Laws including the Home Appliance Recycling Laws and others were enacted beginning in 2001. As a result, Japan's approach to e-waste resembles that of the EU in many ways (Dhir et al., 2021; Oguchi et al., 2012; Zoeteman et al., 2010; Kirby & Lora-Wainwright, 2015). Because Japan requires consumers to pay a transport and recycling fee when they turn in their obsolete devices, some have opted instead to sell them to exporters as "second hand" items (Dhir et al., 2021; Zoeterman et al., 2010; Sugimura & Murikami, 2016).

Korea. This nation requires a collection fee for e-waste recyclables, which can be avoided if a new replacement product is purchased, whereby the retailer or producer would be responsible for the collection fee. Some areas arrange for pickups of the e-waste items. The country's e-waste devices are perceived to have some inherent value even if they are obsolete or can no longer be used (Jang, 2010; Kim et al., 2013; Kahhat et al., 2008).

Vietnam. In this Southeast Asian nation, citizens attribute value to e-waste and therefore a larger proportion of e-waste is stored and kept beyond its useful life. Therefore, it is not seen as an urgent and immediate problem since the quantities being discarded are not that large. Since there aren't that many e-waste policies, this is a developing area at the moment. In recent years, recycling of e-waste and extraction of metals has expanded greatly in the country (Brindadevi et al., 2023; Pariatamby & Victor, 2013; Nguyen et al., 2009).

Thailand. More than half of households hold onto their obsolete devices in Thailand, both because of their perceived value and due to lack of an organized collection system. If e-waste devices are not sold or traded in, they are-offered for donation (Monomaivibool & Vassandumrongdee, 2012, 2011).

Australia. Australia is one of major contributors to e-waste in the world, given its high level of consumption of electronics products. In fact, there has been steady growth of e-waste generation from 410 kilotons in 2010 to 554 kilotons in 2019 (Forti et al., 2020). While there were few regulations and policies prior, in 2009 the National Waste Policy was established which dealt with approaches to managing e-waste in the country. The goal of this policy was to follow international accords and conventions, reduce the amounts created, and establish guidelines for ensuring that the recycling methods employed were safe and effective (Islam et al., 2020; Ongondo et al., 2011; Golev et al., 2016; Davis & Herat, 2015; Premaltha et al., 2014.)

Africa

Africa is somewhat different from some of the other regions discussed, since while the continent does not generate much e-waste compared with other regions, manufacturing of electronic and electrical devices is also generally rather low, however the continent plays a major role in the processing and recycling of e-waste. Most of the e-waste generated within Africa comes from South Africa, Egypt, and Algeria, while the processing and recycling occurs in various nations, including Ghana, Uganda, Nigeria, South Africa, and Rwanda. While a number of African nations have ratified the Basel Convention, e-waste is imported in sizable amounts into the continent, with the predominant attitude among the importing nations is that that the economic opportunities outweigh the risks to the environment and the population. In addition, limited policies and infrastructures have resulted in most of the e-waste to being recycled informally and using rudimentary methods, creating risks to workers and the environment (Maes & Whyte, 2022; Lebbie et al., 2021; Maphosa & Maphosa, 2020; Gollakota et al., 2020, Asante et al., 2019).

Ghana. This country is well known for a large e-waste dumping site called Agbogbloshie in Accra, together with others within the country, where a large amount of e-waste is dumped. Most of the e-waste is collected by individuals who go door to door, paying for the devices to be collected. At the same time, most e-waste is being dumped into landfills, causing an enormous health and environmental problem in the country (Owusu-Sekyere et al., 2022. Oteng-Ababio, 2012; Asante et al., 2011).

North America

United States. The United States is one of the top generators of e-waste, while at the same time lacking a national policy on this form of waste; it tends to delegate the management and handling of e-waste to the state and municipal levels. There have been proposals to tie in state and regional efforts with some form of national oversight, through the EPA's Electronic Stewardship program (US EPA, 2016). Currently, the disposition of e-waste in the US is divided between a portion which is stored, one part which is disposed of, and a certain amount which is recycled. To provide a perspective on the volumes involved, roughly 15-20% generated in the U.S. is recycled within the country, with the remainder exported to Mexico, China and other parts of Asia, Latin and South America (Althaf et al., 2020).

