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Saudi Arabia E-waste management strategies, challenges and opportunities, effect on health and environment: A strategic review

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ABSTRACT

The strategic review explores the evolving landscape of electronic waste (e-waste) management in Saudi Arabia, shedding light on the strategies implemented, challenges faced, and emerging opportunities in the realm of sustainable waste management. The comprehensive analysis encompasses the environmental and human health implications in association with the inappropriate handling of electronic waste. Saudi Arabia, a rapidly advancing technological hub, has witnessed a surge in e-waste generation, prompting the need for robust management frameworks. The review delves into the existing strategies employed by Saudi Arabia to tackle the growing e-waste dilemma, evaluating their effectiveness and potential areas for enhancement. Key challenges, including regulatory gaps, technological obsolescence, and awareness gaps, are examined to provide a holistic understanding of the obstacles hindering optimal e-waste management practices. Furthermore, the document explores opportunities for innovation, collaboration, and policy refinement to address these challenges and build a more sustainable e-waste management ecosystem. A crucial aspect of this review is the examination of the direct and indirect impacts of e-waste on human well-being and the environment. Insights are drawn from existing studies and data to illuminate the potential risks associated with improper disposal and the liberation of dangerous substances. The review highlights the urgent need for comprehensive e-waste management strategies to mitigate adverse consequences on both human well-being and the environment. In total, this strategic review aims to contribute to the ongoing discourse surrounding e-waste management in Saudi Arabia, offering valuable insights for policymakers, researchers, and stakeholders. By identifying key strategies, challenges, and opportunities, it seeks to inform and guide future initiatives, fostering a sustainable approach to electronic waste management in the Kingdom.

1. Introduction

The swift progress of technology is a major factor in the rising amount of electrical and electronic equipment trash (e-waste) produced annually, which presents serious environmental problems. An estimated 59.4 million tons of e-waste were produced in 2022, and unless significant improvements are made to industrial processes, consumer patterns, and the adoption of efficient laws, this amount is predicted to increase yearly [1]. Ineffective e-waste management harms the environment, puts people's health at danger, and impedes the UN's 2015 Sustainable Development Goals (SDGs) from being met [2]. E-waste management entails a number of complex steps, such as gathering, sorting, treating, recycling, recovering, and disposing of these leftovers at the end [3]. Natural resource depletion and soil, ocean, and groundwater pollution are caused by inadequate methods of treatment, recovery, and disposal. Furthermore, because of the chemical makeup of e-waste, improper recycling facilities can lead to contamination and labor exploitation, which can have a serious negative impact on health [4]. High-impact polystyrene, polypropylene, acrylonitrile butadiene styrene, and polystyrene are among the thermoplastics found in significant quantities in e-waste, as are epoxy-based compounds and composites, poly (glycerol sebacate), and poly (octamethylene maleate (anhydride) citrate) [5]. Certain technologies are needed for the proper recycling of these plastics, which may contain flame

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retardant components [6]. There are four primary approaches to recycling that can be used: the first two involve mechanical processes like size decrease, categorization, cleaning, and melt processing; the third process uses chemical operations to recycle plastic; and the fourth approach uses technologies like pyrolysis, gasification, and plasma arc to turn waste into energy [6]. Toxic substances including mercury, lead, and arsenic, rare materials like indium and palladium, and valuable metals like gold, silver, and copper are also found in e-waste. This emphasizes how crucial effective e-waste management is, especially when it comes to recycling and repurposing. However, there are a number of obstacles to e-waste management, such as a dearth of collection locations, a lack of environmental education and awareness, a lack of strict laws and regulations, poor government control, and a lack of recycling and sustainable alternatives [7].

Numerous studies have attempted to improve the efficient management of electronic garbage (also known as "e-waste") by recommending and assessing technological solutions and environmentally friendly instruments in response to this situation [8]. The research [5] reviewed the body of scientific literature to provide a thorough analysis of the composition of e-waste and its main impact on society and the environment. Urban mining and the circular economy (CE) have become key tactics for advancing efficient e-waste management. In an effort to decrease the harmful environmental effects of e-waste, research on the 4 Rs (reduce, reuse, remanufacture, and recycle) was expanded to include the 10 Rs [8]. This included ideas like refuse, rethink, repair, refurbish, reproduction, redesign, and recover. The study [9] underscored the importance of carrying out current, empirical research, especially in nations that have not previously been the subject of scientific studies. The [2] highlighted the critical role of CE and the need for collective societal participation to address issues related to this waste category by identifying trends, insights, improvement possibilities, and pertinent laws and legislation associated with e-waste management. Beyond scientific study, e-waste has become a major issue on political agendas, prompting a number of nations and economic blocs to strengthen laws and regulations to better handle e-waste, reducing negative environmental effects and fostering more social responsibility [10]. Producers of electrical and electronic devices also have a big role in improving e-waste disposal procedures and reducing associated issues. Businesses are urged to employ reverse logistics and eco-design and modular design concepts to enable product reuse, recycling, or appropriate disposal at the end of their life cycle. Hence, environmentally friendly e-waste treatment not only helps businesses reap financial rewards but also minimizes negative effects on the environment, generates employment possibilities, and ensures political legislation are followed. But other businesses face difficulties managing e-waste because of things like the waste's complexity and heterogeneity, the lack of suitable recycling and treatment technologies, and the need for large capital expenditures, to name a few [11]. In light of this, the work's goal is to fill the research gap by suggesting ideas for solutions that support corporate organizations' efforts to manage e-waste sustainably [12]. As a result, the present investigation presents the subsequent research query: What part may business entities play in e-waste management's development and advancement. What are the best practices and lessons learned from other countries or regions that can be applied to enhance e-waste management, what are the current e-waste management strategies, what are the opportunities that exist for improving e-waste management practices, and government policies and regulations in addressing e-waste challenges in Saudi Arabia? This article's main goal is to suggest processes for the advancement and enhancement of corporate initiatives that can enhance e-waste management and enable businesses to help accomplish the Sustainable Development Goals (SDGs). Fig. 1 illustrates the variety of materials that make up e-waste. It is expected that this research will significantly aid in reducing the adverse effects resulting from the increasing production of e-waste.

