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REVIEW ARTICLE

Towards a sustainable and green approach of electrical and electronic waste management in Rwanda: a critical review

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Abstract
Electric and electronic equipment (EEE) consumption has grown to worrisome proportions in developing countries (DC_S), resulting in massive amounts of electrical and electronic waste (e-waste) being produced. A diagnosis of e-waste proliferation is required for its sustainable management plan in Rwanda. This review is based on open-access papers with e-waste as a keyword, the present situation of EEE, and e-waste in Rwanda. The need for various information communication and technology (ICT) tools, such as end-user devices, cooling-system devices, network equipment, and telecommunication devices, is strongly encouraged by Rwandan national plans, which deem ICT as a vital enabler of knowledge-based economy and development. In 2014, EEE was 33,449 tonnes (t), which is expected to be 267,741 t in 2050, with a yearly increase rate of 5.95%. In this regard, out-of-date EEE is being dumped as e-waste in large quantities and at an increasing rate across Rwanda. E-waste is often disposed of in uncontrolled landfills together with other types of household waste. To address this rising threat, as well as to preserve the environment and human health, proper e-waste management involving e-waste sorting/separation from other waste streams, repairs, reuse, recycling, remanufacturing, and disposal has been proposed.

Keywords E-waste · Electrical equipment · Electronic equipment · Information · Communication · Technology

Introduction

The growth of information communication and technology sectors (Sharma et al. 2020) and the quest to discover new equipment (Fanthi et al. 2021) have encouraged the use and increase of EEE equipment enormously. When EEE has reached its end-of-life (EoL), it is termed "e-waste" and is deemed dangerous to the environment and public health (ITU 2019; WHO 2020; Onyara 2020). EEE is equipment or device that needs electrical currents or electromagnetic fields to accomplish its intended purpose (Law Insider 2023). The word "e-waste" is defined in various ways, depending on the viewpoint of the consumer (Onyara 2020). On the other hand, e-waste is taken as EEE that is no longer usable by the owner or has reached the EoL, which includes computers, refrigerators, cell phones, etc.

The demand for EEE, especially ICT equipment, is growing globally (Twagirayezu et al. 2021; Shittu et al. 2021). This refers to the total quantity of e-waste created throughout the globe, which will be available for a long time as new technologies and readily accessible products are launched into the marketplace (Forti et al. 2020). This new technology

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associated with advanced marketing leads to a surge in the consumption of electronic items (Pandebesie et al. 2019). Increased consumption has environmental and health effects, whether during raw material extraction or after using final goods (Halim and Suharyanti 2020). E-waste is now among the fastest-growing pollution issues worldwide due to several harmful substances that can contaminate human health and the environment (Borthakur and Singh 2021; Twagirayezu et al. 2022). Keeping EEE usage to a minimum level is crucial to preserve human beings and the environment.

There has been no spared DCs from the consequences of ICT. These countries hastily integrate networks and technology that offer unlimited access to government, education, business, and healthcare service data (Baldé et al. 2017). This is producing an extraordinary amount of e-waste at an unprecedented rate. It is anticipated that several DCs have seen double-digit yearly growth for the first time (Twagirayezu et al. 2021). Nonetheless, if EoL of all EEE or components has come and the user can no longer utilize them, they are thrown away in containers that should be mixed with other waste and then transported to be dumped in landfills. The leachate that follows from dumping e-waste is full of poisonous heavy metals and organic compounds that are terrible for human and animal health and the environment (Roy et al. 2022a). Typically, the rapid evolution of the EEE results in a product being obsolete before it reaches its end of life (Shahabuddin et al. 2023). Over the past few years, over a billion personal computers have been deemed obsolete (Guo and Yan 2017). When a new item is brought onto the market, thousands of older electronic items are discarded as waste, even if they are still useful (Alghazo et al. 2018; Twagirayezu et al. 2021), contributing to an increase in massive amounts of e-waste. In 2019, e-waste produced worldwide was approximately 53.6 million metric tons (Mt) and was estimated to be increased to 74.7 Mt by 2030 (Forti et al. 2020). About 83.0% of the entire amount of e-waste created in 2019 was not recorded and either burned publicly or discarded illegally, while only 17% was collected and recycled appropriately (Shahabuddin et al. 2023). Lack of strong oversight and legal institutions, associated with technical and socioeconomic challenges, is an obstacle for the government in DCs to effectively manage e-waste (Ashwani 2018). In addition, financial difficulties faced by DCs prevent the creation of organized recycling facilities, resulting in a large volume of e-waste handled by illegal and informal recyclers that may pose a danger to the health of people and the environment (Hameed et al. 2020). This indicates that e-waste processed in DCs should threaten human health and pollute the environment due to a lack of facilities for repair, rehabilitation, or being mixed with other waste (Kumar et al. 2017; Maheswari et al. 2020). Because e-waste is not segregated from different sorts of waste, the large bulk of e-waste incinerated in landfills presents health and environmental concerns (Baldé et al. 2017). For instance, rudimentary methods to recover valuable metals are being practiced by people who lack the facilities to safeguard the environment and public health in the countries such as China, India, Pakistan, Vietnam, the Philippines, Nigeria, and Ghana (Ikhlayel 2018). On the contrary, e-waste management has been successfully deployed in developed countries across Europe and the American continents (Gollakota et al. 2020). Those developed countries use an advanced approach to managing their e-waste waste.

However, managing e-waste in DCs presents significant environmental, economic, and social challenges associated with the lack of organized recycling, reuse, and remanufacturing culture (Rochman et al. 2017). In conformity with findings from a study done in developing countries, gastrointestinal, respiratory, and other infectious disorders are among the most common health concerns identified by unorganized e-waste employees (Nithya et al. 2021). During the financial meltdown in DCs, several organizations supported importing low-cost vicarious EEE from rich nations to save money. In the absence of effective monitoring, handling, and recycling approaches, e-waste can release dangerous compounds into the environment, resulting in major repercussions and detrimental public health impacts such as vomiting, lung cancer, abdominal pain, muscular pain, headache, diarrhea, sleeplessness, and abdominal pain (Borthakur and Govind 2019). For the sake of better e-waste management, it is suggested that informal e-waste dealers should be well-informed about the hazards of improper e-waste disposal and the damage it causes to the environment (Turaga et al. 2019; Lou et al. 2022). For example, the University of Duhok (Iraq) has substantially influenced e-waste processing by integrating awareness and management of e-waste into courses for environmental sustainability (Twagirayezu et al. 2021). This implies that DCs have a limited understanding of e-waste, and consumers prefer to hang on to the item for as long as possible, either because of its value or because they are entirely unaware of the potentially hazardous nature of e-waste items (WHO 2020). E-waste should not be dumped together with other types of waste. But many businesses still need an e-waste disposal strategy (Maheswari et al. 2020). Inappropriate disposal sites and a lack of understanding about e-waste segregation from other waste streams hinder waste management in many DCs, including Rwanda.

To date, e-waste management processes and a unified repository of information about e-waste in Rwanda have not yet been explored. Therefore, a critical and comprehensive review highlighting e-waste management in Rwanda is necessary. The objective of this study is to establish a sustainable and green approach to electrical and electronic waste management in Rwanda, in which this approach displays a broad picture of e-waste in Rwanda, including why it is increasing, what problems it can cause, how it should be appropriately managed, and opportunities it can offer for people. This review paper aims to make people aware of the hazards and values associated with e-waste. In addition, it is conducive to reestablishing national and institutional policies for proper management and improvement.

Research methodology

This review article was accomplished based on the PRISMA 2020 statement guidelines (Page et al. 2021), in which whole processes for this critical review are depicted in Fig. S1. Herein, search terms such as e-waste, electrical, and electronic waste were used in the search different search engines to get relevant literature studies on the overview of the exciting e-waste production. Laconically, after identification via SpringerLink, Wiley Online Library, Web of Science, Google Scholar, Scopus, Taylor, and Francis Online, records screened were 632 research papers. After that, reports assessed for eligibility were 135 research papers. Finally, reports included in this critical review were 89 research papers after excluding some other reports because they did not clearly display e-waste management information and did not evince the needed information on e-waste. On the other side, 28 websites and organizations altogether were also retrieved and used in this review. It is worth noting that only English language journals were included following the protocols adopted in similar review articles. Data related to e-waste in this literature were extracted and then used in this critical review. Based on eligibility criteria, duplicates and other studies based on exclusion criteria by screening the titles and abstracts were excluded through discussion. The full text of the remaining studies was further revised to check their eligibility. Figure S2 displays the relative frequency of words considered in this manuscript.

This review (i) summarizes the most recent information on the e-waste situation around the world and in Rwanda, (ii) provides an overview of needed green and sustainable approaches to e-waste management in Rwanda, (iii) summarizes the health and environmental effects of improper e-waste management, and (iv) presents concerns about the challenges and roadblocks involved with the process of e-waste management in Rwanda.