Overall, responsibility is placed in the hands of consumers, rather than producers, and so the concept of ECR (Extended Consumer Responsibility) is emphasized over EPR (Extended Producer Responsibility). The attitudes and policies toward e-waste appear-to vary widely by region, familiarity, and convenience. Roughly half of the states in the U.S. have laws addressing the management of e-waste, but they do not form a unified whole, and the myriad of approaches and regulations actually work to hinder an effective means of addressing the e-waste being generated (Schumacher, 2016). Some states like California and Maine have established laws regarding e-waste management, with specific kinds of collection and acceptance policies varying by both state and municipality. This implies that what is allowed to be collected for recycling (including e-waste) can be quite different based on where a consumer lives, and if fees are charged. Therefore, many consumers in the US store their obsolete and electric devices for many years even though they are determined to be obsolete (Althaf et al., 2021; Lepwasky, 2012; Wagner, 2009; Li, 2011; Kang & Schoenung, 2005).

Canada. This nation, which resembles the United States in certain ways with its emphasis on ECR, has its own approach to "product stewardship" programs. Simply put, the emphasis of financial responsibility is on consumers, however some public funds are used to run e-waste management programs. In this latter case, these programs are established in specific Canadian provinces, and charge consumers an Advanced Disposal Surcharge (ADS) which is collected on purchases of electronic and electronic devices, and later used to cover the costs of collection and recycling of these devices (Habib et al., 2023; Ali & Shirazi, 2023; Xavier et al., 2021; Lepawsky, 2012).

Europe and EU

European Union (EU). This group of European nations has a well-organized set of policies and programs to address e-waste within its borders. Specified by the WEEE Directive (2012/19/EU) it provides guidelines for the collection, processing, and recovery/recycling of e-waste. Having a reasonably good track record of results, it has as its foundation the EPR structure for managing this endeavor including the producer, manufacturing, and collection/processing sections. There are specific devices covered under this directive, as well as effective assessment methods of the inflows and outflows of e-waste. Much of the e-waste generated is processed within the EU rather than exported to other countries (Gollakota et al., 2020).

Switzerland. This country is credited as being a nation with a formalized and organized system to manage e-waste, based on the concept of EPR (Extended Producer Responsibility). Not only are there guidelines and policies directed towards the collection of e-waste items, but also attention given to who pays for the transport and recycling, while relying on cooperation from both producers and consumers (Ali & Shirazi, 2022; Duygan & Meylan, 2015). Consumers pay an Advanced Recycling Fee (ARF) at the time of product purchase, which pays for the costs of transport and recycling. The system is coordinated by producers who arrange for the transport and processing (Khetriwal et al., 2009). Consumers cooperate by bringing their obsolete e-waste items to collection locations or to retail outlets set up to collect obsolete items. There are two organizations in charge of these take back systems, SWICO and SENS which are designated as "Producer Responsibility Organizations" (Ali & Shirazi, 2022; Savi et al., 2013).

Germany. Germany has a culture where it's a household's responsibility to dispose of e-waste at specially designated collection locations. This is considered a more acceptable option than having it collected for a fee. Contrary to established guidelines, in some cases, households simply dispose of the unwanted devices in the trash. The establishment of the EAR project was designed to help monitor and ensure compliance among municipalities and produces, so that the stated goals and procedures can better be met (Manomaivibool & Vassanadumrondee, 2012; Sthiannopkao & Wong, 2013).

Spain. This nation has a recycling rate lower than many other European nations, with the majority returned through retailers and local take-back systems. However, the majority of devices are discarded together with other garbage, some of which are subsequently recycled or disposed of in landfills. As of 2005, there has been new legislation which mandates that producers establish e-waste management systems to collect and recycle obsolete and unwanted devices free of charge to consumers. In addition, there has been a renewed emphasis on the recovery of raw mineral resources from e-waste (Torrubia et al., 2023; Perez-Belis et al., 2015; Savi et al., 2013; Queiruga et al., 2012).

