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REVIEW

Electrical and electronic waste (e-waste) recycling and management strategies in South Asian region: a systematic review from Sri Lankan context

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Abstract
Electrical and electronic waste (e-waste) has become a global crisis. Managing this ever-growing problem has become very critical and yet challenging, especially in the South Asian region; otherwise, it may undermine the sustainability of development and growth of numerous industries. Hence, to explore the current context of e-waste management, recycling, and strategies in Sri Lanka, we conducted a systematic literature review process using peer-reviewed research articles retrieved from Google Scholar Database. We searched for articles containing keywords such as "e-waste", "management strategies and recycling", and "Sri Lanka". We screened out papers ($n=20$) selected from papers ($n=327$) initially retrieved over a 17 period of time (2005–2022). The analysis of the screened articles showed that the main challenges to successful e-waste management were a lack of management strategies, policies, and inadequate recycling practices as well as identifying the potential and opportunities to actively enhance the comprehensive awareness, collection, storage, proper disposal, and other e-waste management steps in Sri Lanka. Further, the study identified technological, financial, socio-economic, and institutional sectors as fundamental sectors to formulate a strategic plan for e-waste management. Also, the study suggests that enacting laws to practice and adopt e-waste management, establishing central command and management institutes to control all e-waste management bodies, providing financial assistance to informal e-waste collectors and recyclers, and introducing e-waste management to school curricula are some of the possible actions that can be taken along with enhancing the awareness of e-waste management.

Keywords Collection and recycling · Disposal · E-waste management strategies · Sri Lanka · Sustainable development goals

Introduction

Electronic waste (e-waste) and world context

From the dawn of human civilization, waste management has been the top priority of national governments and policymakers since waste management plays an important part in civilization development and inhabitants' health [1]. A major part of human history, people battle with organic material. The industrial revolution has drastically changed humanity's understanding of waste and its' management policies. The dawn of the electronic era after the 1950s and the third/fourth industrial revolution made electronic and electrical waste one of the fastest-growing waste streams in the world, thus posing a direct challenge for human health and the sustainability of the environment [2]. Electrical and electronic equipment has emerged as one of the most important aspects of our everyday lives, as modern humans are heavily dependent on electrical and electronic equipment to fulfill their tasks. Unfortunately, this high demand for electrical and electronic equipment turns into a negative environmental impact when they end up as waste in the environment. Waste generated from the end-of-life of

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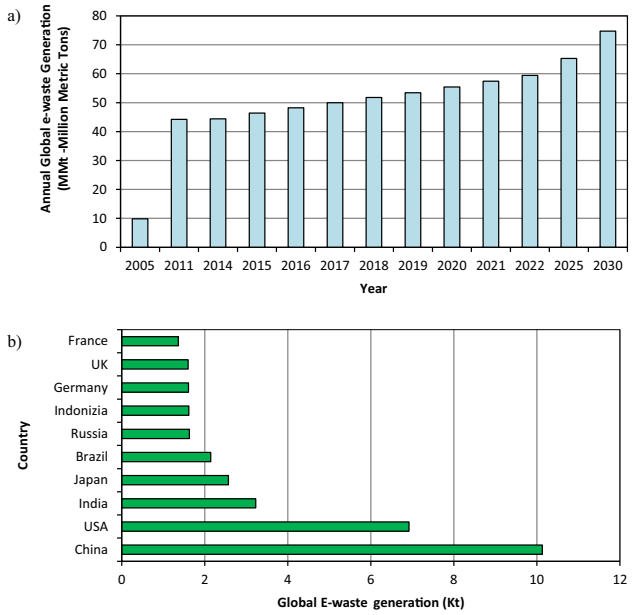

Fig. 1 **a** Total annual global e-waste generation by region and **b** major global e-waste producers by country

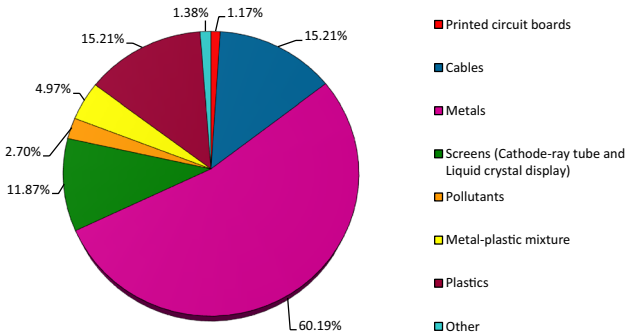

Fig. 2 A typical composition of e-waste (Source: [11], adapted with permission)

electronic and electrical products is called "e-waste". As per the definition of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, e-waste is considered as "electrical or electronic equipment, which is waste, including all components, subassemblies, and consumables, which are part of the equipment at the time the equipment becomes waste" [3]. This e-waste generation has become a global crisis due to the heavy supply of manufactured electrical and electronic appliances in the world.

According to current statistics by the United Nations (UN), in 2021, the average generation is predicted to be nearly 7.6 of e-waste per capita, amounting to a huge 57.4 MMT (million metric tons) worldwide [4]. Hence, e-waste is becoming a rapidly expanding residential waste source in the global context. Furthermore, it was estimated that by 2030, the worldwide production of e-waste will reach 74 MMT (Fig. 1a). As per Fig. 1b which portrays the countries and regions that accounted for e-waste generation, Asia contributed the most e-waste generation, followed by the Americas, Europe, Africa, and Oceania [5, 6]. This highlights the fact that most of the countries in the Asian region are responsible for e-waste generation and the lack of well-established policies and strategies for waste management has made the matter worse. This signifies the importance of understanding the behavior of e-waste, the importance of e-waste, and current practices of e-waste management regionally to understand the loopholes and shortcomings with respect to e-waste management challenges.

As reported by the World Health Organization (WHO), computers, monitors, motherboards, chips, wireless devices and other peripheral items, printers, copiers and fax machines, telephones, mobile phones and tablets, video cameras, televisions, stereo equipment, cathode ray tubes, transformers, capacitors, cables and batteries, lamps and light bulbs, large household appliances, toys and sports equipment, tools, and medical devices are grouped under the categories of e-waste [7]. In terms of the impacts of e-waste, unlike other waste, e-waste contains valuable economically viable materials that can be recycled [8]. For instance, e-waste contains a variety of components, especially low degradable matter including metals, glass, and plastics (Fig. 2). With regard to the major hazardous compounds in e-waste, both inorganic and inorganic elements and compounds exist. For example, inorganic substances such as C, Pb, Cu, Si, Be, Fe, Al, and thermosetting plastics and organic substances such as large amounts of persistent organic pollutants (POPs), such as polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), and dioxin, will be released into the surrounding environment [9]. The composition of e-waste products comprises hazardous chemicals and heavy metals which have direct health and environmental impacts such as air, water, and land pollution and cause human health degradation [10].