2. The pollution by E-waste: a global challenge

The rapidly growing production of enormous volumes of electronic debris, or "e-waste," is a problem that the electronics industry is leading the way on [13]. E-waste includes garbage from devices that run on batteries or electricity in addition to outdated, end-of-life electrical and electronic equipment (EEE). This covers products like as laptops, cell phones, electronic lab equipment, and other gadgets, as well as any parts that users may trash [14]. A small percentage of electronic equipment are formally recycled, and some owners discard their devices even before they come to the time of their useful life [15]. The main causes of the rise in e-waste production are the falling costs of electronics and the gradual shortening of their lifespan, which increase the accessibility of electronic equipment to a wider audience while hastening its obsolescence [16]. Furthermore, it is difficult to properly classify e-waste due to its rapid growth and complexity [16]. E-waste is currently a significant issue in the field of sustainable production and consumption [14]. A rapidly expanding multidisciplinary challenge, it is a crucial issue spanning technology, business, power, telecommunication, society, waste management, ecosystems, human well-being, rules regulations, and international affairs [14]. According to reports, the quantity of e-waste produced globally reached 53.6 million tons in 2019. The major contributors to this amount were China (10.1 million tons), Japan (2.57 million tons), Indonesia (1.62 million tons), Europe (12 million tons), and the USA (13.1 million tons). Together, these countries accounted for approximately 70 % of the total amount of e-waste produced worldwide. World-wide, just 17.4 % of e-waste was reprocessed; the unsettled 82.6 % gets disposed of, left unprocessed, or treated unofficially [17]. As per the data, the amount of e-waste produced could increase from 7.3 kg per person in 2019 to 9.0 kg per person in 2030, or 74.7 million tons, by 2030 [15]. Interestingly, because recycling prices are lower in Asian, South American, and African

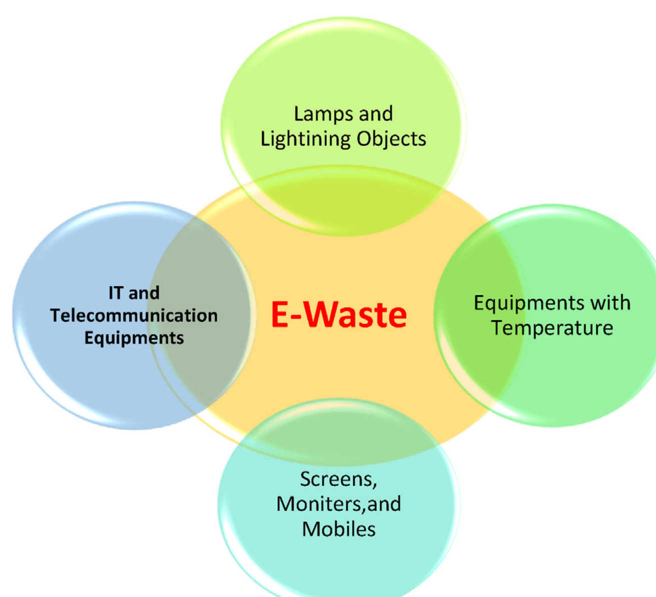

Fig. 1. Composition of E-waste.

nations and there is a chance for illegal dumping or contributions, a large amount of the e-waste produced in Europe and North America and is then transported to these regions. About 80 % of these goods are non-functional and wind up in garbage sites or are recycled informally by low-skilled workers without the required personal protective equipment (PPE), while a tiny percentage may be in functioning order for secondhand use [18]. The ecosystem and public well-being are solemnly threatened by the yearly 5 %–10 % growth in electrical and electronic equipment (EEE) that is disposed of correctly [19]. As a result, e-waste has become a critical issue that requires particular attention in both wealthy and developing countries [20]. It is made up of a variety of components and elements, some of which are hazardous and valuable and can harm both the ecosystem and the health of humans [21,22]. Indirect activities, which make up 98 % of the e-waste industry in underdeveloped nations, are characterized by labor-intensive, unregulated methods employing basic equipment [23]. Only 20 % of electronic waste is properly recycled, according to the United Nations Sustainable Development Goal 12, with the remaining garbage being disposed of carelessly. This leads to thousands of papers on waste and its environmental impact over the past 20 years [24].

2.1. Air pollution

Approximately 50 tons of mercury and 71 thousand tons of dangerous brominated flame hampering were found in the 53.6 million tons of e-waste that was reported in 2019 [17]. Furthermore, because of the high quantities of rare earth elements (REEs) in its products, it may play a major role in the contamination of rare earth elements (REEs) [25]. Given the widespread usage of metals in electrical and electronic equipment (EEE), such as copper in power wire and cadmium in batteries, pollution by heavy metals is typically expected in e-waste disposal sites [26]. If incorrectly disposed of and recycled, electrical, electronic, and mechanical equipment (EEEE) containing printed circuit boards and other hazardous materials can endanger human health as well as the environment and food supplies [27]. Because e-waste contains toxic compounds and dangerous materials, inappropriate handling and disposal can seriously compromise air quality [28]. In low- and middle-income nations, the majority of e-waste recycling activities—such as transportation, material breakdown, burning, and smelting for metal recovery, such as gold and copper—are done informally. Due to the rusting and roasting of e-waste, which releases airborne contaminants, these practices have the potential to cause air pollution [29]. Volatile organic chemicals may also be released during e-waste dismantlement [30]. Previous research has shown that the combustion of e-waste releases a number of dangerous air pollutants, such as furans, HCl, dioxins, polyvinylic aromatic hydrocarbons, polyhalogenated aromatic hydrocarbons, and measurable levels of particulate matter (PM). Burning in an open is still used in Thailand to extract copper from cables in e-waste, which puts workers at risk of breathing in PM and other pollutants [31]. Illegal e-waste recycling was found to be a substantial source of PM over permissible levels in a previous study [32]. Heavy metals, polyvinylic aromatic hydrocarbons, polychlorinated biphenyls, perfluoroalkyl and polyfluoroalkyl substances, brominated flame retardants, polychlorinated dibenzofurans, and polychlorinated dibenzodioxins are just a few of the inorganic and organic pollutants that can be released by inappropriate recycling of e-waste [32]. Some of the most dangerous substances and pollutants connected to e-waste are shown in Fig. 2.

2.2. Water pollution

Toxic metals included in many electrical and electronic equipment (EEE) products can contaminate water if they are disposed of incorrectly. For example, it is estimated that one cell phone battery can contaminate 600,000 gallons of water. Mercury is an important component of e-waste that may be found in all three forms. It can especially contaminate water when it's liquid, and the effects can last for decades [33]. As per the previous study, unregulated e-waste reprocessing negatively affected livestock, fish, shellfish, rice, vegetables, and other food sources by introducing heavy metals and persistent air pollutants [34]. Nearly 70 % of e-waste ends up in developing countries like Guiyu in Asia, where it is frequently abandoned and shipped. This creates serious environmental hazards. According to reports, about 12.5 percent of this waste is recycled using antiquated techniques, which causes hazardous materials to leak into the environment. In addition to persistent organic pollutants, Guiyu's rivers and groundwater are contaminated with many heavy metals, making the water unsafe for cooking or drinking [34]. Additionally, e-waste does not contaminate only water but produces a large volume of wastewater as it goes through procedures like the hydraulic shaking bed extraction process, which is used to collect copper particles [35].

2.3. Soil pollution

E-waste has a substantial negative influence on soil and its biochemical constituents. This is especially true in places like Africa, China, India, and Pakistan, where e-waste builds up in mountains and dumps, disrupting the microbial populations in contaminated areas. The ecological functions of soil can be significantly impacted by changes in microbial communities. The typical soil microbial biota is known to be reduced by e-waste's presence of dense metals such cadmium, lead, arsenic, mercury, nickel, and chromium as well as persistent organic pollutants [36]. Uncontrolled e-waste dismantles activities have resulted in significant soil contamination with cadmium and copper, according to a study done in an e-waste deconstruct location in southeast China [37]. One of the main ways that heavy metals and other toxic chemicals are released into soil habitats is through open burning [37]. Several nations have documented adverse effects on soil ecosystems as a result of the recycling and disposal processes related to managing electronic trash. Metal contamination can arise from recycling techniques such as circuit burning, melting plastic, recuperate copper from cables, and extracting gold using acidic materials [33]. Because e-waste contains heavy metals, these operations may also result in surface soil pollution [38].