GLOBAL RESEARCH FRAMEWORK

While e-waste is a seemingly straightforward concept to understand, a broad range of issues, impacts, and solutions exist, which vary by country and locale. Therefore, a global research framework/ categorization would be helpful for those attempting to manage the maze of variables, issues, and studies which have been conducted. The differences by region and country also need to be accounted for, since they vary widely and are yet another dimension added to the complexity of understanding e-waste management and the research conducted on this area (see Table 6).

Table 6. Global research framework table

ISSUE	OPTIONS	NORTH AMERICA	EUROPE & EU	ASIA AND OCEANIA	AFRICA	SOUTH AMERICA	AREAS FOR FUTURE RESEARCH
Awareness, Information,Support	• Marketing and Awareness Programs • Formalized recycling programs • Producer sponsored programs	• Emphasis on ECR • US/ Canada State and province • Oriented Programs	• Emphasis on EPR • EU-WEEE Directive • Greater emphasis on this area in Europe	• Varies by country • China • India • EPR Japan • EPR Korea • Taiwan	• Minimal in these Areas	• Brazil has EPR take back program • Colombia also has programs/ policy on e-waste	• More effective awareness and promotions • Culture • Circular economy • Reverse supply chain • Recycle/ Refurbish emphasis
Collection, Transport, Logistics	• Point of purchase EPR • Take-back programs EPR • Curbside collection • Drop-off events • Pick-up buyers and programs	• Regarded as "waste" to be discarded. • Most are exported overseas	• Varies by country • Major Initiative in EU • Swiss Program • Noted (EPR managed program)	• Regards e-waste as having value, to be "sold"	• Most-e-waste collected from Egypt, South Africa, Algeria	• Varies by country and region	• Innovative programs for collection • Cultural differences • Automated methods – technology, AI, robotics, smart cities
Processing, Recycling, Recovery	• Landfilling • Incineration • Varying recycling methods (informal and formal)	• Largely Exported to other regions for disposal and Recycling	• EU countries collect and recycle a large amount of its own e-waste. • Some are Exported to other regions	• Major recycling done; mostly informal	• E-waste imports • Recycling done in Ghana, Uganda, Rwanda Including Much Informal recycling	• Export to other regions for recycle and processing	• Sustain-able and "green" Recycling methods • Biol-leaching • Better urban mining methods

The research framework shown above presents e-waste from two perspectives: three general categories of issues, and from the viewpoint of geographical differences. Basically, we take the broader perspective by relating Awareness, Information, Support to cover the promotion, information dissemination, and marketing about the importance of managing and recycling e-waste. Here we note differences in terms of ECR in nations such as the United States and Canada, and a greater emphasis on EPR for Europe, Asia, and South America.

As for Collection, Transport, and Logistics, the situation varies, with some countries having loose, individual state-administrated rather than country-wide programs such as in the United States, contrasted with well-organized initiatives such as those in Switzerland and the European Union. Other countries such as many in Africa have little or no organized e-waste programs at all.

Finally, when reviewing Processing, Recycling, and Recovery, it was found that some more developed nations like the United States export much of its e-waste to other nations to be recycled, the European Union recycles a much greater percentage of its own e-waste, and developing nations in Africa and Asia take on much of the recycling burden in terms of imported e-waste.

SUMMARY, CONCLUSION, RECOMMENDATIONS

The need to understand and address the ever-increasing problem of e-waste is an urgent one, since many parts of the world have been involved in the broad and increasing use of communications, computing, and electronics devices. Even factoring out the broad use of computers to access the Internet, the sheer number of mobile phones being used can by itself create a large problem with the amount of e-waste generated. Together with electrical devices, household appliances and other forms of e-waste, this represents a huge challenge that needs to be addressed. If the problem of e-waste was given the attention of other health and environmental problems which exist in the world today, perhaps more would have been done to address the ever-increasing e-waste problem. However, this may not be the case, and a likely reason might be the perception that it is a problem akin to, or bundled together with, other forms of waste and garbage recycling, which may not seem as an urgent and pressing issue requiring the expenditure of efforts and resources. Also lacking are consistent measurement guidelines and standards, which makes the comparison and analysis across nations to be confusing and difficult.