E-waste scenario around the world

The production of e-waste globally is at a rate of around 57.4 Mt/year (Roy et al. 2022b). This is because technology keeps getting better, which means that technology companies keep upgrading their equipment, which is part of their business model. E-waste overflow has led to a 5% rise in the municipal solid waste that is generated worldwide (Earth911 2023). As depicted in Fig. 1, there has been a tremendous rise in the amount of e-waste produced globally from 2010 to 2019 (Forti et al. 2020; Andeobu et al. 2021). The global e-waste quantity is predicted to increase to a massive 74.7 Mt by 2030 (Forti et al. 2020), representing high EEE consumption. According to the United States Environmental Protection Agency data from 2009, the total number of new electronic items sold was 438 million tons of electronic

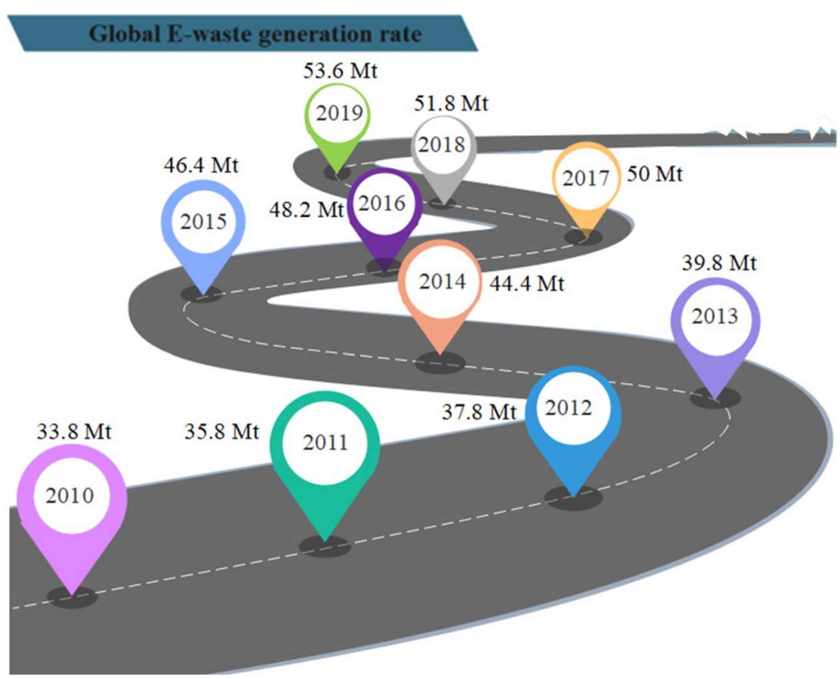

Fig. 1 Global e-waste generation rate in million metric tons

items were sold in the USA (Ilankoon et al. 2018). EEE in storage accounted for approximately 5 million tonnes, with ready-to-EoL electronic products accounting for 2.37 million tonnes, with only 25% of e-waste collected for recycling (Awasthi and Li 2017).

Presently, e-waste is one of the most concerning environmental problems on a global scale. For instance, around 41 million tons of e-waste were produced worldwide in 2014, an increased rate of 3–5% annually (Kumar et al. 2017). Approximately 75–80% of the 20–50 Mt of e-waste produced globally every year is transferred to poor countries, particularly in Asia and Africa, to recycle and dispose of them (Getachew et al. 2019; Poudel et al. 2023). Accordingly, India and China are the top two importers. Nigeria, Ghana, Bangladesh, Pakistan, and Kenya are major countries that import e-waste for recycling. For instance, in 2015 and 2016, Nigeria imported between 60,000 and 71,000 t of used EEE via two main ports in Lagos, with the majority (77%) produced by the European Union (Maes and Preston-Whyte 2022). In addition, Ghana registered 0.215 Mt of e-waste brought into the country in 2019, where 30%, 14%, and 56% were new products, second-hand e-waste that required processing (Maes and Preston-Whyte 2022). However, these nations lack comprehensive, suitable handling and recycling methods with little regard for worker safety and minimal concern for environmental preservation, which are restricted by the 1992 Basel Convention and other relevant national environmental legislation (Singh et al. 2020).

For instance, e-waste produced by countries in 2012 is represented in Fig. S3 (Live Science 2013), where there was 10.933 Mt in Europe, 10.3 Mt in the USA, 7.995 Mt in China, 3.033 Mt in India, 3.022 Mt in Japan, 1.556 Mt in Russia, 1.530 Mt in Brazil, and 1.138 Mt in Mexico. However, as the country's economic development improves, the amount of e-waste produced also fluctuates. According to the amount of e-waste generated in 2018 (Baldé et al. 2017), about 50 Mt of e-waste was created around the world, where Asia was at the forefront in terms of overall e-waste creation, with 18.2 Mt. The fact is that China ranks as the most technologically advanced nation in the whole world and therefore generates the highest quantity of e-waste. In addition, the e-waste is imported into South Asia for recycling purposes. Asia is followed by Europe, America, Africa, and Oceania, which produce 12.3, 11.3, 2.2, and 0.7 Mt, respectively. However, Oceania, the world's smallest population, comes out on top when one counts the per capita e-waste output since it generates 17.3 kg/inhabitant. The shares of the other regions are distributed as follows: Europe with 16.6, America with 11.6, Asia with 4.4, and Africa with 2.2 kg/person. But, Europe ranks first in the world regarding e-waste collection, with a rate of 35%. The USA comes in second with 17%, where 15%, 6%, and 0% come from Asia, Oceania, and Africa, respectively.

E-waste status in Rwanda

E-waste is rapidly becoming a problem in Rwanda as the country develops into an information-rich society, as ICT deployment grows, and as more people access electricity. These factors, combined with the rapid growth of new technological solutions to meet a wide range of needs, are causing an increase in out-of-date EEE that must be discarded. This section discusses the classification and sources of e-waste, the growth of EEE and e-waste, e-waste management structures and procedures, current environmental agreement, and an institutional framework for e-waste management in Rwanda.

E-waste classification and its sources

The term "e-waste" denotes EEE that has either reached the end of its usable life or is reaching the end of its useful life. Rwanda's National e-waste Management Policy defines e-waste as all EEE that has been thrown or disposed of as waste (The Republic of Rwanda 2016). Currently, the government is encouraging rural ICT penetration through various projects, including one laptop per child program and an off-grid rural electrification program, and there is an effort to get all services offered online via Irembo, which is a technology company founded in Kigali in 2014 with the mission of transforming Rwanda into a digital society by allowing citizens to apply for and pay for various government services. However, no plan existed for what to do with EEE after their valuable lives had expired. The government and other private organizations had previously rented facilities to keep all of their e-waste, which was both costly and unsustainable. The government desired a solution that took a holistic approach to the problem. Table 1 lists some of the most common EEE types observed in different stores in Rwanda, especially in cities.

Tendencies and procedures

The development of ICT has substantially contributed to societal and economic advancements, such as increased employment and access to higher living standards for a more significant number of people (Habibi and Zabardast 2020). Rwanda recognizes the importance of ICTs to socioeconomic progress as a substantial development engine (NNW TEAM 2020). Implementation of the project, such as one laptop per kid, fiber optic coverage across the nation, improving power availability, and other non-aligned movements of EEE, continually underline the need for growing EEE. Consequently, there is a tremendous increase in EEE in families, businesses, institutions, etc. Waste dealers gather

Table 1 E-waste categories in Rwanda

No.	Categories	Examples
1	Television and accessories	Television, satellite dish, decoder, receiver cables, DVD player
2	Computer and accessories	Laptops, notebooks, CD-RW and DVD, desktop computers, CD-R, USB sticks, computer speakers, CDMA sticks, computer, printers, keyboards, mouse, and hard drives
3	Mobile devices and accessories	Mobile phones, headsets, phone batteries, and chargers
4	Other electronic items	Power dividers, radios, stoves, power adaptor, tape recorders, rechargeable batteries, ironing machine, power cables, different types of lamps, men and women beauty equipment, juice maker refrigerators, coffee grinder, washing machines, vacuum cleaners, air conditioner, dry cell batteries, and kettles

the waste from different locations and dispose of it at designated disposal sites, with no distinction made between e-waste and other types of waste. Occasionally, non- and valuable contents of e-waste are mixed with other forms of waste, but most of these wastes are hazardous to the environment.

As a result, Rwanda has an alarmingly high rate of e-waste creation. For example, mobile phone penetration increased from 0.0046 in 2000 to 56.8% in 2013, and Rwanda was rated second in Africa in terms of the yearly mobile telephone proliferation growth rate in 2010 (ITU 2014; Rutebuka et al. 2015). Additionally, a study conducted in Rwanda from November 2014 to January 2015 to determine the state of e-waste revealed that imported ICT equipment increased five times between 2010 and 2014. E-waste production capability in Rwanda was 9417 tons, with individuals contributing 81.52% of that total, public organizations contributing 12.14%, and private organizations contributing 6.34%, showing that Rwanda can generate e-waste annually (The Republic of Rwanda 2016).

As shown in Fig. 2 (Mbera 2018), in 2014 and 2020, 8790 t and 12,432 t of e-waste were produced from 33,449 t and 47,309 t of EEE, respectively; it was estimated that 16,597 t, 22,155 t, and 70,360 t of e-waste will be delivered from 63,155 t, 84,308 t, and 267,741 t of EEE, respectively. Based on this, the annual growth rate of EEE imports in Rwanda would be about 5.95%, related to the creation of e-waste. However, no current regulations for e-waste management say households must pay themselves for waste collection and disposal. Due to the specific composition of e-waste, which includes infrastructural elements that might harm the environment, it cannot be disposed of as ordinary waste. Special procedures, knowledge, and facilities are required for their disposal.