In the case of improper disposal of e-waste that contains Pb, Cd, and Hg, heavy metals accelerate soil and water contamination leading to inorganic pollution. These toxic materials can cause kidney, neurological, and cancer damage through ingestion [12, 13]. Also, massive burning of e-waste emits dioxins and furans which ultimately lead to airborne diseases such as asthma and bronchitis [14]. Among the most vulnerable communities that are susceptible to e-waste exposure, e-waste collectors and recyclers are at a huge risk for toxic chemicals [15]. Apart from that, children are more vulnerable to the negative effects of e-waste because their bodies are still developing and because they have a higher

intake of certain toxins per body weight [16]. In addition, appliances such as televisions and computer monitors contain cathode ray tubes that can emit X-rays. When these devices are not handled properly, workers and people living near e-waste recycling plants can be exposed to harmful levels of radiation. Hence, improper handling and disposal of e-waste can also lead to the spread of disease through inadequate sanitation. This happens in cases where e-waste is not handled and stored in a clean and safe manner, allowing bacteria, viruses, and parasites to spread. As a result, this can cause a variety of health problems, such as gastrointestinal infections, skin diseases, and respiratory infections [17]. However, most of these negative impacts are more common in the least-developed or developing countries than in developed countries, as they are in a deficit of proper management strategies and planning related to e-waste. Consequently, improper disposal of this e-waste has become a major contributor in the South Asian region to this issue, and this phenomenon prolongs the achievement of sustainable development goals (SDGs) [4]. On that account, it is crucial to investigate and address the strengths, weaknesses, threats, and opportunities of e-waste recycling and strategic management to ensure environmental protection and sustainability.

E-waste and South Asia

Rapid population growth and accelerated industrial growth led by India and Bangladesh have made South Asia one of the hot spots for e-waste generation [18]. Unfortunately, South Asia and other least-developed countries have become dumping grounds for e-waste and hazardous materials. Economic advancement created in the region has subsequently increased e-waste. According to estimations, Bangladesh generates 2.8 million tons of e-waste every year, and as per the predictions done by Alam and Bahauddin, 500,000 personal computers (PCs) were in use in 2004 with an annual increase of 11% and 100% increase in mobile phones [19].

However, the current trends of electronic product consumption show a very high obsolescence rate in the electronic market. Rapid technological and manufacturing growth coupled with improvements in logistics has made electronic devices easier to manufacture. Most electronic devices have a very short life span and are routinely changed to accommodate new features (especially in the West) and then simply either discarded or re-export to developing nations as second-hand devices [20]. To justify that, the StEP database has illustrated that India leads in e-waste generation in South Asia with the production of 2.75 MMT within its borders. Pakistan and Bangladesh produce 0.30 MMT and 0.18 MMT, respectively. Maldives (1690 MT) produced the least amount of e-waste followed by Bhutan [21]. Figure 3 illustrates that India leads the generation of e-waste in South Asia while Bhutan and Sri Lanka score

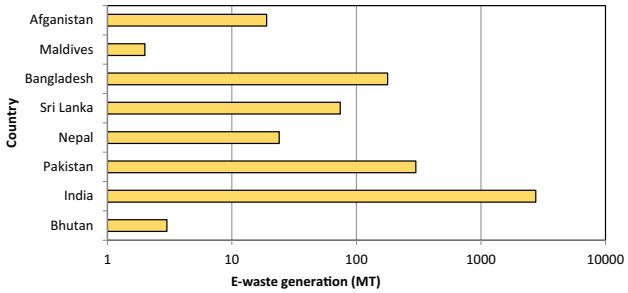

Fig. 3 E-waste generation in South Asian countries (Source: [21], adapted with permission)

relatively high per capita e-waste generation compared to their economic size. Afghanistan is at the bottom of the list due to the less wealthy generation in the country.

E-waste management in India

With the second largest population on the planet and predicted to be the largest soon, India is a developing country that owns a large consumer market. Moreover, India has become a magnet for the second-hand electronic devices market and a dumping ground for e-waste. Due to the higher landmass of the country and the complex dynamics of the governing structure, it is very difficult to qualify and quantify e-waste generation in India [22]. India's per-capita waste production is relatively low due to the large population, but a considerable amount of e-waste is imported due to cheap and readily available informal methods of recycling [23]. Concerning e-waste, various governmental and non-governmental organizations (NGOs) have given different estimates on e-waste. According to Lakshmi and Raj [24], it is estimated that 7.2 MT of industrial hazardous waste and 400,000 tons of e-waste are annually generated in the country. Figure 4 shows the percentage of e-waste generated from different states in India.

Like the majority of South Asian countries, the sector of Indian e-waste collection and recycling is dominated by

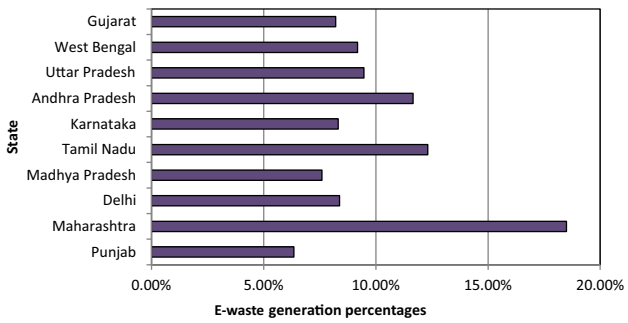

Fig. 4 Percentages of e-waste generated from different states in India (Source: [24], adapted with permission.)

informal collectors and recyclers, which consist of small groups of considerable manpower filled by women and children [25]. The informal sector is constrained by minimum safeguards for health and the environment. Furthermore, similar to many developing Asian countries, India lacks the regulatory framework to minimize health and environmental implications due to the informal sector [26].

In 2005, the Central Pollution Control Board of India published the guideline for environmentally sound management of e-waste [27]. This broad guideline document has provided directives for the identification of various e-wastes and has provided recommendations for the proper handling and discharge of e-waste. E-waste Management and Handling Rule 2011, that was enacted by the Ministry of Environment and Forestry, has made the manufacturer of electrical and electronic items share responsibility for collecting and providing e-waste management finance through the producer's responsibility for a product extending to the post-consumer stage of the product's life cycle called "Extended Producer Responsibility". In recent history, the Government of India has enacted several acts and laws to give further teething for law enforcement agencies to manage and handle e-waste. New E-waste Management Rule 2016 and further amendments were done in 2018 by the Ministry of Environment and Forestry [28].

E-waste management in Pakistan

Rapid growth after economic reforms since 1960 has seen rapid growth in e-waste generation in Pakistan. The combined effect of economic development and increased pollution has created a perfect storm of e-waste generation in Pakistan, especially in home appliances (television, refrigerators, washing machines, etc.) and telecommunication equipment.

As the sixth most populous nation and is becoming fifth most populous nation, Pakistan is a developing country with less capital and infrastructure to handle escalating municipal waste and e-waste [29]. As a result of low purchasing power, consumption of Pakistan people tends to prefer second-hand electronic items, thus creating a lucrative market for the importation of second-hand and used electrical and electronic items to Pakistan. Most of these imported items are not regulated, or quality checked, hence contributing to ever-growing issue of e-waste problem in Pakistan. It is also worth noting that due to this second-hand electronic item demand, Pakistan has increasingly become a dumping ground for e-waste from rich and affluent countries [11].

In Pakistan, e-waste and other hazardous recycling are followed in informal facilities due to a lack of legal and capital compliance. Cheap cost-effective recycling methods, such as open burning, physical dismantling, and acid treatments are commonly practiced without any protective equipment and methods, therefore contributing to environmental pollution and health issues [30].