2.4. Complications on human well-being

Because e-waste pollution can be exposed to people through a variety of routes, it poses a serious worldwide health risk. Numerous studies have been conducted on the body effects of e-waste, emphasizing the dangers associated with occupational exposure, ingestion, and inhalation [21]. Pain in back, itchy red eyes, and work-related injuries were more common among e-waste laborers than in the control group, as per the comparative cross-sectional study combining workers and bystanders [22]. The reports on the comprehensive research on the health effects of e-waste exposure, people who live close to e-waste locations are exposed to high levels of heavy metals and persistent organic pollutants. High concentrations of these harmful substances have an adverse effect on the hormones and growth of newborns in the

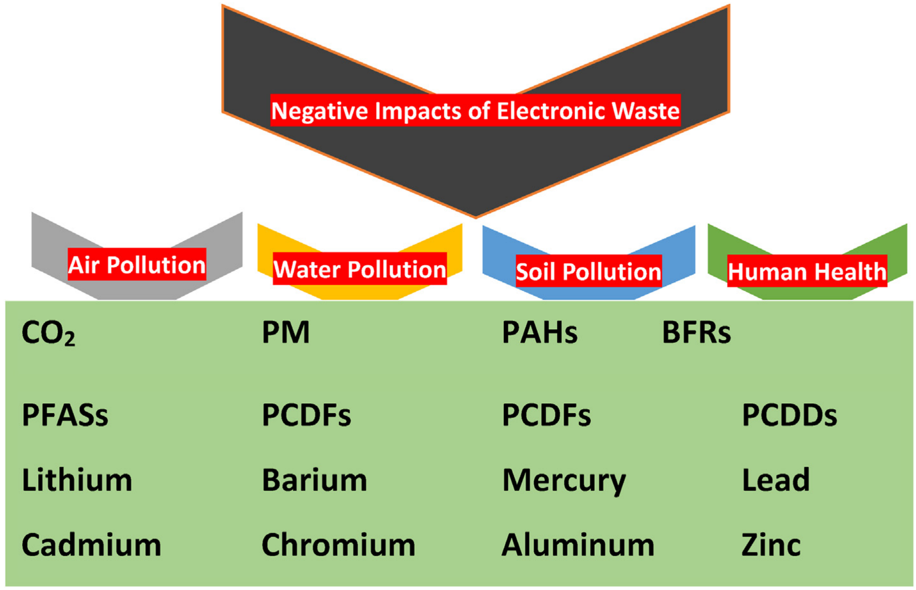

Fig. 2. Improper management of E-waste leading to formation of Major pollutants and hazardous materials.

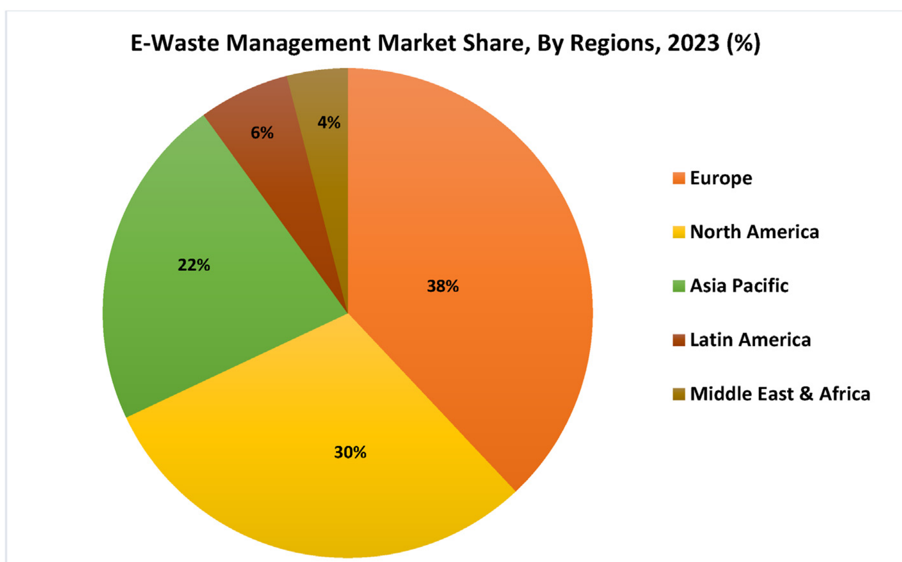

Fig. 3. Global generation of E-waste.

exposed population [39]. Research carried performed in Ghana and South Africa confirms the disastrous human exposure to many toxins found in e-waste, including arsenic, cadmium, and mercury. It has been discovered that burning e-waste releases contaminants that irritate the eyes, cause respiratory problems, and aggravate asthma [38]. Unofficial recycling and disposal methods add to the toxins found in milk, bodily fluids, and blood, which can have negative consequences like immunotoxicity, genotoxicity, organ damage, irregular growth of reproductive organs, and intellectual impairment [39]. Furthermore, a study discovered that pre-schoolers in areas with e-waste are vulnerable to lead exposure, raising the likelihood of oral health concerns such periodontitis and other dental disorders [40]. To sum up, exposure to e-waste causes a range of severe health effects in people and calls for prompt and efficient response [39].

3. Research framework

A thorough literature review was warranted by the need for a thorough understanding of electronic waste (e-waste), including its characterization, processing, recycling, and new challenges. For article investigation and insight, search engines such Scopus, Web of Science, PubMed, Elsevier, Springer, Emerald, Cell Press, Bio-Bacta, Google Scholar, and Wiley were used. Manually searching citing publications was done as additional research. As advised by Kitchenham et al. [41] and Liberati et al. [42], citation manager software was used to handle all referenced papers and screen them in accordance with PRISMA guidelines to ensure a methodical approach. In the literature review, a variety of keywords and objective tactics were used, and articles were filtered in accordance with the established study methodology. After titles and abstracts were reviewed, a more thorough analysis was conducted on a subset of the selected papers, which resulted in the deletion of 55 articles that were redundant or unnecessary and did not primarily address waste. This methodical approach sought to know the nation's e-waste generation, compare it to regional and worldwide generation, and evaluate the contribution of effective e-waste management to environmental sustainability. The study, which focused on the social, environmental, and economic facets of sustainable management, also included an explanation of the model for forecasting and estimate that was chosen. Important topics covered included the impact of social awareness, consumer behavior, and the supply chain network. The study made clear how much more documentation is necessary for the creation, gathering, and extracting of e-waste. The article presents a general summary of e-waste in Saudi Arabia, highlighting obstacles and examining potential prospects.