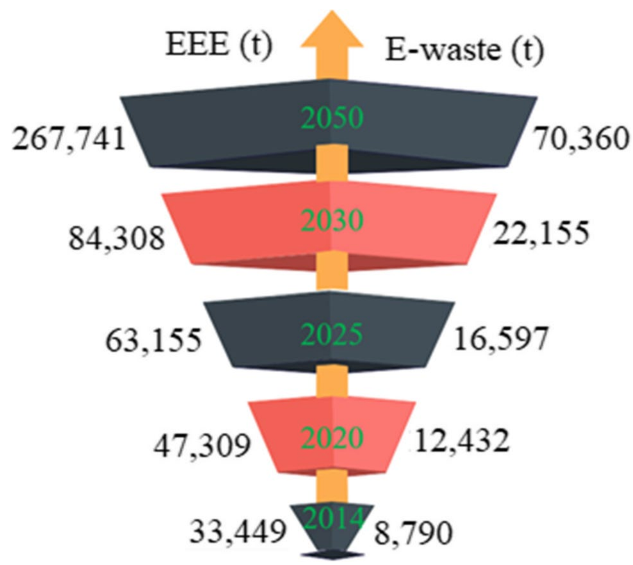

Fig. 2 EEE and e-waste patterns in Rwanda

Procedures and structures for e-waste management

As initiatives to upgrade ICT reach a high level, e-waste management is becoming more critical to sustainability policy (NNW TEAM 2020). Rwanda is a country gradually embracing digital materials like computers, smartphones, televisions, laptops, cell phones, etc. This should result in a substantial rise in e-waste as well as increased consumer desire for new devices. Therefore, Rwanda urgently needs better management of e-waste. Rwanda Green Fund and the Ministry of Trade have worked together to remedy this problem, even though it is not entirely due to population and development growth. Previously, a recycling and dismantling factory was established in Rwanda, designated as a world-class e-waste processing and recycling facility, and can process more than 7000 tons of e-waste each year (Africa Green Growth Forum 2017). Thus, unwavering dedication of Rwanda to sustainable development and green growth is a smart option.

Typically, all institutions listed below should carry out their responsibilities in e-waste management, as shown in Fig. 3 (Twagirayezu et al. 2021). MINICOM (Ministry of

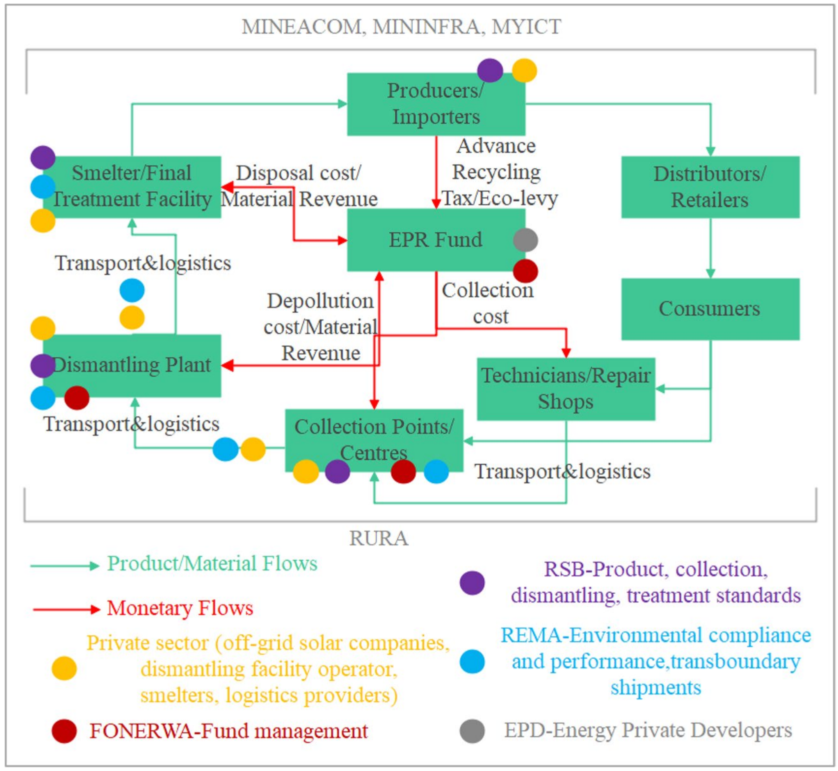

Fig. 3 Government-private recycling scheme hybrid of e-waste

Trade and Industry) should guide the growth of external trade, firms, and cooperatives in the market, as well as the development of investments and consumer rights in EEE. MININFRA (the Ministry of Infrastructure) is responsible for crafting national policies, legislative and institutional frameworks, master plans, and strategies related to transportation and energy. The Rwanda Standards Board (RSB) is responsible for the product, collection, dismantling, and treatment standards. MYICT Rwanda (Ministry of Youth and ICT, Rwanda) is responsible for ICT policies and programs. FONERWA (National Fund for Environment and Climate Change) is accountable for the fund's administration. REMA (Rwanda Environment Management Authority) is responsible for environmental protection and management with transboundary exports. EPD (energy private developers) is responsible for bringing together private companies with a stake in the energy sector, and EPR (extended producer responsibility) is responsible for the lifespan of the products.

E-waste recycling facility financed by FONERWA is part of the organization's e-waste management strategy, which includes inventory, private investment, and policy development. Proper collection and disposal methods of hazardous fractions might increase costs. Therefore, additional financing from EPR funds is needed to maintain economic sustainability. Therefore, FONERWA, as a main partner in constructing recycling plants, might be considered during the funding. EPR funds may also be managed by private or non-profit groups, similar to the European producers' accountability organizations in the USA. EPD and other industrial organizations within the Private Sector Federation may be able to perform this function through the off-grid solar business. One such organization is the Rwandan ICT Chamber, which represents IT equipment and telecommunications company resellers. RURA, RSB, and REMA are responsible for providing assistance, licensing, and supervision on various topics, such as cross-border delivery and monitoring, as well as setting standards and establishing guidelines. This study suggests that collaboration between all institutions involved in putting their respective duties into practice is essential.

E-waste management policies and legal frameworks in Rwanda

Even if there is no standardized way for the different sectors to manage e-waste, the government of Rwanda is devoted to environmental protection agencies due to the tremendous expansion of e-waste. Rwanda has developed national policies that regard e-waste management to deal with climate change and environmental degradation as one of the most significant obstacles to achieving medium and long-term economic goals (The Republic of Rwanda 2016; NNW TEAM 2020). Through its policy and regulatory framework, Rwanda has acknowledged e-waste as a danger to the environment, but it has failed to anticipate the special problems created by it. This demonstrates that the present rules, laws, and regulations do not adequately deal with e-waste management. Typically, e-waste is controlled under a subset of the hazardous waste control and management regulations (The Republic of Rwanda 2016). The existing waste laws in Rwanda need to be more precise and expressly include a comprehensive e-waste management strategy. Therefore, the current legislative framework has to be reformed with a comprehensive plan for managing e-waste to preserve Rwandans' environment and health. Table 2 (Twagirayezu et al. 2021) summarizes Rwanda's national policies, regulations, and laws regarding the management of e-waste to maintain

Table 2 Rwanda's e-waste laws, environmental policies, and legal frameworks

No.	Laws or regulations	Environment policy and legal framework	Source
1	Law N° 39/2001 of 13th September 2001	Initiating RURA with the responsibility of collection and disposal of waste from commercial and residential buildings, etc	Rura (2001)
2	Environment Organic Law N° 04/2005 of 08/04/2005	It was established for protection, conservation, and facilitation of the environment by indicating the way in which waste should be collected, transported, and disposed of. However, it does not deal with EEE waste management explicitly and efficiently	Official Gazette of the Republic of Rwanda (2005)
3	Law N° 16/2006 of 03/04/2006	Introduced the structure, procedures, and responsibilities of REMA, such as seeing that the environmental policy is put into effect, reviewing and authorizing environmental impact assessments for new construction, and making measures to mitigate environmental risks	Aime (2011)
4	Law Nº 43/2010 of 07/12/2010	Authorize the energy, water, and sanitation authority (EWSA), which is currently divided into the Water and Sanitation Corporation (WASAC) and the Rwanda Energy Group (REG) Limited, by outlining and defining its roles, organizations, and functions, as well as outlining and defining its responsibilities, like developing waste management approach	Official Gazette n°4bis (2011)
5	Law Nº 1of 25/10/2011	It was set up by the Rwanda Standard Board (RSB) and the ministry in charge of ICT to limit the detrimental effects of EEE on human health and the environment by limiting the import of used computers and electronic parts	The Republic of Rwanda (2016)
6	Law N° 09/2013 of 01/03/2013	Initiating RURA and determine its powers, functioning mission, and organization. In addition, it collaborates with Law Nº 16/2013 in assessing the organization, and responsibilities of REMA during the waste management without taking into account e-waste	Rura (2013)
7	Law Nº 24/2016 of 18/06/2016	Provide permission for establishing and operating a network and dealing with electronic communications services. It also has the responsibility to decide what criteria must be met to provide information to those interested in doing so, as stated in Article 130 (60 K) of the ICT Act, No. 24/2016, of June 18, 2016	JuriAfrica (2016)
8	Law on Environment Nº 48/2018	This is a revised Environment Organic Law N° 04/2005 of 08/04/2005. In a manner identical to that of its predecessor, this law does not effectively deal with the problem e-waste	Official Gazette (2018)
9	NÛ 011/R/STD-ICT/RURA/020 of 29/05/2020	The goal of this law is to provide a framework for the importation, distribution, and formal authorization of EEE in Rwanda to assure the public that the materials used, for instance, in telecommunications networks will not affect their network	Rura (2020)

national and international agreements and conventions that meet the challenges created by the rapid developments in EEE.

