E-Waste Management Strategies and Prediction Methods

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Electronic waste generation is increasing dramatically throughout the world. Consequently, this increase in E-waste harms the environment, health, and other aspects of human life. Moreover, hazardous substances and the informal disposal of E-waste severely threaten human health and the environment. Saudi Arabia is the largest Arab country in terms of electronic waste generation and is the Arab country that generates the most E-waste. Over the past few decades, several initiatives and policy implementations have been undertaken in the country. However, the management of E-waste is still a source of distress and an unresolved issue. Sustainable development requires much more effort, primarily efficient E-waste management, which can only be achieved by establishing a formal collection system, early forecasting, and accurate estimations.

E-waste E-waste generation E-waste management

1. E-Waste Supply Chain Network (S.C.N.)

For economic circulation as well as sustainable E-waste management, it is mandatory to consider the supply chain. Supply chain networks comprise two major components; one informal and the other formal. The informal one is considered to be on the micro-scale. It is highly labor-consuming, mostly unregulated, and involves poor technological utilization or the provision of resources and services. The formal sector dominates due to the monitoring and regulatory opportunities. This is the sector that contains the most information in Saudi Arabia, as most of the E-waste is produced and regulated in the informal sector [1]. Improper management techniques such as acid leaching, dismantling, and improper landfilling make sustainable management difficult, while their existence and widespread nature make the adoption of formal recycling [2]. The multifaceted nature of E-waste causes the handling and segregation, along with the dismantling, to be more difficult as well [3]. E.P.R. is considered to be the most feasible approach, but it has a weak implementation framework [4]. E-waste management can be achieved by considering the following factors: the analytical hierarchy process (A.H.P.) along with quality function deployment (Q.F.D.) for decision-making, evaluations, and system management [5][6]. Using both structures will help to regulate the predefined critical factors, enhancing the efficacy of the S.C.N. The largest e-generator handling systems are being managed by this model, which shows the significance of this process. Moreover, a study has suggested that an increase of $1000 in G.D.P. will increase the amount of E-waste generation by 0.5 kg. This clearly demands sustainable and dynamic management [7].

2. E-Waste Management Policies and Strategies

Several strategies have taken place in this field. These strategies include E.P.R., L.C.A., M.F.A., M.C.A. [8], and VBNT. Some countries have used analytical management tools [9] and GIS-based [10] systems for E-waste management. However, only some tools can be considered to be the prime method. Collectively, these tools can complement each other's impacts. The success of these models depends upon the environmental footprint, secure recycling, and the recovery of precious metals through formal collection and segregation protocols.

The life cycle assessment (L.C.A.) has gained global acceptance, with a particular emphasis on Europe, Asia, the North-eastern and African regions, as well as Switzerland. In these areas, extensive research has been conducted on the eco-friendly and economic benefits of recycling systems [11] Asian countries have adopted the L.C.A. mostly for the estimation of electronic waste management and its impact. This has shown significant economic and environmental results [12]. In comparison with conventional approaches—i.e., incineration, landfilling and the disposal approach—L.C.A. is the most significant E-waste handling strategy [13][14]. In India, when using the L.C.A. model, E-waste prediction and its estimation is carried out using software, tools, and E-waste datasets which are then compared with real time datasets. These studies have shown the significance and reliability of the L.C.A. predictions [15].

On the other hand, material flow analysis (M.F.A.), a decision support system, is another significant tool used to spatially analyze the flow and timeliness of E-waste during recycling, E-waste collection, disposal, and the stocking route. In this way, M.F.A. provides information on the interface linkages from the initial stage to the destination [16] This includes considering the flow of E-waste and its assessment in terms of environmental, economic, and social value. India, China, Indonesia [17], Australia [18], Japan [19], and Nigeria have adopted the M.F.A. tool to map the flow of E-waste, as well as its collection, recycling, and cross-boundary trade [20]. E-waste generation and estimation in the USA have also been examined using the M.F.A. model using previous and future electronic gadget sales details and their average life span. This has provided the baseline for the end of the life span information of electronic components, and has linked the EoL with E-waste generation and management. Therefore, it is suggested that by decreasing the EoL of electronic computers, E-waste generation can be decreased [21]. M.C.A. is suggested to be the best tool to incorporate social enablers in E-waste handling [22]. This decision support system has been adopted by the USA, Spain, and Cyprus to optimize and locate recycling plants and E-waste handling. This tool comprises two phases which enable the evaluation of any constraints and issues followed by efficient data processing. In this way, a balance between the environmental and economic footprints can be achieved. Among these tools, E.P.R. is a national approach that provides information on the environmental aspects and directs the responsibility of the manufacturers to take back products after they have reached the end of the life phase [23].