4. Generation of E-waste worldwide

As per the global E-waste monitoring program, as shown in Figs. 3 and 53.6 million metric tons of E-waste were produced globally in 2021, with an average annual growth of 2.5 million tons. This is worrying since, in just seven years, there has been a considerable growth of over 20 % in E-waste, compared to 2014 when 44.4 million tons were documented [43]. With a per capita contribution of 13.3 kg and an annual production of 13.1 million tons, the USA is the country that produces the most E-waste among the countries under study. Unfortunately, only around 1.2 million tons of the nation's total e-waste are handled correctly in accordance with USEPA regulations. An American household uses more than 20 electronic devices on average [44]. Europe, which produces 12 million tons of E-waste, or 42.3 % of it, has the highest level of formal and sustainable E-waste management, with 5.1 million tons created. With 24 million tons produced, Asia is the region with the biggest amount of e-waste; just 2.9 million tons are recycled. With 16.2 kg of e-waste produced annually per person, Europe likewise tops the world in this regard. With 10.1 million tons produced, China is among the world's top producers of e-waste, India coming in second with 3.2 million tons. Nevertheless, when compared to the global average of 7.3 kg, India's per capita contribution is comparatively low at 2.4 kg. The output of e-waste has increased by 58 % in the last nine years [44]. Less than 40 % of the world's production, or 44.3 million tons, are officially managed, according to data on e-waste management. High-income countries ship a large amount of their E-waste to developing or lower-income countries. With almost 0.6 million tons of electronic waste ending up in trash cans, the majority of household devices are disposed of in the trash, which is one of the main reasons why e-waste is not included in official collecting and documentation processes. The trash generation forecast for the next ten years predicts a sharp increase of 121 % between 2020 and 2030 [45]. The correlation between GDP and E-waste creation is responsible for this high projection and non-linearity, suggesting that achieving a better economic wealth position is associated with E-waste generation saturation [46]. Compared to other regions, the majority of European countries showed a comparatively higher trash creation per capita (20–25 kg/capita) in 2019. India produced the least amount of E-waste per person among Asian nations, at about 2 kg per person, presumably as a result of its high population density in relation to E-waste output [47].

4.1. E-waste generation in arab countries

With a mere 0.1 % management rate, the production of e-waste in Arab nations has increased significantly over the last ten years, from 1.8 million tons to 2.8 million tons. Additionally, there has been a 30 % increase in the amount of Electronic and Electrical Equipment (EEE) per capita of the population (EEE-POM), which increased from 3.2 million tons (8.8 kg per inhabitant) in 2010 to 4.1 million tons (9.5 kg per inhabitant) in 2019. With 595,000 tons (13.2 kg per inhabitant) as the greatest E-waste generator per country, it increases to 600,000 tons (0.7 kg per inhabitant), indicating a significant diversity across the region. Although there is comparatively little manufacturing of EEE, there is a favorable association between GDP and the development of EEE-waste and EEE-POM. For Arab countries, an increase in GDP for Purchasing Power Parity (PPP) corresponds to an increase in EEE-POM. At 24.9 kg per person, Qatar has the highest EEE-POM, while Comoros has the lowest, at 0.8 kg per person. Egypt is the world's second-largest producer of E-waste in absolute terms, with the highest EEE-POM ranking at 1.1 million tons, as illustrated in Fig. 4. Saudi Arabia, Iraq (459,000 tons), and Algeria (458,000 tons) are the next countries in line.

4.2. Scenario of E-Waste in Saudi Arabia

As per the E-waste monitoring conducted by the United Nations, the Kingdom of Saudi Arabia is the largest producer of E-waste in the Arab world, producing 595,000 tons (16.3 kg per person), or 21 % of the total. The Kingdom has the second-largest EEE-POM value, after Egypt, at 758,000 tons [48]. The relationship between GDP and EEE-POM shows that E-waste output has significantly increased in Saudi Arabia along with rising living standards, more access to technology, the IT revolution, and urbanization. Only 22 % of the hazardous trash generated today is handled; the remaining material is either left untreated or is treated informally [49]. The quantity of waste produced in the nation has increased by over 40 % in the last four years [50]. Laws and regulations for the handling of e-waste were not created until 2017, despite the fact that e-waste is produced in large quantities. With Saudi Arabia's Vision 2030 aiming for 100 % E-waste recycling via the waste-to-energy and environment sustainability efforts, the National Transformation Program (NTP) 2020 was announced in 2022 with the goal of reducing E-waste by 40 %. Sustainable handling is hampered by technological issues and a lack of knowledge about e-waste [51,52]. Due to the predominance of an informal waste management system, management of current waste procedures involve individual collection through bins and disposal in landfills, accounting for 10–15 % of all garbage. Certain waste management firms do not use an advanced recycling facility designed exclusively for E-waste; instead, they rely on manual sorting. Furthermore, information about the nature and regulation of e-waste has not yet been recorded [53]. The US Environmental Protection Agency (USEPA) projects that, out of all the Arab nations, Saudi Arabia will produce the most e-waste. Given population expansion, increased living standards, and industrial improvements, the annual amount of E-waste could increase from 5 % to 10 % in 2040, resulting in a potential range of 1,345,000 tons to 4,507,000 tons [54]. In Saudi Arabia, managing e-waste effectively and sustainably necessitates an ecosystem approach that considers the environment, human behavior, social characteristics, and the economy [55]. The significance of pinpointing hotspots and high-performing regions as well as evaluating the efficacy of methodologies for technical components and sustainability in WEEE (Waste Electrical and Electronic Equipment) was brought to light by a case study conducted in Romania [56]. By projecting E-waste generation, models for precise E-waste anticipation and readiness, like gray model E-waste forecasting, can support short-term planning [57]. The critical need for a strong E-waste management and regulatory framework in Saudi Arabia that addresses everything from local garbage collection to

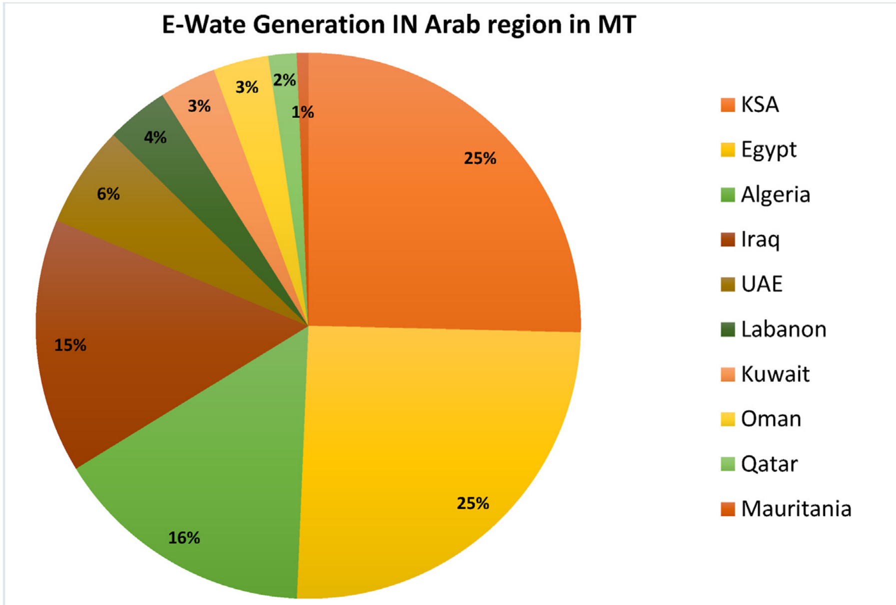

Fig. 4. E-waste generation in the Arab region.

cross-border interchange is highlighted by a comparative analysis of worldwide E-waste management approaches. To have better results, the public needs to be more aware of the situation and socially conscious [58]. The Value-Belief-Norm Theory (VBNT) and the Extended Producer Responsibility (EPR) are two commonly used skeletons for the nature analysis in e-waste management. Their goal is to convert waste effectively prior to landfilling, improving e-waste disposal management and the sustainability of the environment [59,60].