Based on the summarized information shown in Table 1 [30], Pakistan imports 60,000 tons of electronic items, of which the majority ended up in open dumping sites once they were used. Moreover, the generation of e-waste is not quantified, thus leading to a lack of understanding of total e-waste generation in Pakistan. Due to rapid economic growth and urbanization, it is estimated that 72% of the country's population uses mobile phones, the purchasing of television is forecast to increase by 12% and computers are projected to increase by 5.8% annually [31].

For most developing countries, the Basel Convention plays a major role in the establishment and ratification of local indigenous environmental regulations. Pakistan has enacted several important legislations that deal with environmental management. Some of the important legislations followed in Pakistan are listed below (Table 2). Those mentioned ordinances and acts just cover general and overall hazardous waste, thus restricting the implementation. More

Table 1 Quantities and weight of major electronic items imported to Pakistan in 2017 (Source: [30], adapted with permission)

Item name	Average import unit (million)	Average import weight (tons)
PCs	1.42	35,522
Laptops	0.25	889
Monitors	1.03	14,577
TVs	0.20	6414
Printers	0.19	1270

Table 2 Legislations for e-waste management in Pakistan (Source: [32], adapted with permission)

Year	Legislation
1983	Pakistan Environmental Protection Ordinance
1984	Pakistan Environmental Protection Council
1992	National Conservation Strategy
1997	Pakistan Environmental Protection Act (PEPA) Section 11 of which prohibits discharge or emission of any hazardous chemical into environment Section 13 Regulations on Importation of Hazardous Elements and Products to Pakistan Section 14 Regulation on Handling of Hazardous Material in the territory of Pakistan
2005	National Environmental Policy
2007–2008	Import Policy Order
2016	Amendment

specific targeted legislation for e-waste management and handling is very much needed [28, 32].

E-waste management in Bangladesh

Bangladesh is one of the most populous countries in the world, with a population of over 164 million people. Bangladesh has become one of the world's fastest-growing economies due to rapid industrialization and globalization. Bangladesh, like other South Asian nations, lacks a legal framework and awareness of e-waste management policies [6]. Bangladesh, like Pakistan, tends to prefer second-hand electronic goods, creating a lucrative market for the importation of second-hand and used electrical and electronic goods.

Bangladesh has attracted the shipbreaking industry, as depicted in Fig. 5, due to its abundant supply of inexpensive labor. This has contributed to rapid environmental pollution and degradation and caused Bangladesh's government significant waste management concerns [33].

Bangladesh, like many South Asian nations, lacks a solid legal framework to support e-waste management and minimize its environmental impact. Due to the pervasiveness of the informal sector, it has become difficult to implement and enforce legal statutes, despite the existence of some. Table 3 depicts the Bangladeshi regulations and laws applicable to the management of e-waste.

The National Environmental Policy, enacted in 1992, and the National Environmental Protection Act, enacted in 1995, have become the foundation for the management of e-waste and hazardous materials in Bangladesh [36]. In 2011, Bangladesh adopted "Electrical and Electronic Waste Rules (Management and Handling)" as a matter of policy. However, recent developments in legal provisions for the management of e-waste are encouraging. Bangladesh adopted Hazardous Waste (e-waste) Management Regulations in 2021. The Department of Environment issued these regulations pursuant to the National Environmental Protection Act of 1995 [36]. The rule encompasses a broad range of electrical and electronic products and emphasizes the collective responsibility of users, collectors, sellers, and transporters to mitigate the environmental impact of hazardous waste (e-waste). According to the Environmental Protection Act of 1995, violators face a maximum sentence of 2 years in prison, a fine of two hundred thousand taka, or both. There is also a provision regarding how to handle repeat offenders. Due to the pervasiveness of the informal sector, implementation of these rules and attaining legal force have become challenging [28].

These current contexts of e-waste management emphasize the fact that the South Asian region is struggling to sustainably tackle this e-waste issue as it encounters numerous adverse environmental impacts. Mainly, the negative health effects of the informal recycling of e-waste have been a focus of efforts by international organizations and national governments of the South Asian region, and NGOs in the region [37]. To date, e-waste policies and initiatives have primarily aimed at the environment as the main aspect, but this is beginning to change. As a result of these new developments, existing international conventions, such as those in Basel Convention will be unable to adequately address the expanding domestic e-waste streams in developing countries [37]. The development of efficient protective policies will depend heavily on evidence of the human health effects of exposure to e-waste. As a developing South Asian country, Sri Lanka has seen a significant increase in investment, consumption, and exports, generating e-waste from the general consumption of large household appliances that represents the largest percentage of waste, followed by information and communication technology equipment and consumer electronics [38]. Sri Lanka is today dealing with a massive problem of e-waste, both domestically created and imported from other countries. Overall, these hazardous wastes are currently disposed of in a haphazard way along roadsides, in dump yards, and even in backyard gardens. According to Hossain et al. [21], this is usually due to low public awareness of the hazardous nature of e-waste management techniques, lack of management strategies, and inadequate e-waste handling and recycling practices used in developing countries like Sri Lanka. Therefore, this study attempted to summarize the literature on one of the developing countries in Sri Lanka to explore the current context, existing concerns, and limitations and to understand the potential of the successful implementation of e-waste management. In addition, the study finds answers to the following research questions: (1) what is the composition of e-waste and the current situation of e-waste management in Sri Lanka, (2) what is the process and means of collection and recycling of e-waste at present in the country, (3) what are the main challenges faced by Sri Lanka with reference to e-waste management, and (4) how can we strategically manage e-waste in the country to move toward SDGs?

Methodology

Systematic literature review

A systematic literature review facilitates the identification, assessment, analysis, and interpretation of significant research literature in consideration of a particular research issue. In the present study, a systematic literature review was carried out to identify e-waste management policies and their contribution to the development of recycling e-waste in a developing country, Sri Lanka as a model. This study serves as a comprehensive study to which the e-waste management stakeholders can refer, which helps to integrate strategic and inclusive e-waste management to overcome

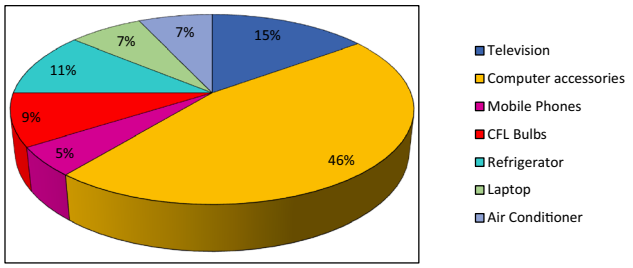

Fig. 5 Generation of e-waste in Bangladesh. *CFL* compact fluorescent lamp (Source: [34], adapted with permission)

the environmental impacts created by unsustainable e-waste disposal.

Identification

The Google Scholar Database was used to find originally published peer-reviewed papers and review articles. The title search was conducted using keywords and the Boolean operators, "e-waste" and "Sri Lanka" and "management strategies" and "recycling". The initial search yielded 392 articles in the Google Scholar Database.

Screening

In the process of article screening, the search period was narrowed down from 2005 to 2022. In addition, the screening process selected peer-reviewed articles published in the English language. Ultimately, a total of 371 peer-reviewed English language articles resulted in the screening.