Compounding the problem is that while the issues of processing, resource extraction, and disposal exist, the need to establish policies and laws, to encourage recycling compliance, together with the establishment of regulated and monitored collection and processing facilities which are safe and pose little danger to workers, and also do not pollute the air, water, and soil are critical. Behavioral changes to ensure that end-users participate in an effective and manageable program to safely discard or reuse obsolete devices is another aspect of a complete and comprehensive management plan.

Overall, there appears to be little consistency in how e-waste is perceived across regions and country borders. In some countries end users believe old devices are "junk" or "waste" and are eager to dispose of them even if one is required to pay a disposal fee, or to deliver (or have collected) the unwanted items. On the other hand, in some countries, e-waste is regarded as a "valuable commodity" which ideally would be sold to the highest bidder. Therefore, understanding these beliefs and conditions is fundamental to coming up with a more effective system that works for and benefit**s** everyone.

While small, informal e-waste processing businesses can be hazardous both to the individuals working there as well as residents who live in that region due to pollution, in many lower income countries this is the primary means of recycling, and taking these away in favor of safer, regulated processing facilities may be met by resistance and hostility.

When evaluating the future trends and challenges which are associated with e-waste, there are several which are of importance and significance. Considering general approaches to e-waste, the concept of a circular economy for sustainable e-waste management has become prominent, together with proposals to use artificial intelligence (AI) to help manage and improve various aspects of the e-waste management process. There are also some changes in the types of devices which are defined as e-waste, based on evolution and obsolescence of what we are using and discarding.

The *circular economy* concept has as its emphasis the reuse and regeneration of products and materials, including recycling, refurbishing, and reuse, with the goal of a sustainable and environmentally-friendly approach to managing e-waste. This has become a general guiding principle and theme from which a more preventive "upstream" solution can be proposed, rather than examining it from improving collection and recycling methods, termed "downstream" solutions (Sipka, 2021; UN EW Coalition, 2019; Bakhiyi et al., 2018).

Artificial Intelligence (AI) is an evolving technology, and has been used to solve problems in various areas, and e-waste is one area where AI-based approaches have been proposed. The implementation of AI has been looked at as an important component of the stages of the e-waste management process, including organizing and planning the flow of waste and materials, finding the most efficient routes for e-waste scheduling and pickup, and also in conjunction with robotic technologies, the ability to allow for the effective automated pickup of e-waste items which can be differentiated from other forms of garbage (Brazier & Prasetyo, 2023; Nafiz et al., 2023; Madhav et al., 2022; Baker et al., 2021; Huang & Koroteev, 2021; Sipha, 2021; Li, Jin & Krishnamoorthy, 2021; Nowakowski et al., 2020).

Design for recycling. There have been proposals for adapting the production process away from traditional materials, towards those which are more attuned to the concept of "designing for recycling." For instance, when making circuit boards, glass fiber, epoxy resins, and copper circuits which are more difficult to recycle, can be replaced with a paper-based alternative which is far more recyclable and sustainable (Sudheshwar et al., 2023).

"Green" cloud computing. One approach to reducing the amount of e-waste which needs to be managed is to employ cloud computing as an alternative to setting up your own computer center, and instead making use of computing technologies available through the Internet. This helps to alleviate the e-waste problem at the source by requiring a minimum of hardware to be acquired and used. (Onorgunesin et al., 2021; Li et al., 2021; Radu, 2017)

Evolution of e-waste. While the "traditional" definitions of what constitutes e-waste constitutes electronic devices such as computers, mobile phones, and household electronic devices, this definition may be evolving. First, there is an expansion in the types of products which involve technological components, some of which come under the broad category of IoT (Internet of Things), which refers to any device, machine, or gadget which can or is connected to the Internet (Fathi et al., 2022; Razip et al., 2022). Also, there are e-textiles which contain electronic components, devices which are designed to automate agricultural processes, clean energy technologies such as solar panels, and even satellites and space rocket components which are no longer used and deemed obsolete. All of these can contribute to the e-waste generated in the future (Shittu, Williams, & Shaw, 2021).