5. Supply chain network of E-waste (S·C·N.)

The supply chain must be carefully considered for both sustainable E-waste management and economic circulation. The informal and formal sectors make up the two main parts of supply chain networks. The informal sector is small-scale, labor-intensive, mostly unregulated, and does not use sophisticated technology or provide resources and services. On contrary, whereas the bulk of E-waste is created and controlled in the informal sector, the majority of information in Saudi Arabia is held by the formal sector, which is defined by regulatory scrutiny and monitoring [61]. Sustainable management is hampered by the widespread use of inappropriate management practices such acid leaching, disassembly, and poor landfilling. Adoption of formal recycling is further complicated by the widespread nature of these practices [62]. E-waste's complicated nature makes handling, sorting, and disassembly procedures more difficult [63]. Although Extended Producer Responsibility (E.P.R.) is thought to be a workable strategy, its current implementation framework is inadequate [64]. E-waste operation can be accomplished by considering elements like Quality Function Deployment (Q.F.D.) and the Analytical Hierarchy Process (A.H·P.) for system management, evaluations, and decision-making [65]. These structures operate together to help regulate certain essential parameters, which improves the efficiency of the supply chain network (S·C·N.). The fact that this model oversees the biggest E-waste generating handling systems highlights how important it is. Furthermore, a study indicates that a $1000 gain in GDP causes a 0.5 kg growth in the output of e-waste, emphasizing the necessity of dynamic and sustainable management [66].

6. Policies and strategies in E-waste management

In the realm of managing e-waste, a number of solutions have been put into practice, such as the Value-Belief-Norm Theory, Material Flow Analysis, Extended Producer Responsibility, Life Cycle Assessment, and Multi-Criteria Analysis [66]. The effectiveness of these tactics, which frequently work well together, is dependent on a number of variables, including the environmental impact, safe recycling practices, and the recovery of important metals through official gathering and segregation procedures.

Life Cycle Assessment (L. C. A): Widely recognized, especially in Europe, Asia, North-eastern and African countries, and Switzerland, L.C.A. emphasizes the financial and environmental advantages of recycling systems. L.C.A. has been embraced by Asian nations, demonstrating notable environmental and economic outcomes, making it an important E-waste management method [67].

Material Flow Analysis (M.F.A): Geographically, this decision support system analyzes the flow and timeliness of e-waste during recycling, collecting, disposal, and the stocking route. M.F.A. offers details on the interface connections between the starting point and the end point. A number of nations have implemented M.F.A. to map the movement of e-waste and its gathering, recycling, and cross-border commerce, including Nigeria, Australia, China, Indonesia, India, and Japan [68].

Multi-Criteria Analysis (M.C. A.): The most effective method for including social facilitators in the management of e-waste is M.C.A. M.C.A. has been implemented by nations including the USA, Spain, and Cyprus to optimize and locate recycling facilities and E-waste handling. It contributes to striking a balance between economic and environmental footprints [69].

Extended Producer Responsibility (E.P.R): A national strategy that imparts information on environmental issues and focuses on manufacturers' obligations to retrieve products once their useful lives are up. A key component of sustainable e-waste management is E.P.R [70,71].

Digital Technologies and Industry: A sustainable approach to managing e-waste appears to be offered by the 4.0 industrial revolution, which integrates robots, smart tracking systems, sensors, RFID tools, smartphone applications, monitoring real-timing, and sovereign systems. Robotics, intelligent tracking, and real-time monitoring are examples of digital technologies that are becoming useful tools [72,73].

Triple Bottom Line (TBL) Technology: Turkey has embraced TBL technology to computerize the management and forecasting of e-waste. It entails forecasting the production of e-waste, putting forth a sustainable collection, characterization, and segregation center model grounded in digital technologies, and putting the TBL idea into practice for the best possible results [74,75].

Gulf Countries and Legislation: Gulf nations rely on current legislation and adherence to the Basel Convention with an aim to manage their e-waste. Laws pertaining to EPR have been put into effect in the United Arab Emirates, and other nations in the area are now passing legislation along these lines. There are particular laws governing the import of old telecom technology probes in some nations, such as Egypt [76].

Vision 2030 and Sustainable Environmental initiatives: Nations such as Saudi Arabia are concentrating on Vision 2030 and eco-friendly environment programs, paying particular attention to waste-to-energy and composting possibilities. Because of these policies and the increasing creation of organic waste, composting and waste-to-energy are receiving more attention [77].

Manual Practices and Landfilling: E-waste management initiatives are frequently labor-intensive, manual, and informal in some areas. Currently, the most popular methods for managing trash are landfilling and incineration; however, efforts are being undertaken to diversify and enhance waste management techniques as part of Vision 2030 activities [78].

7. Classification of electronic waste

Across the world, there are ten distinct categories for electronic garbage, or “e-waste.” The proportionate share of each category may differ depending on variables including consumer behavior, socioeconomic status, and the extent to which families and businesses rely on electrical and electronic equipment (EEE). The following are the categories and average percentages:

Large household items: Leading contributor, accounting for 42.1 % of e-waste.

IT and Telecommunication: Contributes 33.9 % to e-waste.

Consumer Devices: Represents 13.7 % of e-waste.

Small Household Equipment: Accounts for 4.7 % of e-waste.

Medical Devices: Contributes less than 2 % to e-waste.

Lighting Equipment: Represents less than 2 % of e-waste.

Electrical Tools: Contributes less than 2 % to e-waste.

Electronic tools: Accounts for less than 2 % of e-waste.

Automatic Dispensers: Represents less than 1 % of e-waste.

Toys, Sports, Monitoring and Control Devices: Contribute less than 1 % to e-waste [79].

Large devices like TVs, PCs, and cell phones sometimes make up the maximum of e-waste in poor nations [80].

8. Recycle and recovery of e-waste

E-waste management undoubtedly depends on efficient recycling and recovery, which improves the economy, the environment, and public health. Only when valuable components are effectively recovered and recycled is e-waste genuinely regarded as a resource. The procedures for gathering and managing e-waste will be covered in detail in the below sections.