Eligibility and inclusion

The screened peer-reviewed English language publications were chosen for further examination to check whether they are open-access research and review articles. There were 192 full text articles, and all selected entries were exported to an Excel file as CSV data after removing duplicates. Further, the studies that were not relevant to e-waste but were relevant to solid waste management or vice versa were excluded. After screening the titles and abstracts, the complete texts of 20 papers were examined, and all 20 articles satisfied all inclusion requirements.

Results and discussion

Thematic areas and trends in current e-waste research in Sri Lanka

Despite the fact that e-waste is rising at an astounding pace, few studies in Sri Lanka are being performed for critical discussion. Only 20 studies were completed in Sri Lanka throughout the 17-year period of the literature review. Furthermore, approximately 80% of the research was conducted after 2015. The results of the number of articles screened in the literature review under major keywords, the analysis process from 2005 to 2022, and the number of articles under each main thematic area studied are shown in Fig. 6a–c respectively. Figure 6a depicts the visualization of keywords in research publications using the keyword analysis technique. The keyword dataset was obtained from Google Scholar. The study covered a total of 20 publications. As a result, eight keywords met the threshold. According to Fig. 6c, the majority of studies have been performed by focusing on generation and composition (15%), management practices/strategies (13%), future recommendations (13%),

Table 3 Rules and legislations for e-waste handling in Bangladesh (Source: [35], adapted with permission)

Acts and rules	Explanation
The Factory Act (1965)	Disposal of wastes and polluted liquids from factories was regulated
Ship Breaking Rule (1990)	No ship containing hazardous waste can enter the nation without pre-cleaning outside the country
Environment Protection Act (1995)	The authority to take any steps to protect/improve the environment
Medical Waste Management Rules (2008)	Safe handling of hazardous medical waste
Government 3R Rules (2010)	National 3R strategy to reduce e-waste problems
Hazardous Waste (e-waste) Management Rules (2021)	Establishment of licenses for importers, transporters, and manufacturers Establishment of individual or joint collection centers and set aside funds for the management Rules on management of florescent light bulbs and establish proper recycle collecting centers

and recycling practices (11%) for e-waste. Additionally, several studies have focused on policies/legislations (8%), hazardous nature of e-waste (6%), and challenges of e-waste management, and few studies have focused on other aspects, such as collection, other handling practices, and awareness of e-waste in Sri Lanka.

E-waste generation and composition and status in Sri Lanka

This section of the paper explores the answers to research question 1 of the current review analysis. Chen et al. [39] revealed that e-waste generated per inhabitant in Sri Lanka is around the same as that in China and ranks quite high within Asia–Pacific developing nations. Although there is no accurate estimate of the quantity of e-waste in Sri Lanka, it is approximately 70–75 MT per year. The annual e-waste discharge is predicted to be more than double, rising from 10,000 MT in 2010 to 43,000 MT in 2030 [40]. Figure 7 illustrates the rapid growth of e-waste in Sri Lanka and there has been rapid exponential growth in e-waste since 2010.

Although more cohesive studies on generation e-waste categories in Sri Lanka have not yet been discovered, the review analysis depicted that there are nine main categories of electrical and electronic gadgets that generate e-waste (Table 4). These appliances are widely utilized in residential, commercial, and industrial settings. Currently, PCs, printers, televisions, mobile phones, refrigerators, air conditioners, copier machines, washing machines, and batteries are included under e-waste in Sri Lanka [42]. E-waste has a diversified composition that varies between product sources and categories (Table 4). The majority categories of e-waste produced and the life span of that e-waste, particularly from the residential, industrial, and commercial sectors, are described in Fig. 8 [40, 42].

E-waste collection practices in Sri Lanka

Figure 9 illustrates the established collection methods in Sri Lanka. It demonstrates the connection between consumers and the contribution of different sectors of the collectors and organizations established in Sri Lanka. This section of the paper analyzes the answers to research question 2. In detail, there exist three main ways of collecting e-waste namely, (1) informal collection through informal waste collectors, (2) regular and established collectors, and (3) local private recycling centers or international recycling centers. Rapid growth in the Telecommunication Industry in Sri Lanka and the rise in the middle-class society have increased the consumption of electrical and electronic items leading to a huge generation of e-waste afterlife. Unfortunately, most of the e-waste generated in Sri Lanka ended up in direct disposal by consumers [43]. This is because the majority of the urban population of Sri Lankans who are heavily dependent on electrical and electronic appliances live in separate housing units with a small garden attached, thus making direct disposal and open burning of waste a common practice in Sri Lanka. The consumers' perception of treating all waste products including e-waste into a single category has undoubtedly made e-waste management a worse end. Along with that, the minimal level of awareness about health implications caused by poor handling of e-waste contributes to unsustainable common practices by Sri Lankans [39, 44].

Informal (irregular) collecting centers/collectors

Referring to Fig. 9, irregular collectors play a major role in collecting electronic and electrical items directly from consumers. Most of them are underprivileged and members of marginalized poor communities. Irregular collecting centers prioritize extracting copper, iron, lead, and other usable plastic materials and tend to directly dispose of them through open burning of the remaining waste, hence having a direct impact on the environment [44]. As aforementioned, irregular collectors play a significant role in waste management, especially in the context of e-waste. It is very important to give due recognition and integrate this section into wider national policy when formulating national policy in e-waste management.

Regular and established collectors

The establishment of SDGs and renewed pressure on environmental sustainability have created more awareness of managing e-waste among policymakers. This has contributed to the establishment and strengthening of regular e-waste collectors and organizations in Sri Lanka. Current ad-hock policies and management strategies have made these established organizations and collectors less efficient, thus having a minimum impact on e-waste collection and management [44]. For this reason, streamlining and strengthening the present policies, addressing the loopholes in policies, and enhancing the communication between intergovernmental organizations and private collection are vital to revive e-waste management in Sri Lanka. Using low-cost approaches and already established infrastructure and organizations such as Post Offices, Samurdhi Offices, and Cooperative Societies can be greatly improved by increasing collecting capacity and raising awareness among communities about the importance of proper handling of e-waste [45].

Local private recycling centers and international recycling centers

Based on the established law in Sri Lanka, every formally established waste collector should obtain a license to operate [44]. By observing the Central Environmental Authority (CEA) of Sri Lanka with regard to licensing issues, it is visible that out of 15 licensed collectors, one was established around Colombo, the capital of Sri Lanka, clearly indicating a limitation in the collection process [44, 46]. All licensed collectors were limited to collecting e-waste from government and private institutions around Colombo. The established guidance and methodology available at present are to export collected e-waste subject to the license obtained. Sri Lanka lacks the technology and infrastructure to recycle e-waste, and establishing such recycling centers does not seem viable due to government budgetary and capital constraints. It is noted that there is a huge difference between the number of electronic items imported and exported for recycling, thus raising concern about the amount of e-waste lost in the cycle [44].