Sustainable E-waste management can only be accomplished following an accurate analysis of the existing E-waste, its generation rate and future prediction. For this purpose, quick predictor models such as Bass, Gompertz, Logistic, ARMA, and the Exponential Smoothing model have been utilized to determine future E-waste generation; the content of precious metal ions in computers in Japan, Australia, New Zealand, the USA, and South America were examined. These models have offered reduced error indices, reliable in-sample estimation, baseline mapping, and a framework for E-waste estimation [24]. Most countries follow the Basel Convention and Stockholm Convention 2001. Along with these, digital technologies are also emerging as promising tools for E-waste management. The 4.0 industrial revolution has offered several socio-economic and environmental solutions to reduce pollution, curb waste generation, and improve working conditions by adopting smart vehicles, robots, A.I. tools, real-time monitoring, and sensors [25]. With these emerging robotics, smart tracking systems, sensors, RFID tools, smartphone apps, real-time monitoring, and autonomous systems, sustainable and eco-friendly E-waste management is achieving remarkable outcomes [26]. Although robotics bins, intelligent routing, autonomous cars, and real-time monitoring are practiced interventions, they require further ecosystem development to achieve optimal results [27]. In Turkey, triple bottom line (TBL) technology has been adopted to digitalize E-waste management and its prediction. In this process, E-waste generation is predicted for the coming four years, and then a novel sustainable collection, characterizing, and segregation center model is proposed. The model is based on digital technologies using the TBL concept according to the projected increase of E-waste. This concept can further be utilized by municipal companies and other authorities showing the center model's implacability [28].

The E-waste management in Gulf countries relies on existing laws and compliance with the Basel Convention, as no specific regulations exist. However, the United Arab Emirates has recently implemented EPR-related laws, and Jordan, Kuwait, and Algeria are also in the process of enacting similar legislation. Other countries in the region have yet to introduce any laws or regulations pertaining to E-waste management [29].

In addition, article 46 of Egypt's Telecommunication Regulation Act (No. 10/2003) prevents importing utilized telecommunication technology probes for interchanging [30]. For E-waste management, the adopted activities are often manual, informal, and labor-intensive. Under the Vision 2030 policy and sustainable environment initiative, composting and waste-to-energy opportunities are gaining increased attention in the country. Composting is considered due to the high organic waste generation (around 40%). All E-waste management activities are coordinated and financed by the government. The most practiced approaches in the country are currently landfilling and incineration [31].

3. E-Waste Recycling and Metal Recovery

Currently, the most appropriate physical processes used as pre-treatment techniques according to the technological aspect are:

- Pyrometallurgy;
- Hydrometallurgy;
- Biohydrometallurgy;
- Pyrolysis.

Non-chemical approaches are now becoming the most feasible approaches prior to the recycling or treatment of E-waste [32]. The pyrometallurgical methods involve the use of magnetic separation, eddy currents, air currents, and vacuum metallurgical separation [33]. Hydrometallurgy uses chemicals, whereas bio-hydrometallurgical uses "green technology," i.e., microorganisms for metal abstraction [34][35]. Using microorganisms to regain noble metals is a relatively economic and environmental approach regarding several other resources [36]. The thermal cracking (pyrolysis) or thermal conversion of E-waste is quite a beneficial and emerging technology. However, it cannot be implemented at a larger scale due to restrictions regarding thermogenetic and initiation energy and yield [35][36]. These sophisticated adopted technologies are indispensable for better recycling and environmental sustainability. They are on hand to help restore natural resources while also reducing the hazardous and economic burden [36]. The recovery scheme involves the use of mechanical separators to sort, crush, and separate electronic parts, followed by pyrometallurgical treatment that deals with nonferrous metals and separation of metallic and noble elements and the separation of metallic and noble elements. For metallic item recovery, electrometallurgical treatments are carried out, followed by a treatment with liquid in which the acidic wastewater is neutralized and treated before discharge [37].

4. E-Waste Estimation and Prediction

Presently, many strategies have been established for the efficient and eco-friendly handling of E-waste management worldwide, specifically in developed countries. **Table 1** summarizes the adopted technologies used to propose specific interventions. A detailed discussion is then carried out below the table.