Current environmental agreement of Rwanda

Different industrialized nations already have specific laws and regulations for properly managing e-waste. EPR can be a methodical and well-considered approach for managing e-waste worldwide. Thomas Lindqvist was the pioneer who initiated the first strategy for the management of e-waste in 1990 in Sweden (Islam et al. 2017). The regulations and laws governing e-waste management may be developed considering indigenous characteristics, traditions, socioeconomic culture, etc. (Gollakota et al. 2020). Despite the widespread recognition of the need for an e-waste management framework, formal advancement in the management of e-waste in developing countries has been rather slow (Rasheed et al. 2022). This process entails the establishment of appropriate recycling facilities, the development of a collection system, and the establishment of laws (Xiao et al. 2018). However, Rwanda is confronted with a number of obstacles concerning the management of e-waste in each of the aforementioned sectors.

The government of Rwanda is devoted to environmental protection in light of the increasing amount of e-waste. Table 3 summarizes a number of international environmental agreements, both regional and worldwide, with Rwanda. Through its environmental policies and regulatory frameworks, Rwanda has brought awareness that waste is a danger to the environment in general; yet, the country still needs to adequately prepare for the specific problems created by e-waste. Rwanda should set up a way to track and manage EEE standards (The Republic of Rwanda 2016).

Table 3 Multilateral environmental agreements of Rwanda

Categories	Agreements
Agreements concerned shipping of e-waste between countries	In August 2003, Rwanda signed the Basel Convention on the regulation of cross-border transfers of hazardous wastes and their disposal; however, for the years 2014–2021, REMA has been executing the national implementation plan of the Basel Convention for the regulation of cross-border transfers of hazardous waste
	During in the Bamako Convention, the Organization of African Unity (OAU) restricts the importation of hazardous waste into Africa
National legislative framework on e-waste	The Law on Environment No. 48/2018 is a comprehensive environmental protection law that specifies that waste collection and treatment should be carried out in a responsible environmental way; it does not directly address e-waste
	The national sanitation policy, which was approved by the cabinet and gazetted in December 2016, is an Umbrella Policy that offers guiding principles for all elements of sanitation, such as industrial waste, e-waste, and solid and liquid wastes. The sanitation policy advises the implementation of a specialized e-waste management strategy
	The draft National E-waste Policy, which was released in August 2016 and is now awaiting approval by the cabinet, was prepared to give specific advice and policy direction on the proper legal and regulatory instruments for e-waste disposal
	Ministerial Order No. 1 of 25/10/2011 by MYICT issued in partnership with the Rwanda Standard Board banned and regulated the import of secondhand computers and electronics, which are often used as a conduit for WEEE disposal in developing countries
	E-waste Bill of Rwanda, which is still in draft form, establishes the legal framework for the management of e-waste. Here, the bill is done according to the producer responsibility concept and applies to the complete spectrum of EEE as well as e-waste (Article 2, Scope of Application). As such, solar items fall within its purview by definition
	RURA Regulations: RURA has been tasked with the responsibility of enforcing and implementing the requirements of the e-waste Bill. The Regulations define the duties of several actors, most notably producers and recyclers, and provide minimum licensing criteria, as well as sanctions and penalties for non-compliance
Agreement on Energy Policy, specifically off-grid solar product waste	Rural Electrification Strategy (RES): The RES's two defining features are a goal of 35-39% access through off-grid and mini-grid technologies and a focus on the private sector as the primary driver in the off-grid domain. Indeed, the GoR increased the off-grid aim from 22 to 38%, significantly increasing the adoption of off-grid solar items
	The East African Customs Management Act (EACMA) and the Law on Value-added product (VAT) No. 02/2015: As part of this effort to expand access to electricity, some solar devices, such as solar phone chargers and solar-powered fans, etc. have been exempted VAT
	An effort by the Ministerial Guidelines on the Minimum Standards for Off-Grid Solar Items to ensure that consumers are not locked into low-quality products

Institutional framework for e-waste management

The Rwanda government has created environmental protection agencies. However, there is no defined mission or competence to efficiently manage e-waste. Table 4 illustrates the established institutions' roles and responsibilities for managing e-waste in Rwanda (The Republic of Rwanda 2018). These institutions should collaborate to handle the growing issue of e-waste management sustainably and long term. In 2017, the GoR built and opened an e-waste recycling and dismantling facility in Bugesera District. The goal was to reduce the environmental risks caused by e-waste and to boost economic growth and green job creation (KTPRESS 2017).

Environmental and health effects of e-waste

Various e-waste components are processed in a manner that contributes to environmental problems such as land contamination, air pollution, water pollution, and climate change (Zhu et al. 2022). The environment substantially influences the world's condition, and it will keep playing a vital role in determining the health of future generations. Typically, the soil is essential to making food, increasing biological productivity, keeping the environment clean, keeping plants and animals healthy, and saving water (Twagirayezu et al. 2022). However, high concentrations of heavy metals (lead, cadmium, and arsenic) in soil represent a greater threat to the environment, food safety, human and animal health, etc. (Ren et al. 2019; Sonone et al. 2020) due to improper management.

The methods used to manage waste, particularly in developing nations, may harm the soil and human health (Vaccari et al. 2018; Ferronato and Torretta 2019). Several studies have demonstrated that it is challenging to regulate pollution since it is everywhere, including on farmland, at e-waste sites, and in open burning places (Wu et al. 2019; Chai et al. 2020). If we do nothing, pollution may advance to the point where the whole soil becomes depleted and cause a serious health concern. The improper disposal of e-waste might result in environmental degradation. Disposal sites and illegally dumped e-waste pose a danger to the contents of soil and hence affect agricultural output (Chen et al. 2022; Twagirayezu et al. 2022). In Rwanda, most of the environmental issues generated by e-waste result from a lack of knowledge regarding waste disposal, ineffective enforcement of legislation, and a lack of a system or organizations to oversee the dumping of e-waste. Toxic compounds from abandoned e-waste items may seep into the earth and harm the drinking water aquifer (Twagirayezu et al. 2022). The environmental effects of e-waste are depicted graphically in Fig. 4.

Typically, more than 1000 potentially dangerous chemicals, including organic compounds and heavy metals, are found in e-waste, categorized into 26 distinct types that pose a risk to the environment and human health if disposed of incorrectly (Garlapati 2017). The main components of e-waste are plastic, glass, ferrous metals, non-ferrous metals, and others (e.g., wood, ceramic, and rubber) (Alghazo et al. 2018; Twagirayezu et al. 2022). Most Rwandans need more awareness of what constitutes e-waste, making proper disposal of this material a pressing issue. Incorrect disposal and incineration of e-waste release a wide range of hazardous substances that harm

Table 4 Established institutions with oversight roles and responsibilities for e-waste management

Ministry and agency	Responsibilities and roles
MINICT	Lead the creation of the ICT Act and e-waste management policy in conjunction with the RSB guidelines
Ministry of Infrastructure (MININFRA)	Lead the development of a national sanitation strategy that will serve as a guiding principle for all aspects of waste generation and management
Ministry of Environment (MoE)	Revise environmental laws and policy to compensate for e-waste management. It is also in charge of developing a ministerial directive for managing of e-waste
Ministry of Trade and Industry (MINICOM)	It leads the building of an e-waste recycling and disposal plant and negotiated a public–private partnership (PPP) agreement with a private investor to manage and operate the facility
RSB	It makes recommendations for a proper management of e-waste, including storing, collecting, transport, treatment, and disposal
RURA	Elaborate on e-waste regulations and a structure for certifying operators in the e-waste management sectors
REMA	Concerned with environmental legislation and regulatory compliance. In addition, it conducts a descriptive survey of the quantity of e-waste produced in Kigali
FONERWA	It will develop a plan for constructing an e-waste facility, as well as conducting research and developing regulatory frameworks for managing e-waste