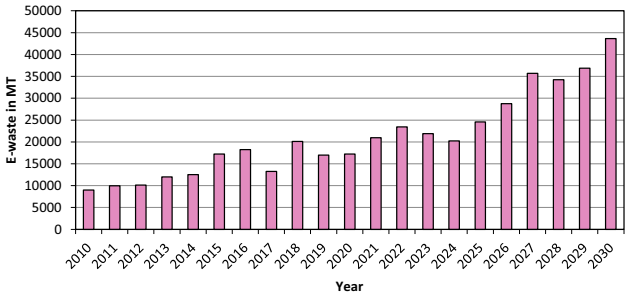

Fig. 7 Projection of e-waste in Sri Lanka up to year 2030. *MT* million tons (Source: [41], adapted with permission)

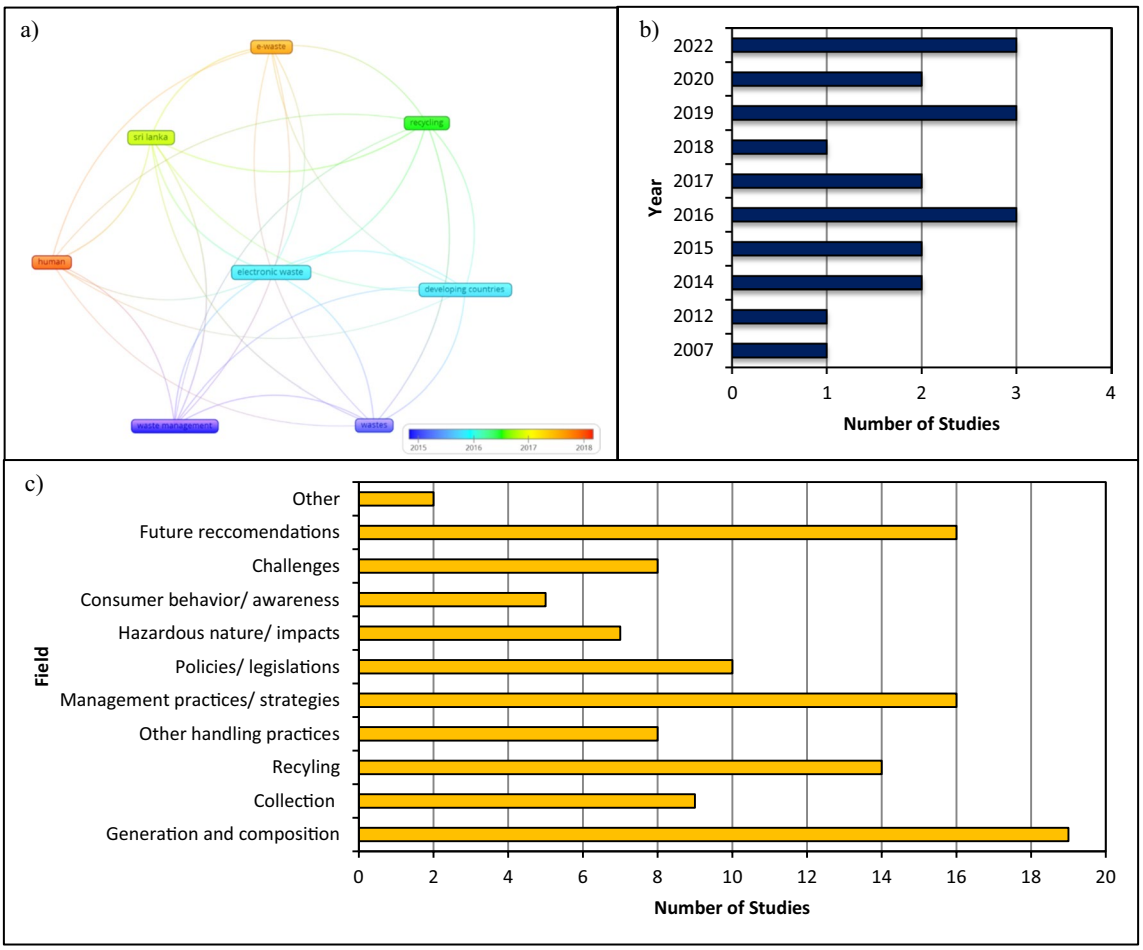

Fig. 6 **a** Networking of the keywords used in e-waste management peer-reviewed published articles; **b** number of e-waste studies conducted in Sri Lanka from 2005; **c** different fields of e-waste studies in Sri Lanka. Other handling practices included export, treatment, and disposal of e-waste, and others included integrated e-waste management and SWOT analysis

E-waste recycling process in Sri Lanka

Gunarathne et al. [38] stated that as in many developing nations, the e-waste recycling sector in Sri Lanka is still in its infancy. Electronic equipment consumers (main e-waste generators) such as households, business organizations, and government institutions and upstream intermediaries, such as local governments, informal, semi-formal, and formal e-waste collectors are the primary upstream partners of the Sri Lankan e-waste recycling industry [38]. The primary recyclers (who mostly execute dismantling) and secondary recyclers are at the center of the e-waste recycling sector. Moreover, the downstream partners include "downstream intermediaries" such as e-waste buyers and exporters, as well as "end consumers" who purchase recycled e-waste commodities, such as organizations that use e-waste as an input [38]. Table 5 displays the most frequent treatment methods for various forms of e-waste in the country. This reveals that many types of e-waste in Sri Lanka have no treatment options and that even accessible remedies are simple and time consuming. It is clear that Sri Lanka as a country primarily collects, sorts, and pre-processes e-waste accordingly. As a result of a lack of technological know-how on sorted or pre-processed commodities, the generated e-waste is now exported overseas for final processing in Sri Lanka [47].

E-waste and hazardous effects in Sri Lanka

In Sri Lanka, e-waste creation is increasing at an alarming rate; however, most of it is e-waste that is burnt in landfills, resulting in environmental pollution. Recent studies found that such behaviors are frequent among people in the household [42]. It was also mentioned that e-waste recyclers and customers lack facilities and know-how, and they frequently burn e-waste in the open areas, which releases dangerous compounds that harm both the environment and human health. According to this view, De Silva [46] noted that harmful substances included in e-waste may break down in a long-term dump, leak into deeper soil, and contaminate groundwater, which may be the source of a number of freshwater supplies. Direct use of these water resources might be extremely dangerous for both people and animals. Field irrigation for crops using this contaminated water might cause toxic accumulation in the plants and in the agriculture fields. Samarakoon [42] concluded that bioaccumulation of toxic substances and the consumption of such crops might pose significant risks to human life via food chains and lead to environmental degradation. Also,