8.1. Collection

The collection of waste produced by homes and businesses is the first stage in the electronic waste management, or e-waste [81]. Pretreatment is the next step in the waste management process, which comes before the materials are sent to treatment facilities or disposal locations. The collection/gathering can be classified into four categories: official take-back system, mixed residual waste, collection outside of official take-back system in countries with advanced waste management, and collection outside of official take-back system in countries with less developed waste management [82]. According to national e-waste rules [83], e-waste is collected in the first category by authorized collectors or government organizations like councils or producers. By using this technology, pre-treatment procedures are applied before the e-waste is sent to cutting-edge treatment facilities so that valuable materials can be recovered. Mixed residual waste is the second collection category in which users place their e-waste in bins with other business or home rubbish [84]. This method collects e-waste, which is frequently burned or disposed of with other rubbish because it is unlikely to be separated. Within the third classification, electronic trash is gathered by licensed individual garbage dealers or businesses, who subsequently sold the e-waste to reproduction firms. This is known as “collection outside the official take-back system”. Lastly, disorganized methods of managing electronic trash are used in Bangladesh and other nations without e-waste legislation. Informal collectors and recyclers handle e-waste, and there is no centralized planning or control over it [85]. With 5.1 million tons—42.3 % of the world's total—and an estimated $5.48 billion in worth, Europe emerged as the top e-waste collector in 2019. With 2.9 million tons (11.7 %), Asia was the second-largest collector, followed by the Americas (1.2 million tons; 9.4 %), Oceania (0.06 million tons; 8.8 %), and Africa (0.03 million tons; 0.9 %). The present global e-waste generated is valued at $57.0 billion, but only $10 billion of that is recovered and recycled in an environmentally responsible way, saving 15.0 million tons of CO_2 [86]. The infrastructure for managing e-waste, public awareness, economic conditions, and law all have a major impact on the collection technique selected in various countries [86]. There aren't many e-waste statistics available in many developing nations, especially in Southeast Asia and Northern Africa, where e-waste laws are lax or nonexistent. The governments of these areas frequently rely on impoverished and independent contractors to gather and recycle electronic debris. These people work door-to-door, gathering e-waste from customers' houses, sorting the things, and then selling the divided goods to city merchants for recycling or refurbishment [85]. Many unskilled people continue to use this informal collection approach as a way to make a menial living, despite the health dangers it carries and its poor efficiency in both collection and management. For example, it has been projected that Bangladesh collects approximately 0.95 million tons of e-waste informally each year [85], while small-scale recycling facilities in Dhaka city are anticipated to make up to $3410.0 each month through informal channels [87].

8.2. Pre-treatment and recovery treatment methods

After being gathered, electronic waste is first treated before being delivered to a facility for further processing [88]. The purpose of pre-treatment is to separate various recyclables from the bulk of mixed electronic waste so that the latter can be delivered to the proper recovery treatment facilities. As for the pre-treatment procedure, there are three types: (a) manual disassembly; (b) mechanical dismantling and separation; and (c) a mix of mechanical and human operations [89]. Hand disassembly is frequently used to separate valuable and hazardous materials, including batteries, PCBs, monitor casings, and monitors. This process can occasionally be expensive and labor-intensive [90]. Size reduction, crushing, shredding, and metal-non-metal separation are all part of the mechanical pre-treatment process [89]. It is noteworthy that the combined manual and mechanical pre-treatment techniques prove to be efficient in terms of both time and money when dealing with complex combinations of different items and equipment. Pre-treatment in industrialized nations usually consists of semi-automatic separation, which is followed by metal recovery in cutting-edge facilities [91]. The majority of metal recovery in developing nations occurs in small workshops after manual separation [92]. Low-intensity magnet drums are frequently used to separate ferrous metals from non-metals, while devices based on electric conductivity are used to separate non-ferrous metals from non-metals [89]. Sifting and other gravity methods employing airflow or water flow tables are commonly used as additional separation techniques [92]. After metals are extracted from other materials, they move on to the last phase of recovery, where pyrometallurgy and hydrometallurgy are two popular techniques [93]. Pyrometallurgy, which includes smelting, burning, incineration, and refinement, uses high temperatures to extract and purify metals [94]. Aqueous solutions are used in hydrometallurgy, on the other hand, to extract metals from concentrated mixes or a blend of other components. While pyrometallurgy is typically used to recover ferrous metals from electronic waste, hydrometallurgy is typically used to recover non-ferrous metals including copper, lead, and zinc [95].

9. Recycling of E-waste

As illustrated in Fig. 5, recycling is a complex process that involves repurposing materials to return them to their initial high- or low-grade condition. This crucial procedure focuses on removing secondary materials from abandoned goods so that they can be recycled either down (where the original quality is preserved) or up (where components are improved to a higher quality or equivalent functionality). Upcycling is preferred, but its viability is frequently limited [96]. Five essential steps make up e-waste management, a crucial component of recycling: collection, toxics removal, pre-recycling end processing, and disposal of non-recyclable items.

Fig. 5. E-Waste recycling.

The effectiveness of recycling e-waste is closely related to the procedures used, namely the steps of disassembly and separation [97]. E-waste recycling is frequently viewed as a gold mine from an economic standpoint because it produces valuable commodities including iron, copper, platinum, silver, gold, and palladium. Technically, these materials—which are widely found in e-waste—can be recuperate and recycled. The United Nations University estimates that the global worth of e-waste is above USD 62 billion in raw materials, which highlights the potential economic benefits of ethical recycling methods [98]. Beyond financial concerns, recycling e-waste is essential for resolving employment-related problems. For instance, China creates jobs by employing almost 100,000 recycling workers in one of its e-waste recycling facilities. Furthermore, by reducing the emission of dangerous substances and pollutants, ethical e-waste recycling makes a substantial contribution to environmental protection. Reduced energy use, a lower environmental footprint, less trash produced, and consequently a smaller social impact is among the environmental advantages [99]. E-waste recycling is beneficial for the environment and the economy since it can reduce expenses by about 50 % while saving 70 % of materials and 60 % of energy [100]. However, there are significant obstacles in the recycling process due to the hard nature of e-waste. Metals (61 %) plastics (20 %) glass (5 %), wood (3 %), ceramics (2 %), rubber (1 %), and other pollutants (5 %) are among the materials that make up e-waste [101]. For the purpose of recycling e-waste, a variety of techniques and technologies have been used, including hydrometallurgy, pyrometallurgy, biometallurgy, and their mixtures, to solve these challenges. Every technique presents a unique set of difficulties and frequently calls for certain pretreatments [101]. Both hydrometallurgy and pyrometallurgy are standard techniques, although they each have benefits and drawbacks. Since hydrometallurgy is a thermal process, it requires a significant energy and financial commitment. However, because e-waste components have different melting points, pyrometallurgy has difficulties regulating emissions and preserving material quality [102]. Problems including inadequate funding, inadequate treatment technologies, unsuitable infrastructure, and a deficiency of expertise and personal protective equipment (PPE) exacerbate the situation. These elements play a part in the discharge of dangerous contaminants that affect the workers in recycling plants. The requirement for responsible and thorough management techniques is highlighted by the fact that uncontrolled reprocessing of e-waste can lead to increase in waste effluents [103].