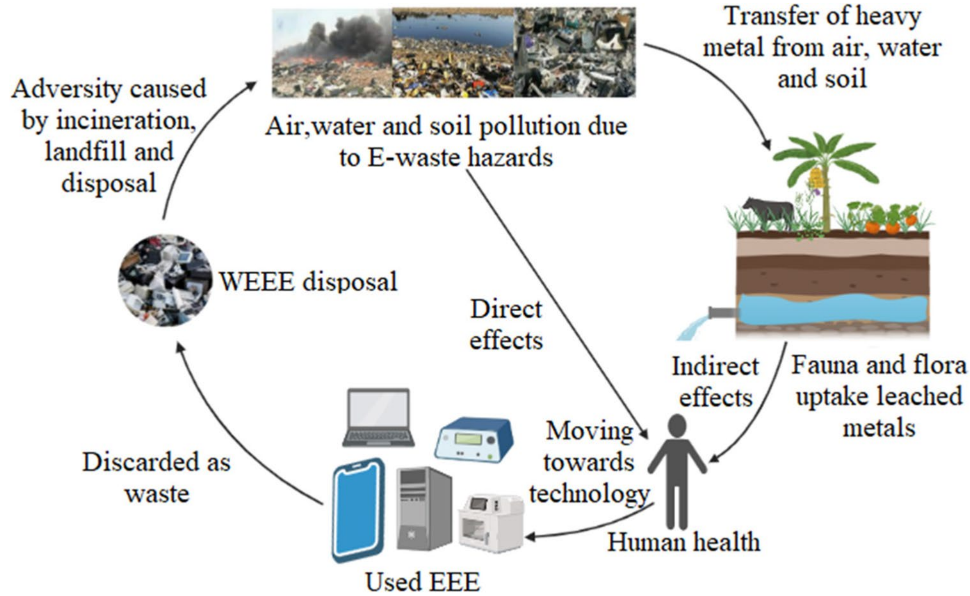

Fig. 4 Representation of the e-waste cycle and their impacts on environment

human health. E-waste collectors, especially youths, are adversely impacted since they do not wear protective clothing when collecting e-waste, resulting in serious health consequences (Rautela et al. 2021). As depicted in Fig. 5, exposure to e-waste might result in headaches, nausea, irritability, eye pain, vomiting, etc. (Jeyaraj 2021). Recyclers are at risk of developing liver problems, renal problems, and neurological illnesses (Li and Achal 2020). In addition, due to their lack of awareness, they should endanger not only their own health but also the health of others in their immediate vicinity (Shaikh et al. 2020).

Environmentally dangerous effects of e-waste have been introduced into the environment mistakenly by careless social citizens on agricultural land, in open places, and in bodies of water. Numerous studies have shown that hazardous metals like lead (Pb) and copper (Cu), as well as organic pollutants like polychlorinated biphenyls (PCBs), polybrominated dibenzo-p-dioxins/dibenzofurans (PCBB/Fs), mercury (Hg), and polycyclic aromatic hydrocarbons (PAHs), can be found in high concentrations in the air, soil, water, and sediments that are near the location of the specific activities (Ouabo et al. 2019). Therefore, workers

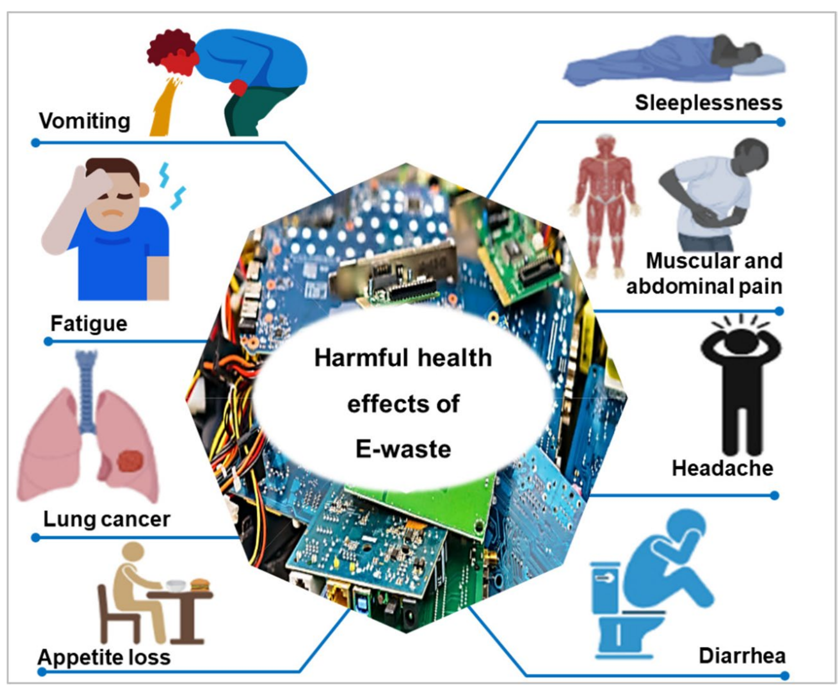

Fig. 5 Harmful health effects of e-waste

and surrounding people may be exposed to these harmful contaminants through direct inhalation, skin exposure, and oral ingestion of food and water. Incineration and landfilling are two standard methods for managing e-waste, but they can pose significant environmental and health risks due to the hazardous compounds found in them (Ikhlayel 2018; Ahirwar and Tripathi 2021). When e-waste is burned, it can release toxic gases into the air, and harmful materials can get into the groundwater through leachate from landfills. Toxic air pollution may result from recycling e-waste, mainly if the recovery business is marginally profitable and often unable to take the essential safeguards to preserve the environment and employees' health. E-waste disposal is a significant challenge to the principal components and the ecological health of the environment (Guo et al. 2018; Twagirayezu et al. 2022).

Most of the time, people in Rwanda must properly dispose of their e-waste instead of storing it in improper containers like those used for packaged rice and maize flour. While these packages hold wet or liquid substances, they may be destroyed. Old and broken materials are often used in certain houses. Containers are placed along the roadside to manage waste, and unpacked waste is collected and returned to its proper owner. When garbage trucks are hand loaded or unloaded by unskilled workers who do not have the appropriate equipment, neither workers nor the environment is maintained safely. Local governments and waste collection companies should establish sound health and safety procedures for loading and unloading these waste vehicles to safeguard their staff's safety. Another thing to consider is educational campaigns about the hazards of toxic substances in e-waste and their risks to human health and the environment (Houessionon et al. 2021; Uhunamure et al. 2021).

Table 5 lists the dangerous compounds, locations, and impacts on humans and the environment (Pathak et al. 2017). Heavy metals like chromium, mercury, cadmium, lead, etc. and halogenated components like CFCs, PCBs, and brominated flame retardants are considered potentially harmful components (Ghimire and Ariya 2020). All of these elements react with one another as catalysts, forming toxic constituents for both human and environmental health (Hsu et al. 2019). Many different kinds of metals may be found in e-waste that people throw away. If these metals are left untreated and exposed to the outside world, they could be very dangerous to humans.

Measures should be taken by the Rwanda government to ensure that e-waste is appropriately segregated from household waste to avoid hurting or compromising human health or the environment. Arsenic (As), Nickel, Mercury (Hg), and selenium, among others, have reached a point where they should be fought owing to their chronic and progressive illnesses, as well as their adverse effects on the environment and human health (Beula and Sureshkumar 2021).

Proposed sustainable and green management approach for e-waste in Rwanda

E-waste generation at the global level increased at an average annual rate of 4–5% between 2014 and 2018 (Statista 2018). A variety of municipal waste is produced daily. However, among the waste, e-waste is a significant component of the waste stream, comprising a variety of heavy metal chemicals such as mercury, silver, cadmium, lead, and gold associated with flammable materials and toxic and corrosive elements (Pandebesie et al. 2019). Landfilling is the most common approach to dealing with e-waste disposal worldwide (Kumar et al. 2017). Table 6 summarizes the major countries and their standard practices for e-waste management.

According to a study of the present and future of e-waste management in Rwanda (Twagirayezu et al. 2021), it has become clear that neither the public nor the private sectors in Rwanda are equipped to manage and dispose of e-waste in a way that is safe for the environment. E-waste management systems are insufficient in Rwanda. Nevertheless, various effective e-waste management techniques are used in diverse and prosperous countries such as the USA, EU, and Australia, which should also be the healthiest alternative for e-waste management in Rwanda.

As mentioned previously, these management practices should be used before thoroughly understanding the following concepts. Most importantly, increased national knowledge and capability in e-waste management might increase investment and job development in the processing and recycling industries. It has been well acknowledged that discarded items cause harm to the environment and the community. Due to the adverse impact on the environment and human health, proper waste management is required. A campaign to raise awareness about e-waste and its management is a good choice for the country (Odili et al. 2018; Ottoni et al. 2020) to educate the people. The greater the awareness of e-waste consumers, the more appropriate management emerges due to the demand for electronic products, and product lifecycles are readily reduced. Although consumers cannot trace the usage of infrequently used equipment by other individuals, it is critical to promote awareness about e-waste and instruct people on how to properly dispose of it (Delcea et al. 2020). Figure 6 depicts the proposed e-waste management processes in Rwanda since there are currently no viable e-waste recovery techniques that can be used to recover precious commodities that compose e-waste.

For this reason, current recycling techniques for e-waste may not be able to sustain the country's economy adequately.