Electronics as a service. Expanding upon the themes of infrastructure as a service (IaaS) and software as a service (SaaS), comes the concept of electronics as a service, where electronic devices, such as mobile phone and televisions, can be leased or rented, rather than being purchased outright and then discarded when it is no longer wanted. Coming under the umbrella of "dematerialization" the emphasis is on electronic devices which are provided as a "ongoing service" where the customer can enjoy the latest in innovative features and updated technology but is not tied into a long-term ownership model. On the part of the companies offering these services, there is an emphasis on extending the life of the products and doing repairs as needed for future customer use, which helps to alleviate the e-waste crisis. (UN E-waste Coalition, 2019).

There are a number of recommendations which are suggested to improve the current state of e-waste, and to move towards a more effective and sustainable solution. These recommendations are summarized in Table 7.

In short, for many the current state of e-waste management across continents and the world is highly variable, uncertain, informal, largely unregulated, and not firmly established within the

Table 7. E-waste recommendations

LEVEL	RECOMMENDATIONS
Awareness Information, Support	Emphasis and promoting goals for recycling, reuse and refurbishment. Learn from and partner with countries with established e-waste programs. Awareness of e-waste issues and generation, recycling, effects on health and the environment, to business and citizens Discourage manufacturing processes which supports obsolescence (and understand reverse supply chain, circular economy). Encourage adoption of EPR principles. Develop effective e-waste laws, regulations, and policies which can be enforced.
Collection Transport Logistics	Monitoring, labeling, identification/tracking of e-waste using technology and online means. Taking into account economic, resource, cultural, and social aspects. Developing E-waste collection and management procedures and infrastructure. Use new technologies – AI, robotics, blockchain, Smart City concepts.
Processing Recycling Recovery	Creation of uniform and global standards for e-waste management. Reduction of use of toxic components; replace with non-toxic substitutes. Regulations reducing exposure to toxic chemicals (including those resulting from e-waste processing). Moving away from informal, to regulated formal recycling methods and facilities. Employ new technologies such as bioleaching rather than traditional recycling methods.

sphere of attention. To properly address this problem, additional measures need to be proposed and implemented so that the vast amount of e-waste generated can be managed and disposed of properly.

LIMITATIONS OF THIS RESEARCH

The goal of this paper is to explain the issues, considerations, proposed solutions, and future trends related to e-waste management on a global basis. The scope of this subject is quite broad, and while the main issues are described and discussed, there are some areas which may require a further and deeper exploration. Among these are technical aspects of the e-waste recycling process, which require an analysis of technical and scientific details which go into the details of how these processes work. In addition, the constantly evolving policies and legislation which are being introduced by various nations is also a topic which requires further detail and analysis to fully understand and interpret.

Both technical and policy-oriented issues need to be explored further, and given the broad scope of this topic, additional research studies need to be done.

AREAS FOR FUTURE RESEARCH

There are a number of fertile areas for future research, given the multitude of technical and management issues, societal impacts, policy issues, and the like.

Blockchain and IoT. There has been research emerging in the areas of “smart cities” which can use a variety of technologies to support sustainable strategies and initiatives with an urban environment. Since waste collection is one area of attention in any city, e-waste is also a viable area for investigation. In particular, to help improve e-waste tracing and tracking, a blockchain-based technology which ties in various stakeholders and IoT (Internet of Things) devices such as “smart waste bins” which can recognize the type of waste being deposited. The advantages of using blockchain methods is that it can help in the efficient management of recording electronic devices created, those sold by retailers, and purchases by consumers. The tracking of these through to waste collection bins and centers, then to recycling and disposal locations can be effectively managed (Khan et al., 2022; Sipka, 2021; Buthelezi et al., 2022).