10. Challenges and opportunities in a structured E-waste management

There are several opportunities and challenges associated with managing electronic trash, or “e-waste.” The lack of comprehensive legislation pertaining to e-waste poses a considerable obstacle, especially in developing nations. As of 2014, e-waste laws were only in place in 61 countries, or 44 % of the world's population [104]. 71 % of the world's population was represented by these 78 countries as of 2019. Interestingly, e-waste legislation has been passed by highly populated countries like China and India, but not by other countries like Bangladesh and Pakistan, which have populations of over 160 million [105]. While Pakistan recently outlawed the import of e-waste, questions remain about the efficacy of this policy [106,107]. Bangladesh, the eighth most populated nation in the world, has just recently thought about e-waste laws, as seen by the proposed guidelines published in 2019 [108] by the Department of Environment. Managing e-waste is still a difficult task because of its complicated mix of dangerous, precious, base, and other components, even with legal measures. E-waste usually consists of 40 % metal, 30 % plastic polymers, and 30 % oxides of other materials [1110]. These percentages can, however, differ significantly. In addition to dangerous compounds like mercury, beryllium, lead, cadmium, and arsenic, e-waste also includes halogen materials, plastics, glass, and ceramics, as well as valuable materials like silver, gold, and palladium, base materials like copper, aluminum, and nickel [109]. The unique difficulty in managing e-waste is obtaining valuable, uncommon, and useable materials while managing dangerous substances in a safe manner. The usage of hazardous substances such as mercury, polychlorinated biphenyls (PCBs), and CFC fluids, as well as dangers associated with manual handling, mechanical safety, electrical safety, and the possibility of cuts, abrasions, and fire or explosion are all considered hazards in waste management [110]. The lack of approved environmentally friendly chemical liquids for the management of e-waste, inadequate infrastructure, thermodynamic limitations in the separation of complex material mixtures resulting in recovery that is not cost-effective, and the requirement for financial and policy support, particularly in developing countries, are additional challenges [111]. On the other hand, when recycled properly, e-waste offers significant prospects. Urban mining is an effective way to recover noble metals from e-waste. For instance, 210 kg of copper and 1.5 kg of gold can be extracted from one metric ton of circuit boards, which is a far higher concentration than what is typically seen in primary mining from ores [112]. When combined with appropriate business models, this efficient precious metal recovery can yield significant profits [113]. The projected monetary value of elements found in global e-waste is greater than the GDP of many nations and more than three times the total economic value of silver mining worldwide [114]. Additionally, effective e-waste management can improve human health and the environment, addressing urgent issues of the current era. While e-waste management has historically received less attention in developing nations, these conditions can be significantly improved by adopting and putting into practice strategies, regulations, and legislation concerning e-waste disposal locations [115].

Only about 20 % of E-waste is legally recycled, despite the fact that EPR laws are in place in two-thirds of the world. Gaps and related solutions are revealed by analyzing the statistics and current practices that have been presented.

Legal Framework: Even though e-waste has the same properties everywhere, different countries have different legislation, which leads to confusion and conflict. Policy-related difficulties will be lessened by creating a worldwide legal framework and making sure it is enforced everywhere.

Traditional virgin mining continues despite the fact that both urban and virgin mining share the same usage of natural resources and metal values. A sustainable environment is achieved through upholding regulations that regulate urban mining, raising public understanding of closed-loop economies, and highlighting the advantages of urban mining. Cost-effectiveness, sustainability, protecting natural resources, minimizing environmental damage, and improving health and safety protocols are some of these advantages.

Developing nations ought to follow international best practices instead of enacting legislation based on personal preferences. Enforcing obligatory licenses and permits for formal processing plants worldwide—as the EU does—improves the efficiency of e-waste disposal.

Benchmark Technology: The shift to a circular economy is aided by e-waste laws, but benchmark technologies and cutting-edge infrastructure are essential. It is essential that world leaders assess the finest technological approaches used worldwide and set benchmark technologies for every stage of the processing of e-waste. Innovation is essential to the development of domestic technology, the advancement of transparency, and the suppression of illicit E-waste disposal practices.

Implementation of EPR: The management of electronic waste is made more difficult by differences in EPR laws between OECD and non-OECD nations. For the management of e-waste to be both legally compliant and environmentally sound, a worldwide EPR law must be established. A common law will make duties and obligations clear for all parties involved and guarantee conflict-free adherence.

Green Policies: Producers are required to identify the chemistry of their products and make end-of-life harvesting easier by mandatory enforcement of green standards, such as Green Product Identification. Government support is crucial in encouraging stakeholders to design, produce, and handle e-waste responsibly through the strict implementation of EPR.

Customer Conduct: Product lifetime, risks associated with incorrect disposal, repurpose, repair, and refurbishing procedures, and compositional characteristics are only a few of the details that manufacturers are required to disclose to customers. Promoting a better environment requires educating customers on how to dispose of E-waste responsibly and holding awareness campaigns.

Transformation of the Informal Sectors: Unsustainable E-waste treatment procedures in the informal sector, which frequently involve disadvantaged communities, pose serious threats to human well-being and the environment. E-waste generation and processing would be more transparent, traceability would be improved, and environmental issues would be addressed by formalizing the sector through legislation and education.

11. Discussion

To gain an understanding of the current studies, policies, and practices pertaining to the management of e-waste in Saudi Arabia, start with a thorough examination of the literature. The strengths, flaws, possibilities, and threats of Saudi Arabia's current e-waste management plans were considered. Several elements, including public awareness, financial resources, technology capabilities, and policy frameworks. found potential to enhance Saudi Arabia's e-waste management practices, such as developing recycling infrastructure, encouraging environmentally friendly product design, putting extended producer responsibility (EPR) initiatives into place, and educating customers [116].

Like many other fast developing countries, Saudi Arabia has substantial difficulties in successfully managing electronic trash, or “e-waste.” The number of electronic gadgets that are approaching the end of their useful lives is increasing as the country moves closer to industrialization and digitization, which presents threats to public health and the environment. With an emphasis on developing practical solutions to reduce related health and environmental hazards, this review seeks to clarify the difficulties of e-waste management in Saudi Arabia [117].

Current Landscape of E-Waste Management in Saudi Arabia: Even with deliberate attempts to update waste management procedures, Saudi Arabia struggles with insufficient infrastructure and regulations designed to accommodate the growing amount of e-waste. Lack of specialized e-waste recycling facilities increases the need for unofficial recycling techniques, which raises health and environmental risks. Furthermore, the difficulties in managing e-waste are made much more difficult by stakeholders' ignorance of appropriate disposal techniques.

Strategies for E-Waste Management: In order to tackle the intricacies of managing e-waste, Saudi Arabia needs to implement a comprehensive strategy that includes legislative modifications, technology advancements, and public education initiatives. Manufacturers can be encouraged to design items with end-of-life concerns by enacting extended producer responsibility (EPR) frameworks, which will make recycling and disposal simpler. E-waste management procedures can also be made more efficient by funding cutting-edge recycling facilities and encouraging cooperation between governmental organizations, business partners, and civil society [118].

Challenges Hindering Effective E-Waste Management: The use of effective e-waste management solutions in Saudi Arabia is hampered by a number of issues. These consist of shoddy infrastructure, low public knowledge, unofficial recycling methods, and regulatory shortcomings. Moreover, the lack of established methods for gathering e-waste contributes to the growth of unofficial recycling businesses and unlawful dumping, which worsens health hazards and environmental deterioration.