Table 5 Components of e-waste that are hazardous, their incidence, and consequences. The different letters at superscript a, b, c and d behind the toxic metals represent critical, hazardous and toxic, radioactive waste; limit in serum/blood, respectively

No.	Substance	Hazardous metals	Limit (ppm)	A disease induced by exposure to a quantity greater than the allowable limit
1	Switches, ceramic capacitors, and batteries	Ag^{a}	5.0	The kidney, brain, lungs, and liver may all be damaged by excessive levels of blue pigments in the body
2	Gallium arsenide is used in integrated circuits, infrared light-emitting diodes	As^{b}	5.0	Long exposure has a detrimental impact on the skin, nerve signaling and lung cancer
3	Fluorescent lamp, electron tube, and lubricant	Ba^{b}	Less than 100	Induce swelling of the brain, muscular weakness, and heart damage
4	Motherboard and power supply boxes	Be^{b}	0.75	Leads to berylliosis, carcinogens, skin disease, and lung cancer
5	Printed circuit boards (PCBs), casing, and PVC cables	Br^{b}	0.1	DNA damages, skin disorder, hormonal issues, hearing loss, and thyroid gland damage
6	PCBs, CRTs, battery, infrared detectors, printer ink, semiconductors, and toners	Cd^{b}	1.0	They induce an existential threat to human health, especially the kidney
7	PCBs	CN^{b}	Less than 0.5	Cyanide at a concentration greater than 2.5 parts per million (ppm), may result in coma and death
8	Hard discs, cabling, as a colorant in pigments	$Cr\ (VI)^{b}$	5.0	This is toxic in the environment, inducing DNA damage and irreversible visual impairment
9	Batteries, switches, LCD, lamps, or backlight bulbs	Hg^{b}	0.2	It causes damage to the brain, kidneys, and fetuses
10	Mobile phones, batteries	Li^{a}	Less than 10d	They should induce diarrhea, drowsiness, vomiting, and muscular weakness
11	PCB, semiconductor, batteries, CRT	Ni^{a}	20.0	They cause lung cancers, allergic reaction, bronchitis, and reduces lung function
12	Transistor, PCBs, CRT, florescent tubes, LED lead-acid battery	Pb^{c}	5.0	They damage reproductive system, brain, neurological system, and kidneys. It induces acute and long-term health impacts for humans
13	Plastic computer housing, CRT glass, and a solder alloy	Sb^{b}	Less than 0.5	Carcinogen, vomiting, diarrhea, leading pain and ulcer of stomach
14	Photoelectric cells, fax machine	Se^{b}	1.0	A high level of concentration results in selenosis
15	Batteries, CRT	Sr^{c}	1.5	There are both somatic and genetic alterations that result from this cancer in the bone, skin, and lungs
16	Luminous substances and batteries	Zn^{b}	250.0	Cramps, pain, vomiting, diarrhea, and nausea
17	Insulation foam and cooling units	$CFCs^{b}$	Less than 1.0 for 8 h/day	It causes ozone layer impacts that might contribute to an increase in the prevalence of skin cancer
18	Capacitors, condensers and transformer	$PCBs^{b}$	5.0	It is known to cause cancer for animals and may cause liver harm in people
19	Monitors, cabling, plastic computer housing and keyboard	PVC^{b}	0.03	Contaminants in the air that are hazardous and harmful, the release of HCl induces respiratory problems

E-waste must be better treated, sorted, and recycled to enhance environmental waste management (Andrade et al. 2019). Therefore, the proposed e-waste recycling processes in Rwanda are shown in Fig. 7. Typically, the greater the availability of recycled items, the lesser the demand for new material. This indicates that the proposed recycling processes will encourage using recycled materials instead of continuing to purchase new materials that will also be discarded and regarded as e-waste. It is known that during recycling processes, 95% of the materials that compose EEE may be recovered (Krauklis et al. 2021). Among these materials, precious metals such as rubber, silver, iron, platinum,

Table 6 Conventional methods used for managing e-waste in different countries

Country	WEEE management procedure	References
Australia	Handling, recycling, regulating and preventing WEEE, formal and informal recovery	Ongondo and Williams (2011)
France	Waste management technique with recovery and recycling chains	Bahers and Kim (2018)
South Africa	Open incineration and dumping, crude dismantling and sorting	Ghosh et al. (2016)
Denmark	Recycling	Parajuly et al. (2017)
European Union	Recycling	Ghosh et al. (2016)
The USA, India	Recycling	Kumar and Dixit (2018)
Brazil	Mechanical and physical separation processes, dismantling process, refining processes, the specific recycling process	Dias et al. (2018)
The USA	Landfilling and incineration, EPR, recycling, material separation (mechanical/chemical)	Lee et al. (2003)
Norway, Switzerland, Sweden, Denmark	Differentiated laws for e-waste management	Román (2012)
South Korea	Reuse, landfill, incineration, recycling	Kahhat et al. (2008)
Japan	Recycling	Li et al. (2012)
The UK	Different treatment method (segregation, dismantling, shredding), metal recovery, reuse product	Ongondo et al. (2011)
Ghana, Nigeria, Morocco, South Africa, Tanzania, Uganda	Informal and formal e-waste recycling	Wath et al. (2011); Li et al. (2012)
China	Internalization of environmental costs into product pricing, decreased natural resource use, waste avoidance and reduction, material reuse, energy recovery where incineration is regarded acceptable, informal, and formal recycling	Li et al. (2012); Yu et al. (2014)

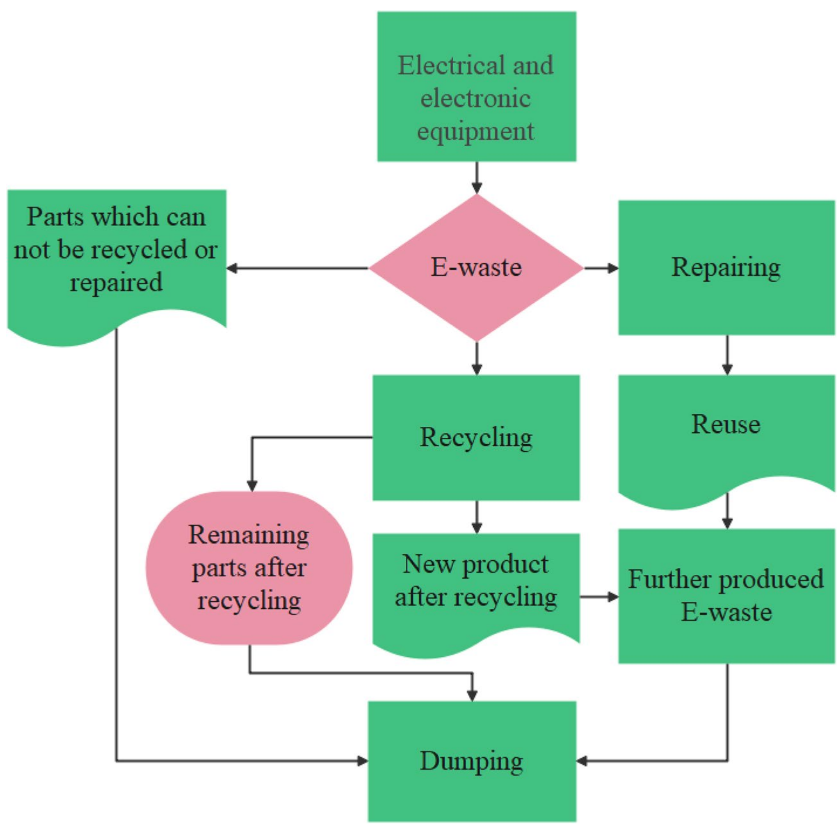

Fig. 6 Proposed e-waste management in Rwanda

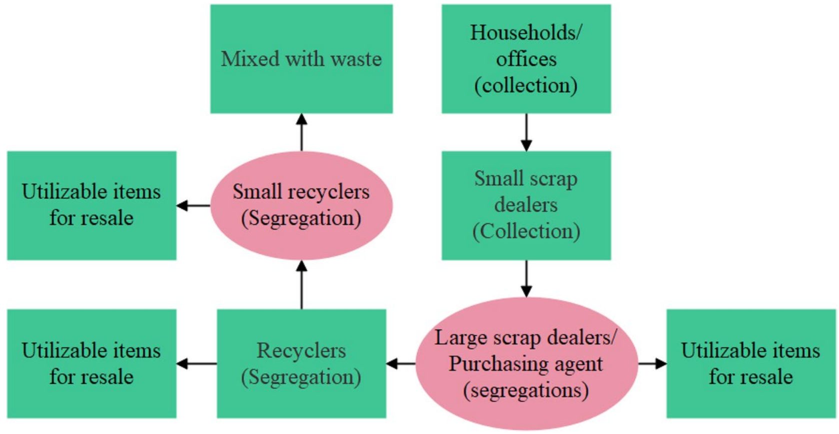

Fig. 7 Proposed e-waste recycling processes in Rwanda

copper, glass, and gold are beneficial worldwide and can repay the recyclers participating in recycling work. Therefore, the application of modern e-waste recovery methods in the process of recovering hazardous components like lead (Pb) from malfunctioning cathode-ray tubes (CRTs) with a minimum amount of unfavorable influence on the environment (Imre-Lucaci et al. 2021) is required. After the useable e-waste components have been recycled, the hazardous components must be disposed of in a safe location far from any human habitation (Andeobu et al. 2021). Typically, recycling e-waste has less impact on the environment than incineration and dumping it in landfills (Rasheed et al. 2022). These proposed recycling processes will assist in preserving our environment and people from the potential adverse effects of e-waste components and lower the amount of waste disposed of in landfills.