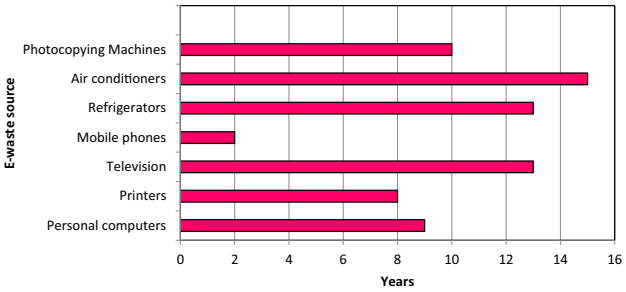

Fig. 8 Different e-waste sources and their life spans in Sri Lanka

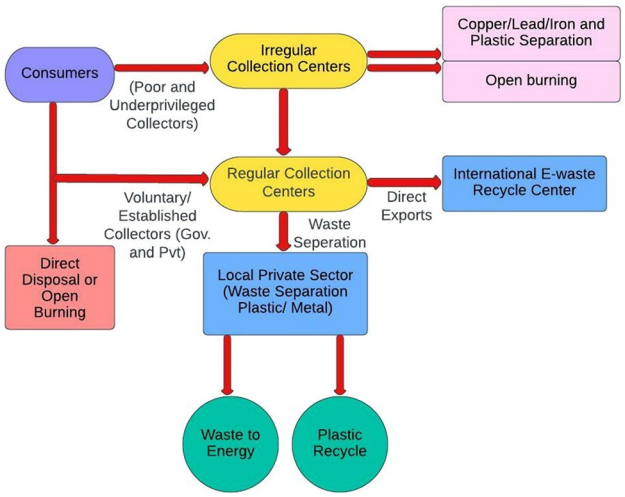

Fig. 9 Current e-waste cycling process in Sri Lanka (Source: [44], adapted with permission)

Table 4 Different types of e-waste sources and their components in Sri Lanka (Source: [40, 42], adapted with permission)

E-waste source	Components
PCs	Nonferrous metals, plastics, circuit boards, cables, precious metal bearings
Air conditioners	Metals
Printers	Nonferrous metals, plastics, circuit boards, cables, ferrous metals, clothing and ribbon, capacitors, glass
Television	Nonferrous metals, plastics, circuit boards, cables, ferrous metals, glass
Mobile phones	ferrous metals, polyethylene, cadmium sulfide
Refrigerators	Polyethylene, cadmium sulfide, chlorofluorocarbons (CFCs), metals
Washing machines	plastics, circuit boards

that study mentioned that many of the substances included in e-waste are unknown toxic compounds, and their release into the environment via discharges and untreated effluents has the potential to have adverse health consequences on both people and the ecosystem. A study conducted by Ranasinghe and Athapattu [44] revealed that emissions that come from the burning of e-waste may result in the production of greenhouse gases that contribute to global warming. Apart from that, leachates from dump sites can contaminate surface and groundwater wells and cause soil to become more acidic. In addition, e-waste contains dangerous particles that build up in the fauna and flora and can affect biological systems through food chains. They also showed that the trading of waste and recycling is a common source of income for the urban poor in Western Province, and it is one of the most hazardous and polluted industries. The majority of these laborers are urban poor who live in illegal settlements near wetlands and rivers and are either unaware or unconcerned about the risks inherent in their handling practices. Another research found that inappropriate recycling of e-waste exposed people to dangerous substances including As, Pb, Hg, and Cd, which had adverse effects on the environment and general health. Ranasinghe and Athapattu [44] highlighted that workers who handled e-waste faced the possibility of inhaling smoke and absorbing dangerous compounds via their skin. Also, Sapukotana [49] mentioned that e-waste that is burned openly discharges toxic gases and materials into the air, including heavy metals, brominated dioxins, and hydrocarbons. The brain system, kidneys, bones, reproductive system, and endocrine system are all negatively impacted by prolonged exposure to these hazardous substances [41]. It is justified that there are massive adverse human health and environmental risks in the disposal of e-waste. On that account, it is vital to understand current e-waste management in Sri Lanka to identify opportunities and threats associated with and minimize the negative impact on society.

Current e-waste management practices in Sri Lanka

The majority of the generated e-waste in developing countries like Sri Lanka is disposed of informally. Furthermore, studies have discovered that one of the primary causes of such actions is a lack of public awareness about the hazards of e-waste and how to treat it [41]. Likewise, weak formal recycling methods exacerbated the situation. At the moment, Sri Lanka now has a few formal e-waste collectors and exporters, and because of the lack of facilities and financial capacity, all of them gather a small amount of waste, mostly only from the capital city of Colombo district [38]. It is worth emphasizing that most formally collected e-waste in Sri Lanka is dismantled or pre-processed before being exported for further processing, and these procedures directly lead to reducing the harmful impact of e-waste. The inadequate formal collection procedures have resulted in increased informal collection and violations of regulations associated with e-waste management [38, 50]. As a result, the illegal collecting of e-waste has become an island-wide practice. In general, consumers prefer to sell their waste products to informal collectors due to financial incentives. Despite this, some people, particularly those in urban areas, dispose of their e-waste combined with municipal solid waste to municipal collectors managed under the local government. On the other hand, buy-back offers made by electrical and electronic stores collect used equipment from customers and send it to formal e-waste collectors. In Sri Lanka, the informal and semi-formal recycling industries frequently employ basic treatment methods such as open burning for metal extraction, acid leaching for precious metals, plastic melting, and open disposal of hazardous materials. To address these concerns, CEA launched the "Electronic Waste Management Project" in Sri Lanka. CEA has signed partnerships with firms in telecommunications, home appliances, office appliances, and service providers as part of this initiative [42]. The purpose of this project was to raise public awareness about e-waste and strengthen e-waste collection in a systematic way. CEA conducted an island-wide e-waste collection week by hand alongside private sector firms in 2014. The local government of Sri Lanka recently initiated a program to collect e-waste, primarily from residences. Besides, various private sectors have worked together to establish an e-waste collection week to collect domestic e-waste, although from a limited number of individuals. Moreover, many of these programs launched by the government and non-governmental groups were restricted to suburbs or major towns of Colombo district, Sri Lanka, not considering or targeting rural regions and resulting in short-term practices [44].

Legal aspects of e-waste and e-waste management in Sri Lanka

Mallawarachchi and Karunasena [51] found that most firms were in the early stages of developing e-waste management systems and that there was no particular policy on existing e-waste management. Table 6 depicts existing policy issues of e-waste in Sri Lanka and possible suggestions for those issues.

Challenges in e-waste management in Sri Lanka

The study finds answers to research question 3 in this section. The lack of a national legislative framework, technological expertise, and awareness has severely restricted Sri Lanka's capacity to establish a framework that facilitates the e-waste management system [44]. Also, studies

have mentioned that, the lack of an institutional and legal context for the handling of e-waste is a significant issue in Sri Lanka's institutional environment for the e-waste system. Currently, Sri Lanka lacks a complete data system for the lifecycle management of e-waste. The absence of accurate data about e-waste generation, importation, and collection in the country is another major challenge. This presents a significant problem for the country's policy development, implementation, and control of e-waste management. Additionally, the lack of institutional and legal requirements for the disposal of e-waste as well as formal e-waste collection facilities has resulted in the emergence of informal and semi-formal activities [49]. To accomplish the expected improvement in the formal sector, enough capacity building, the process of technology transfer, and financial sources based on low interest loan programs should be accessible. The lack of appropriate technologies and particular knowledge and abilities regarding e-waste management is a significant technical barrier. The economic context has difficulties for e-waste recycling as well. Limited economic returns and an absence of tax incentives not only put pressure on the industry's current recyclers but also repel potential investors. Finally, from the standpoint of the sociocultural environment, the lack of knowledge caused by inadequate consciousness of e-waste is a significant concern [53]. Also, the recycling industry is limited by a lack of technical expertise, government assistance, and policy-level directives. Recyclers regularly face difficulties in their recycling operations as a result of a lack of qualified workers. These labor-related problems raise the economic problems of the recycling process and make it difficult to maintain an adequate output. The profits gained on the export market by Sri Lankan recyclers are unattractive because they export products with less added value. Once more, this makes it difficult for recyclers to remain in the industry [44]. Figure 10 shows the future strategies that can be initiated to overcome these challenges.