Opportunities for Sustainable E-Waste Management: Saudi Arabia has the inherent potential to change its e-waste management strategy into a sustainable and circular one, even in the face of tremendous challenges. Utilizing cutting-edge recycling methods, material recovery procedures, and decentralized waste management systems are examples of technological advancements that can improve resource efficiency and reduce environmental impact. Additionally, e-waste can be reduced in its negative impacts on human health and the environment while generating economic opportunities through the promotion of public-private partnerships and the integration of workers from the informal sector into formal recycling networks.

Impact on Health and Environment: Significant health and environmental dangers, including as soil and water contamination, air pollution, and exposure to dangerous substances, are associated with the inappropriate processing and disposal of e-waste. Lead, mercury, and cadmium are just a few of the toxic materials found in electronics that can leak into the environment and harm both human health and the integrity of the ecosystem. Furthermore, unofficial recycling methods that involve burning or disassembling e-waste discharge dangerous toxins into the atmosphere, aggravating respiratory conditions and accelerating global warming. Because of the consequences for the environment and human health, waste management—including the processing of e-waste—has received more attention in Saudi Arabia. An outline of Saudi Arabia's waste management and e-waste handling policies and activities may be found here.

National Waste Management Strategy: With the goal of enhancing waste management procedures all around the nation, Saudi Arabia has created a National Waste Management Strategy. This covers methods for cutting down on, recycling, reusing, and getting rid of various waste materials, including e-waste.

Regulations and Legislation: To control waste management procedures, including the treatment of e-waste, the government has put laws and regulations into place. By ensuring that the right procedures for collection, recycling, and disposal are followed, these regulations seek to reduce threats to the environment and public health.

Awareness and Education Programs: Saudi Arabia has been attempting to increase public and industry knowledge of the significance of appropriate waste management, particularly the management of e-waste. Education campaigns are run to raise public awareness of the risks associated with inappropriate disposal and the advantages of recycling [119].

Investment in Infrastructure: The government has made investments in waste management infrastructure, including as facilities for recycling and e-waste disposal. For the effective handling and processing of waste products, this infrastructure is essential.

Educational Campaigns and Workshops: Initiate focused educational initiatives across many platforms, such as print materials, social media, radio, and television, to cater to various segments of Saudi society. Arrange training sessions, workshops, and seminars in community centers, businesses, colleges, and schools to offer practical advice on managing e-waste and experiential learning opportunities.

School Curriculum Integration: The partnership with the Ministry of Education to include knowledge of e-waste into curricula at different educational levels. created activities and educational resources that are age-appropriate for teaching kids about the negative effects that e-waste has on the environment and human health as well as the value of recycling and safe disposal.

Collaboration with International Organizations: Saudi Arabia works with partners and international organizations to share best practices and expertise about waste management, particularly the handling of e-waste. This partnership facilitates the adoption of international standards and the application of successful tactics. Furthermore, Saudi Arabia is putting into practice Extended Producer Responsibility (EPR) for e-waste by creating laws that require manufacturers to manage electronic items for the duration of their lives. Stakeholders such as the government, business community, and consumers are being involved. Manufacturers have responsibilities that include designing products to be recyclable, collecting them, and recycling them. Sustainability in product design is driven by financial incentives such as eco-modulation fees. International collaboration provides resources and insights into compliance, which is ensured by monitoring and enforcement. Saudi Arabia can reduce e-waste pollution, preserve resources, and advance a circular economy by methodically implementing EPR [120].

Implementing appropriate waste management techniques is expected to result in higher recycling rates, including for e-waste, which lowers the quantity of garbage dumped in landfills. The harmful compounds found in electronic equipment contribute to environmental pollution, which can be reduced with proper handling of e-waste. Both the environment and human health benefit from effective e-waste disposal, which lowers the health hazards associated with exposure to harmful compounds found in electronic equipment. By recovering valuable elements from e-waste, less raw material extraction is required, and natural resources are preserved. The waste management industry may see job possibilities as recycling facilities and waste management infrastructure are established.

12. Conclusion

Finally, the E-waste problem becomes a major issue, similar to the revolutionary effects of the IT and agricultural revolutions. Sadly, the techniques used to process e-waste are showing to be unsustainable, endangering the health of the earth. A perilous imbalance in the delicate balance of nature has resulted from human actions that have damaged the Earth's core, such as the widespread plasticization of the oceans, the illicit dumping of garbage, and vast virgin mining. While rich countries keep moving forward, developing countries face obstacles such a lack of resources, poor infrastructure, and insufficient experience. This widening gap highlights how urgently the E-waste issue needs to be addressed by a group effort. It is imperative that all parties involved, regardless of country borders, acknowledge their mutual obligation to protect the environment. The effects of e-waste are extensive, impacting not only the environment but also everyone's safety and health, with vulnerable populations including women, children, and teenagers being especially affected. The only way we can hope to decrease the negative effects of e-waste and guarantee a sustainable and peaceful coexistence with our planet is via coordinated efforts and a worldwide commitment. Metal makes about 40 % of e-waste, followed by plastic polymers (30 %) and metal oxides (30 %). The gathering, washing, sorting, pre-treatment, and treatment phases are crucial to the reprocessing and recovery of e-waste. Huge household products, IT and telecommunications equipment, and consumer and small household gadgets are the three main categories into which e-waste is divided. With 42.3 % of the world's total e-waste (5.10 Mt) collected, Europe currently leads the world. Asia (11.7 %, 2.9 Mt), America (9.4 %, 1.2 Mt), Oceania (8.8 %, 0.06 Mt), and Africa (0.9 %, 0.03 Mt) follow. Precious materials, basic materials, dangerous materials, halogens, plastics, glass, and ceramics are all included in e-waste. Asia produces more e-waste than any other continent, but only at 5.6 kg/inh per person, compared to higher rates in Europe, Oceania, and America. Alarmingly, 83 % of the e-waste produced worldwide is undocumented, which can result in illicit dumping or open burning and pose major risks to public health and the environment. E-waste is on the rise due to an increase in anthropogenic activities and insufficient management techniques that do not include formal mechanisms for recycling, segregation, and collecting. This puts the management of e-waste in jeopardy and endangers public health, the natural ecology, and environmental sustainability. Saudi Arabia needs a regulated network with early estimation, prediction, and tangible steps to avoid negative impacts because its current processes are inefficient and segmented. It is highly advised to establish a regulatory framework that includes monitoring, estimating, and increased social awareness. In the end, this integrated strategy will help mitigate adverse effects and promote environmental sustainability by controlling and managing e-waste within a secure system. To solve this, national and international organizations must work together to manage e-waste effectively, which is crucial for advancing a circular economy. This includes public awareness campaigns. To sum up, e-waste management in Saudi Arabia requires a concerted effort that includes stakeholder participation, technical innovation, and legislative reforms. Through tackling the fundamental issues and leveraging current prospects, Saudi Arabia may shift to a sustainable e-waste management framework that protects public health, maintains environmental integrity, and stimulates economic growth.

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Declaration of competing interest

I **M. Amin Mir** hereby declare any potential conflicts of interest related to the submitted paper titled "**Saudi Arabia E-Waste Management Strategies, Challenges and Opportunities, Effect on Health and Environment: A Strategic Review.**" I confirm that.

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