Proposed sustainable processes for reusing e-waste in Rwanda

E-waste recycling and reuse are widely embraced in non-government and government operations due to their practicality and manageability. Recycling is a critical component of environmental conservation efforts. The recycling system in Rwanda may need to be considered adequate due to its management and scalability deficiencies. These issues have been exacerbated due to the fast expansion of ICT followed by a consecutive e-waste stream in Rwanda. According to the facts of a thorough investigation of this e-waste recycling approach, the following recommendations may be made to implement an e-waste recycling system that is maintainable and ethical. To reduce installation costs, a technique for recycling e-waste was suggested to be added to the present management system for municipal solid waste (Sudipta et al. 2017). Typically, recycling is a green option for reusing e-waste and should be accomplished via the commitment of people in private and non-private sectors. Figure 8 shows a schematic representation of the proposed system for the sustainable reuse of e-waste.

The system should be separated into many centers distributed among Rwanda's municipal corporations during the e-waste recycling process. City workers should collect and transport e-waste from homes and workplaces to processing facilities, while in rural areas, the local cleaners should collect and carry it to their nearest cities. District cleaning staff would also adhere to standards governing e-waste collection and sorting, including computer chips, wires, and circuits. The various pieces of e-waste will be sent to the divisional recycling facility for processing and reuse. Workers in the supply chain of different components will disconnect the component from the assembly line and then recycle it separately at the municipal recycling plant. After that, a thorough recycling procedure is conducted, and the recovered materials are returned to the constructors. Assembling Corporation creates novel electric goods with a distinctive approach compared to other companies, such as converting CRT televisions into inexpensive televisions for video game shows. Acts include refurbishments that restore non-functioning microelectronics from waste to a functional condition. The total capacity of discarded devices has been channeled into new manufacturing circles. Customers get their hands on the latest products.

Life cycle assessment in Rwanda

The term "life cycle assessment," more often abbreviated as "LCA," refers to the process of evaluating the environmental impacts associated with all aspects of the life of a commercial product, process, or service (Xue and Xu 2017; Ibáñez-Forés et al. 2021). Herein, LCA is regarded as an essential instrument for managing e-waste and reducing its adverse effects on the environment via investigating the consequences of various management approaches (Roy et al. 2022b). As shown in Fig. 9, the proposed LCA is a

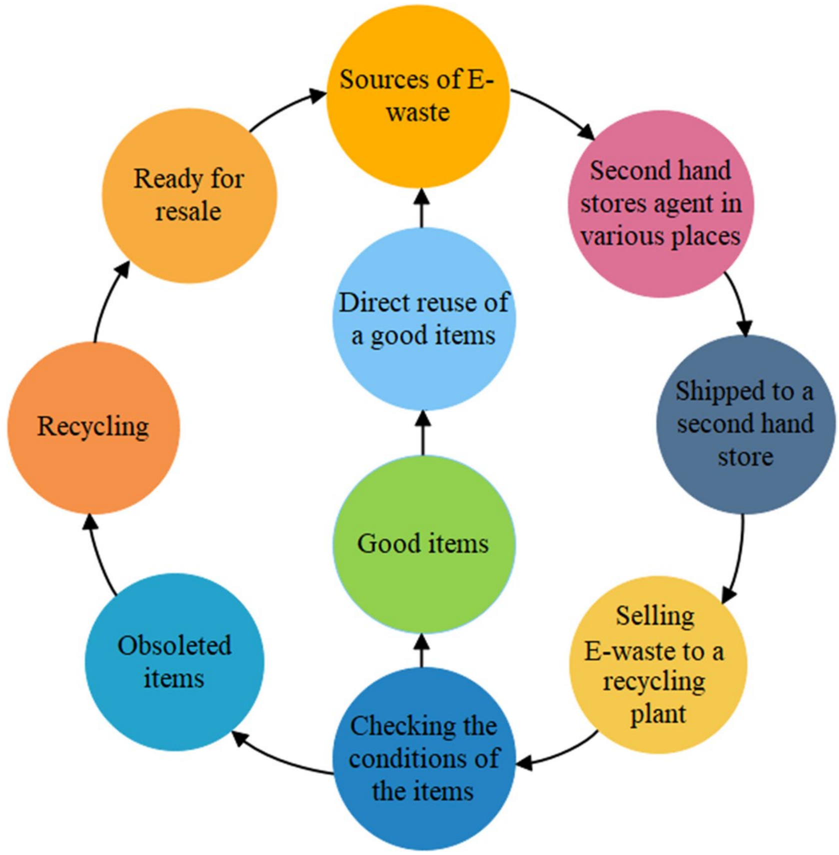

Fig. 8 Proposed concept for sustainable reuse of e-waste

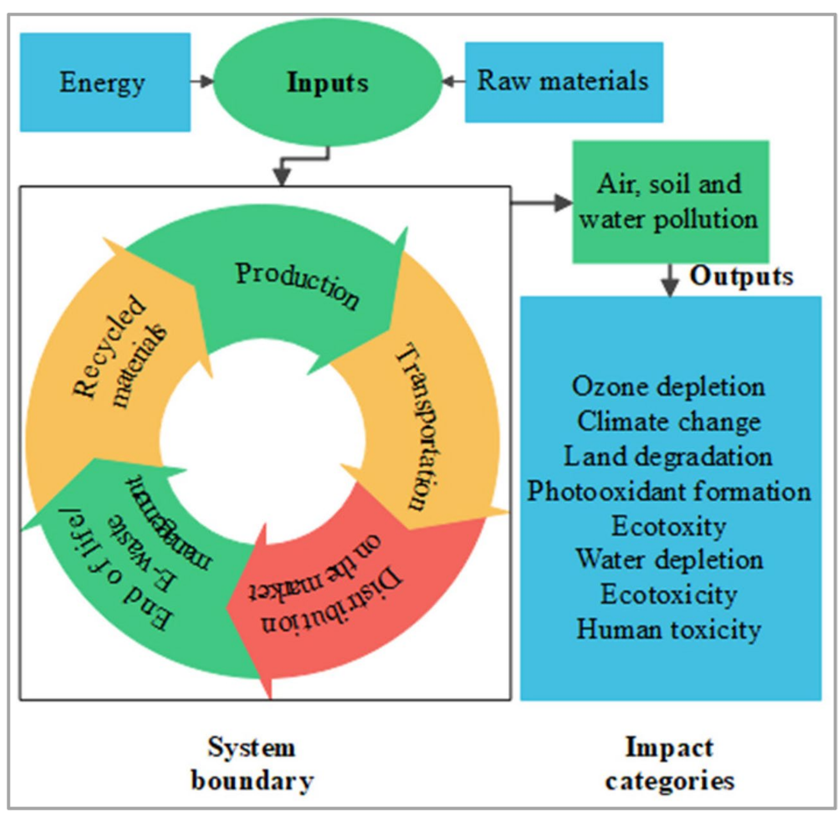

Fig. 9 Proposed life cycle assessment processes for e-waste management

powerful tool that systematically, effectively, and methodically analyzes and identifies the environmental impact, critical factors, decisions, and management processes based on inputs, systems, outputs, and impact categories. In addition, the complete LCA framework must be composed of a life cycle assessment framework containing three main points: goal and scope definition, inventory analysis, and health and environmental impact analysis, which are also vice-versa connected to interpretations. Then, all four together are vice-versa linked to the direct application, composed of product development and improvement, public policy making, marketing, strategic planning, and others.

Regarding functional unit and system boundaries, the goal and scope description outline the product system. The functional unit is the essential base for comparing and analyzing alternative products or services. The functional unit is not only an amount of e-waste produced but also indicates e-waste sources and types associated with its impact on human health and the environment. Life cycle inventory (LCI) is concerned with estimating the input and output of material inside the system's boundary and energy throughout the collection, transportation, treatment, and disposal processes (Andeobu et al. 2021). Typically, waste, energy, water consumption, and the emissions of pollutants into the environment are all factors in the input–output balance. Other LCI phases involved creating a strategy for collecting data, checking the data, evaluating the results, and reporting them.

The life cycle impact assessment (LCIA) is a qualitative and quantitative assessment of the environmental effect of data from an inventory study (Ismail and Hanafiah 2021). It enables a deeper comprehension of the harm induced through the use of resources and the emission of pollutants into the environment. The significant component of LCIA is identifying different environmental effects, like human toxicity, land acidification, and climate change, followed by the classification of impact categories based on LCI results. In addition, it figures out the potential impact for a number of different influence groups based on emissions and resource use, and it also standardizes the implications of the findings based on a reference so that the impact factors can be compared (Roy et al. 2022b). Typically, CML 2001, Impact 2002, EPD 2007, EPS 2000, EDIP 2003, Eco-indicator'99, TRACI, ReCiPe, USEtox, etc., are the methods for LCIA that are used for analyzing the impacts linked with the system (Roy et al. 2022b). However, CML is perhaps the most widely used technique for e-waste LCIA, and it has been thoroughly discussed in the scientific literature. Analyzing inventory data for impact assessment utilizing a number of frameworks and impact categories is performed using several approaches (Xue and Xu 2017). Midpoint or problem-oriented technique and an endpoint or threat-oriented technique are the methodologies used for LCIA. Finally, the results are analyzed to discover the critical issue, the sensitivity and consistency of the data are evaluated, and conclusions and suggestions are developed. Typically, the production and use of EEE are not included in the scope of LCA research for e-waste management, which is the approach adopted in Rwanda. However, its study extensively emphasizes treatment and recycling processes (Laurent et al. 2014). In recent years, applying LCA in research about e-waste administration has become more widespread (Ismail and Hanafiah 2019). However, it is used more often in developed European nations than developing nations for e-waste management research. Due to the high amount of e-waste being produced in developing countries, it is very needed.