Suggestions for the establishment of a strategy for e-waste management policies for Sri Lanka

The study suggests the possible answers to research question 4 in this section. In terms of a strategic approach to managing e-waste, the study identified institutional, financial, economic, legal, and technological sectors as key sectors to which the available expertise and resources should be allocated in the process (Fig. 10). Achieving the potential activities under the aforementioned sectors will endorse comprehensive e-waste management in Sri Lanka and in the process of heading toward the SDGs. Under the umbrella of the main four pillars (Fig. 10), the following activities are suggested as potential steps that can be taken to implement sustainable e-waste management in Sri Lanka.

Table 5 E-waste treatment methods in Sri Lanka (Source: [38, 48], adapted with permission)

E-waste categories and inputs	Treatment process	Outputs
IT and telecommunication equipment (telephones, mobile phones, printers, motherboards, hard disks, RAM cards, processors, circuit boards)	These things are dismantled up into small parts manually or with the support of small machinery. The items are then manually divided according on their category (e.g., motherboards, CD ROMs, etc.) and put into bags before being exported	Separate things are exported, while certain small components and gadgets (e.g., plastic objects, wires, etc.) are kept aside for sale in the local market
Entertainment equipment (e.g., televisions, CD players)	Process same as above	Same output as above
Household appliances (washing machines, air conditioners)	No available mechanism	Not available
Lighting equipment (e.g., CFL bulbs)	Manual separation of mercury-containing bulb components. The components are then put onto machines that separate the mercury and glass. The Al caps and mercury are placed in separate containers for export	Hg, Al cans, glass fakers, and plastics
Electric and electric tools (e.g., drills, sewing machines)	No available mechanism	Not available
Security and healthcare equipment (e.g., CCTV cameras, X-ray machines)	No available mechanism	Not available
Toys, leisure and sport equipment (e.g., exercise machines)	No available mechanism	Not available

IT information technology, *CD* compact disc, *ROM* read only memory, *RAM* random access memory, *CFL* compact fluorescent lamp, *CCTV* closed-circuit television

Enacting strong laws to enforce strict e-waste management practices

Base policy on Electrical and Electronic Waste Management in Sri Lanka was drafted and called for public consultation as early as 2008. National Electrical and Electronic Waste Management Policy was an important piece of legislation with provisions to comply with International Basel and other international conventions ratified by Sri Lanka in managing hazardous waste and electronic and electrical waste [54].

The following are the key components of the Sri Lankan National Electrical and Electronic Waste Management Policy Framework.

- Ensuring proper disposal of e-waste in an environmentally friendly manner (emphasis on waste treatment and final disposal);
- Prevent/minimize the health and environmental impact of people due to e-waste disposal;
- Enhance and establish social responsibility toward sustainable production, import, and consumption of e-products;
- Establish and promote e-waste management methodologies.

At present, even though there is an established national E-waste Management Policy, legal provisions are only there to manage mobile phone and computer-based wastes under scheduled waste management licenses. But in Sri Lanka, the majority of e-waste is generated through household appliances, thus creating a need to establish a proper legal framework to manage them.

When compared to many South Asian countries and developing nations with similar institutional and economic

Table 6 Existing policy issues of e-waste in Sri Lanka and possible suggestions

Existing policy issues	Suggestions
No proper procedures on treatment and disposal of collected e-waste, and organizations do not prefer to collect e-waste without a national strategy on collection and disposal of e-waste	Integration of informal collection/reuse methods with formal recycling Local authorities (LAs) need to be authorized to engage in e-waste management processes Conducting an e-waste collecting day to collect household e-waste, coordinated through an island-wide collection network together with private entities
Less compliance with laws and regulations and unawareness of such laws are issues prevalent within existing legal framework of e-waste management	Creating awareness on legal framework Take action over mismanagement
Less commitment and wrong perceptions of organizations	Cooperate with media organizations to create awareness among people through national programs and conduct awareness programs
Lack of coordination among private and government organizations in e-waste management procedures	Continuance of policies on e-waste management processes, despite changes at ministries Enhanced involvement of private companies in national e-waste management programs
There are no existing national or organizational systems to monitor and evaluate performance of e-waste management processes	Enhanced by operation of a standardized national information portal to which involvement of each organization shall be made compulsory
Existing national information system is ineffective while organizations do not have a system to provide information about their e-waste management processes	Integrated into e-waste management policies by addressing issues related to monitoring, controlling and evaluating procedures at organizations
Financial issues and ineffective mobilization of resources, according to many experts	There shall be due consideration to establish an e-waste management fund, which can be used to provide financial support to implement e-waste management processes partly funded through environmental taxes and penalties
Importing of e-waste, second-hand electronic items, and reaching outdated systems are already addressed by existing national policy on e-waste management. There are no specific guidelines, specifications or procedures to evaluate quality of e-products in existing e-waste management policy	e-waste should be clearly defined and second-hand electronic items shall be considered as e-waste. Enhancement of policy to restrict unauthorized importations and establish required infrastructure and support services to obtain quality certificates
Higher relevance of informal sector, uncontrolled customer behavior, and lesser facilities for recycling and reuse	All companies dealing in electrical and electronics items need to register their products with a relevant regulatory body by providing details of hazardous potential of products with relevant data obtained from producers Restrain electronic items based on their contribution to generation of e-waste

Source: [39, 51, 52]

capacities, Sri Lanka has established institutions and regulatory frames work to manage and reduce e-waste in Sri Lanka, but implementation and effective enforcement are debatable due to the fragmented nature of the law and law enforcement authorities. Following are some of the laws established to govern some hazardous waste. Based on the established regulation, any industrial waste generator, collector, waste recycler, or any concerned party with e-waste and hazardous waste handling, storing, and selling should take relevant certificates and licenses from CEA [41].

Establishment of a central command and management institute to unify fragmented governing bodies and entities on e-waste management

Sri Lanka has different entities to manage e-waste and implement core policies; hence, creating a fragmented approach to waste management is vital. For this aspect, CEA plays an important role in establishing and executing e-waste management policies. Table 7 shows the fragmented nature of law-forcing bodies for electrical and electronic equipment imported to Sri Lanka. This fragmented nature has created many loopholes, thus reducing the effectiveness and enforcement capabilities of the existing law. It is highly needed to establish a central command and management institute to unify these fragments and effectively enforce the law. Therefore, it is essential that CEA should continue maintaining an effective database with the coordination of Sri Lanka Customs and the Department of Import and Export Control and take action to identify the parties who generate and process e-waste to effectively enforce the existing laws [55].

Provide financial assistance for the private sector to expand the e-waste collection and recycling facilities

Most regular e-waste collection centers were established with private investments. These organizations require capital to expand and improve recycling facilities. Even though there are established licensing structures to govern these facilities, the government should consider giving monitory support to make the e-waste collection more attractive to the private sector.