RFID as Waste. While much of the focus of the e-waste research and analysis has been on electronic devices, the usage and disposal of a small, but widely used electronic item, the RFID tag, is another area ripe for further research. While often overlooked and discarded as ordinary garbage, these electronic devices also represent an area which deserves attention. The usefulness of tags to track and manage e-waste transport, recycling, and status, as well as attention on how to recycle and reuse RFID tags (as a form of e-waste), are topics which deserve attention (Condemi et al., 2019; Sipka, 2021).

Bitcoin e-Waste. The process of Bitcoin mining is also research area which is worthy of research attention, because of the fact that the process requires the use of computer hardware which may only be used for a relatively short time, then discarded, due to the fact that Bitcoin operations often result in degrading and overheating due to the intensive processing needed. As a result, this often results in a shorter lifespan for computers used for Bitcoin mining, which adds to the e-waste problem (DeVries & Stoll, 2021).

Interactive Online Maps. The need to track all aspects of e-waste management has often been cited, and the use of online technologies such as interactive online maps has been proposed as one viable solution. This can be tied into a "smart" e-waste collection system using Internet of Things technologies, where the goal is to reduce vehicle emissions, monitoring local delivery services and user requests, and optimizing the routes for e-waste pickups (Shevchenko et al., 2021)

Robotics and e-Waste. Another promising area of research has been studies proposing the use of robotics in e-waste management, with attention placed on the areas of collection and recycling. This includes the use of robotic arms and devices for collection of e-waste, and also automating some of the hazardous aspects of recycling (involving heat, fire and other processes (Baker et al., 2021; Chen et. al, 2021; Madhav et al., 2021; Sipka, 2021; Nowakowski et al., 2020, Brazier & Prasetyo, 2023)

Material Flow Analysis. There has been an area of work related to examining and analyzing the flows and stocks of materials within product lifecycle systems. The use of material flow analysis (MFA) is designed to assess the flows and stocks of materials, by connecting the sources, pathways, and intermediate, and final disposition of the materials in question. This kind of analysis readily lends itself to e-waste management, and assessments have been done both on the e-waste generated in specific countries, and also on specific products such as mobile phones, computers, vacuum cleaners, and batteries (Islam & Huda, 2019).

Smart Cities and Automated E-waste Collection. Expanding upon the robotics area mentioned previously, there has been interest in the concept of developing e-waste programs for "smart cities" where the process of initiating a pickup request, having the waste identified, picked up, and delivered to a processing facility, is largely automated and controlled by artificial intelligence, machine learning, and robotics. This seems to be a fruitful area for further research (Brazier & Prasetyo, 2023; Nafiz et al., 2023; Lee, 2022; Baker et al., 2021; Li, Jin, & Krishnamoorthyl, 2021; Nowakowski et al., 2020).

E-Waste Forensics. There has been much focus on the health and safety aspects of e-waste, particularly the risks involved with recycling and disposal. However, the fact that many e-waste devices being discarded contain data, it brings up the issues of privacy, security, and a potential treasure trove for cyber criminals. While there are countless sources of advice for how to "wipe" or erase the data on a server or computer, these procedures are not always followed properly. As a result, confidential information such as credit card numbers, bank information, and personal data can be retrieved from discarded e-waste. In addition, there are electronic devices which have been purposely installed with malware, which can then gain access to and collect information on the persons buying these supposedly "refurbished" products (Kapoor, Sulke, & Badiye, 2021).

While this area of study is large overall, there are many opportunities for examining new approaches to, and innovative methods for managing, collecting, and processing e-waste more effectively. This, together with recovering, recycling, and extracting the elements which are most useful and lucrative, should be investigated further. What means exist to undo some of the environmental damage that was done previously due to informal e-waste processing? How can e-waste processing be better monitored, regulated, and managed on a global level?

Because of the wide and varied approaches to e-waste management, collection, regulation, and recycling/processing, a great deal can be accomplished in this area, and research can be conducted from a variety of different perspectives.

ACKNOWLEDGMENT

We wanted to give thanks to the Editor in Chief for his help and support of this paper during its review and evaluation process. In addition, our appreciation to the three anonymous reviewers for their insightful comments and suggestions for improving the manuscript.

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