Based on e-waste management, LCA is categorized into three main groups: First is an analysis of a single product's environmental impacts, identification of harmful effects throughout the treatment process, and a comparison with alternative treatment approaches (He et al. 2022). For this, it is based on not only the life cycle evaluation of PCBs, monitors, electronic toys, personal computers, and other e-waste but also the recycling and recovering of metals during the phase of treatment (Roy et al. 2022b). The second is to optimize the environmental effect of e-waste treatment operations by taking e-waste as a whole and not singling out a specific kind of EEE (Islam and Huda 2018). Third is evaluating the environmental impact by focusing on the particular e-waste collection infrastructure (Xue and Xu 2017). In Rwanda, several kinds of e-waste are being increased at a high rate and regarded as other waste, where they are huge located in different institutions, industries, etc. Due to this, LCA is widely carried used in Rwanda.

From linear towards a circular economy of e-waste in Rwanda

E-waste management is among the most critical issues facing today's lives (Islam and Huda 2019). E-waste may begin in numerous ways within the circular economy, like repairing, reusing, recycling, and remanufacturing by end users or customers (Islam et al. 2021). The need to transform EEE via the circular economy has been underlined to reduce resource consumption and to extend product lifecycle (Reike et al. 2018; Ottoni et al. 2020). It is interested in recovering secondary raw resources from e-waste (Xavier et al. 2021). Thus, innovation for e-waste management can be done in collaboration with manufacturers, retailers, and labor investors to ascertain extensive management of the informal e-waste sector works under environmental quality and human health protection while employing workers whose livelihood is dependent on the flow of discarded e-waste (Awasthi et al. 2019).

With environmental protection initiatives, Rwanda has the potential to move from a linear system to a circular economy, highlighted by minimum industrial waste and resource optimization (The New Times 2019). Rwanda sought ways to promote a circular economy, also termed a zero-waste economy, which is defined as extracting the most tremendous amount of value possible from all types of resources and waste. For instance, switching from disposable e-waste (e.g., water dispensers, phones, TVs) to reusable ones are healthy for the environment and more cost-effective. Efforts have been made in Rwanda to coordinate the country's economic development with environmental preservation. Achieving this aim will be impossible without the support of local businesses that create in a manner that benefits both people and the earth. The government of Rwanda has underlined the necessity for industries and enterprises to incorporate the circular economy into their activities rather than continue with the present "take, make, dispose of" paradigm of consumption. As represented in Fig. 10 (Burrows-Smith 2018), in the linear economy, individuals take resources, convert them into items, and then dump them into waste at the end of their existence, whereas, in a circular economy, all of the commodities are reused either through having long-lasting products, repairing and exchanging things, or recycling materials. A circular economy efficiently generates employment, enhances economic development, and raises living standards.

Herein, economic analysis of e-waste should be considered. Typically, there is a considerable cost involved with e-waste, a significant portion of which may be recycled and reused. Therefore, the quantity of secondary material recovered from e-waste is calculated by multiplying the amount of waste material by the recycling yield of the relevant item. The recycling yield of things may be found in various types of literature (Domínguez and Geyer 2019). In addition, although precious and vital metals account for a lesser amount of trash, their proportion to waste is remarkable, given their capacity to provide value and competitive advantage. Thus, determining the extent to which each metal contributes to the economy is critical. Various literature reviews, websites dealing with money management, and other sources provide evidence of the monetary worth of particular metals (Domínguez and Geyer 2019; Islam and Huda 2019).

Recommendations and future prospects

Based on the rate of economic growth associated with the present state of e-waste deposits, the current legal framework, and the anticipated trade conditions for EEE in Rwanda, the most significant crucial measure should be to ensure that the law is effectively put into practice. The government of Rwanda should not be allowed to dump waste under the guise of charitable endeavor, and NGOs should be required to adhere to tight guidelines to avoid accepting contributions of EEE from other countries. If it is discovered to violate these standards, the government/regulatory authorities should take swift and severe action against the violators of the rules. It is critical to educate Rwandan consumers about the importance of their contribution to the effective management of the e-waste created by them, particularly among the youth. The most challenging component in this regard is increasing public knowledge, which may be achieved via mass media like television, newspapers, and social media platforms, as well as awareness programs focused on appropriate e-waste collection, storage, and disposal. Rural education may provide significant strength for the overall process by increasing awareness and creating space for collecting places. The collected e-waste may be immediately sent to a formal treatment facility recognized by the State or Central Pollution Control Board.

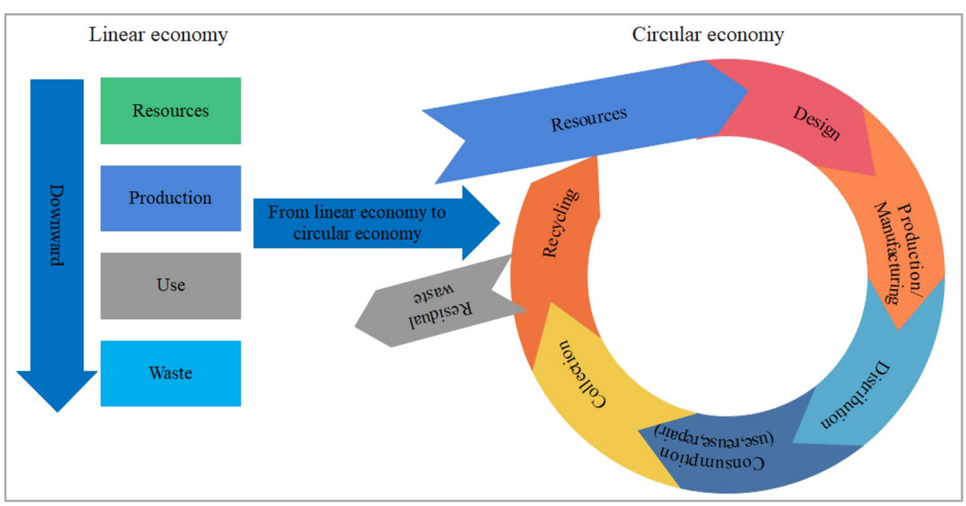

Fig. 10 The circular economy approach of e-waste management

An EPR system should be implemented, together with an advanced collection, transportation, recycling, and disposal fee, to be effective. Under this scheme, customers and suppliers would be charged an additional fee to recycle the things they purchased at the point of sale. These fees could help pay for the cost of recycling e-waste that is thrown away in a landfill. The manufacturer or a third-party needs to be given a government subsidy to recycle each EEE. To enforce the obligations of the product's manufacturer, it is necessary to keep track of sales data for the used equipment and to keep an eye on the black market. To offer effective e-waste management, basic infrastructure, such as collecting, transport, separation, processing, storing, recycling, and dumping must be established at the regional and state levels, etc. Participation by the private sector should inspire the private sector to participate in government projects. To evaluate the social impact of the take-back law, it is essential to provide incentives for the design and production of more environmentally friendly products. The government may give businesses with good waste management or recycling systems more incentives and tax breaks.

Rwanda should fight against rudimentary methods to recover valuable metals e-waste like platinum, palladium, gold, and silver from printed circuit boards (PCBs) as done in China, Pakistan, Philippines, Nigeria, Ghana, and the Philippines (Ikhlayel 2018). Contrary, an advanced recycling approach associated with metal recovered from e-waste should be encouraged because it is a lucrative source of money for recyclers, which might lead to additional employment in the organized sector. This should be done by visiting developed countries across Europe and American continents, where e-waste management has been successful (Gollakota et al. 2020). Those developed countries use a reliable approach when dealing with their e-waste waste. Given the importance of both the formal and informal recycling processes, it is crucial to look at the possibility of a more integrated system so they can work properly. Engineers should enlist the assistance of environmentalists so that they may become more aware of the ecological, social, and health consequences of e-waste in the future, and they should consider this knowledge while designing and developing new products.

Conclusion

In summary, the imported EEE was 33,449 t in 2014, and it is expected to be 267,741 t in 2050, with a yearly increase rate of 5.95% contributing to the significant production of e-waste, which is also likely to continue. However, out-of-date EEE is still being dumped as e-waste in large quantities and at an increasing rate across Rwanda. In addition, it has a restricted database associated with no prodigious management strategies on e-waste produced in conjunction with its management. This shows that e-waste must be appropriately managed to avoid harmful environmental and health effects in Rwanda. E-waste management in Rwanda is hampered by the limited awareness among the people, as well as a lack of sufficient funds, resulting in management approaches which do not fare well enough in Rwanda. In this article, a couple of successful techniques for managing e-waste have been proposed. The proposed methods are critical for the successful management of e-waste in Rwanda. People in Rwanda can solve the e-waste management issue by incorporating these alternative approaches into the existing waste management system.

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