Introducing e-waste management into school education curriculum to teach and practice waste management principles

As previously mentioned, a large part of the e-waste generated in Sri Lankan households is disposed of along with day-to-day normal household organic and normal waste without following proper management methodology. The majority of disposed garbage is used for landfilling by local authorities (Urban Councils and Pradeshiya Sabhas) without adhering

Fig. 10 Strategies to overcome e-waste challenges in Sri Lanka (Source: [2, 38, 51], adapted with permission)

to proper waste management policies, thus releasing a large amount of toxic chemical soup to the environment [38]. This is because the minimal level of awareness among the Sri Lankan public about the effect on health and well-being has made policymakers have the least interest in adapting policies to properly manage e-waste.

The marginal level of understanding and awareness among the Sri Lankan general public is due to a lack of education about waste management since childhood. Sri Lanka has a strong well-established education system, including Primary, Secondary, and Tertiary education [44]. Also, Sri Lanka has a universal 13-year compulsory education, thus clearly enhancing the literacy rate among the Sri Lankan

public. Nonetheless, Sri Lanka lacks a properly established curriculum to educate students about the importance of waste management and handling. This can help to uplift awareness among the students' community and has a cascading effect on information flow to other community members about e-waste management and its importance [56]. Figure 11 shows the proposed strategies to be developed under the current e-waste management sector in Sri Lanka.

Provide more recognition for informal (irregular) collectors and collecting centers

In Sri Lanka, the majority of recycling is done in informal facilities due to lack of legal and capital compliance. Cheap cost-effective recycling methods, such as open burning, physical dismantling, and acid treatments, are commonly practiced without any protective equipment and methods, thus contributing to environmental pollution and health issues. Due to its cost-effectiveness, underprivileged women and children are directly employed at these facilities, thus making their health vulnerable to various complications. This has created some issues among health regulators and undermined the fabric of society.

Giving due recognition and bringing them under a properly established regulatory system will bring much needed protection for the vulnerable communities who are employed at these facilities. This will also support the government and established institutions in bringing more e-waste to the formal recycling system which contributes to the national economy. As a remedy, affordable licensing and de-centralizing the governing practice to the grass-root level such as Pradeshiya Sabha (local governing body in Sri Lanka) will help to manage informal collecting establishments efficiently and effectively.

Provide financial assistance for the private sector to expand e-waste collection and recycling facilities

Conventional e-waste collection centers were largely initially funded by private investments. Unfortunately, these groups lack the capital to invest in recycling infrastructure upgrades. Governments should investigate the possibility of providing financial support to make e-waste collection more appealing to the private sector, although that there are already established licensing structures to govern these facilities.

Efficiently using existing infrastructure to collect e-waste with a low-cost approach (using Post Office, Samurdhi, and Cooperative Societies)

According to the World Bank and other multinational institutes, Sri Lanka is categorized as a lower middle-income country and is suffering from chronic under-investment in critical infrastructure due to budget constraints. Higher budget deficits coupled with a currency crisis and higher inflation have made e-waste management the least priority of the government and the general public. It is fundamental to have a low-cost approach to make e-waste management attractive to the general public and governing institutions. Sri Lanka has inherited some institutions from its past colonial masters. For instance, Post Offices, Cooperative Societies, and Samurdhi Offices are widely distributed across Sri Lanka. These well-established institutions can be used as collecting centers, thus attracting e-waste to the formal sector where government institutions can easily regulate.

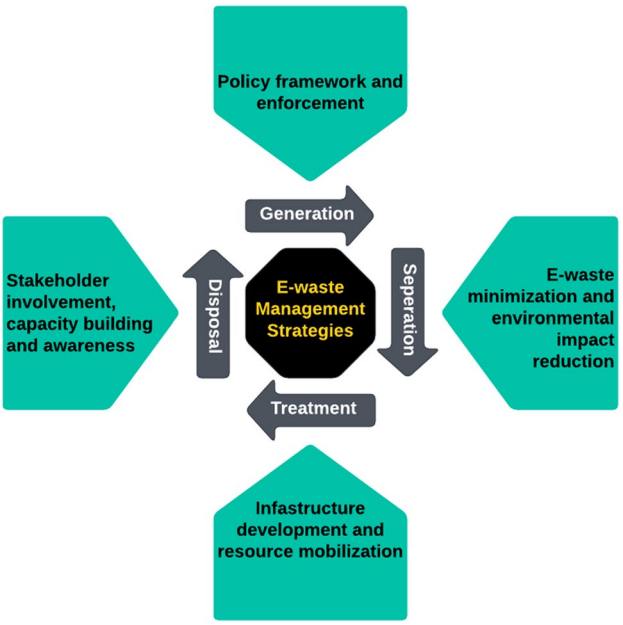

Fig. 11 Proposed framework for the e-waste waste management sector in Sri Lanka

Establish a monetary benefit system to encourage the consumer to segregate waste

The majority of e-waste comes from regular people who use electrical and electronic products; hence, promoting consumer participation who use these products in e-waste management strategies is crucial. Another issue is that many Sri Lankans simply throw their e-waste with their regular organic and normal garbage without giving it the attention it needs. Garbage is either dumped in the open or collected by municipal services and sent to landfills. Consumers will take an active role in e-waste segregation from households if local governing bodies devise an attractive monetary benefit system. By providing tangible benefits to families and consumers, an economic incentive system has the potential

Table 7 Electrical and electronic equipment and their regulating institutes and government institutions (Source: [55], adapted with permission)

Equipment	Preview institute	Target
PCs	CEA	Reduce the damage caused to environment
Washing machine	CEA	Reduce the damage caused to environment
Mobile phones	TRC	National security
Printers and photocopies	MOD	National security
Refrigerators	Ministry of Mahaweli and Development	Reduce the damage caused to environment

PCs personal computers, *CEA* central environmental authority, *TRC* telecommunications regulatory commission, *MOD* ministry of defence

to significantly impact e-waste management in developing countries.

With this said, it is the role of all stakeholders to bring the matter of e-waste management to the arena and brainstorm ideas to successfully implement e-waste management strategies in the Sri Lankan context. To achieve this goal, there must be an integrative approach of economic, environmental, and social aspects that underlines the linkages of e-waste management.

Conclusions

In this article, we provide a comprehensive overview of the situation pertaining to the management of e-waste and e-waste recycling in Sri Lanka, highlighting the most significant obstacles. The article provided an overview of the most significant developments and flaws in the management of e-waste in Sri Lanka, such as a lack of regulations, knowledge, and infrastructure. Most recycling is conducted in a disorganized manner, utilizing obsolete technical approaches to the treatment of e-waste, and without taking into account the substantial risk to public health and the environment. This describes the vast majority of recycling in the world. Even though there has been a discernible increase in the number of times electrical and electronic products are used, there is no clear plan in place to address the resulting increase in waste. A lackluster approach to developing policies and educating the public on e-waste management has a significant impact on the deterioration of the environment, both individually and collectively. This is because both of these elements are necessary for effective waste management. To effectively manage the ever-increasing amount of e-waste, both the national government and local governing bodies should move swiftly to develop cost-effective and practically applicable management strategies. This is required to effectively manage the growing quantity of e-waste.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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