Table 1. Summary of the E-waste prediction and estimation methods and strategies.

Author	Year	Application Purpose	Tools	Proposed Intervention
Hischier et al. [11]	2005	E-waste handling	L.C.A.	Developing economically and socially favorable E-waste strategy developing tool
Kazancoglu et al. [27]	2020	Digitalized E-waste tracking and handling	M.F.A.	Decision Support system for better E-waste handling
Yoshida et al. [19]	2016	Mapping E-waste flow	M.F.A.	Better E-waste collection and cross-boundary trade
Kiddee et al. [8]	2013	E-waste estimation	Decision support system	Developed the linkages during the interfaces from the initial to the final stage in E-waste management.
Andarani and Goto [17]	2014	Mapping E-waste flow	M.F.A.	Better E-waste collection and cross-boundary trade
Kiddee et al. [8]	2013	E-waste collection	E.P.R.	Responsible and formal E-waste collection

Author	Year	Application Purpose	Tools	Proposed Intervention
Roychoudhuri et al. [15]	2019	E-waste prediction and estimation	L.C.A.	Model predictions and comparison with real-time data
Forti et al. [25]	2020	E-waste estimation	Smart technologies	Real time monitoring, estimation and forecasting
Islam and Huda [18]	2020	Monitoring E-waste flow	M.F.A.	Better E-waste prediction
Duman et al. [34]	2020	E-waste prediction in Washinton U.S.A.	Grey Model	Provided reliable forecasting and E-waste estimation based on an open dataset in the USA
Andeobu et al. [38]	2021	Forecast E-waste generation in USA, and UK.	V.M.D., ESM, G.M.	Predicted the future fluctuation trends of E-waste production which helps in the proposal of timely interventions and decision-making as part of the sustainable circular economic goals.

ed a case data was e product lifetime distribution. The number of household devices was collected from published statistical data. A use-phase analysis forecasting method was used to predict future waste based on the collected data [39]. Another researcher performed a survey in Vietnam, collecting the raw data and then using it to assess the amount of E-waste generated by five different kinds of electronic equipment. The number of disposed appliances was determined using a population balance model [40]. A survey approach was used to predict the amount of E-waste from eight different electronic devices in South Korea. The data was collected through a questionnaire, and Weibull distribution was used to analyze the life span distribution of the eight appliances [41][42] used Holts' double exponential smoothing and dynamic life-span technique to estimate the E-waste from 16 electronic devices in the Australian environment from 2010 to 2030. The authors stated that the Weibull distribution prediction model is the best method out of a group of ten prediction models to use to predict the future amount of E-waste. The data was collected from an open source, the passport database "Euromonitor." In practice, such a technique has proven to be beneficial when analyzing time series data connected to EE-waste creation. According to the article, future work could explore another database [43]. One of the efficient ways to engage in recycling and E-waste treatment involves precise estimations using a grey model in which fractional calculus and integral-differentiation operators are used as non-local probes, linking with the E-waste management both in the present and historically which, again, can be broadly applied. In a study looking into the generation process of an E-waste model, it is suggested to enhance the integral model through a differential equation; i.e., a fractional grey model which not only predicts the E-waste, but also offers data on the waste volume and number of metals. This type of model is a non-singularity, involves easy and simple computation, and presents a feasible solution with accuracy and precision [44]. In another study, the grey modeling technique was adopted for E-waste prediction in Washington, USA. This provided reliable E-waste forecasting and estimation. Here, the Nash nonlinear grey Bernoulli model was integrated along with fractional locators using PSO. The specifics were created with the intent of facilitating municipal department usage and reverse logistic operations, thereby dispersing the data employed by formal E-waste management in the years ahead.

In China, the Sales Obsolescence Model technique has been adopted for E-waste estimation and prediction. During this estimation process, the E-waste generation datasets revealed that 8 million tons by weight of E-waste are produced domestically, with 1% of the metal retrieved during the recycling process. This , along with the E-waste estimation, suggests the development of an urban mine for critical metals during the E-waste recycling processes [45]. A recent hybrid decomposition-ensemble model integration approach—which integrates variational mode decomposition (V.M.D.), an exponential smoothing model (ESM), and grey modeling (G.M.)—has been used to forecast E-waste generation in the USA and the U.K. The most significant prediction result for E-waste data also predicts the future fluctuation trends of E-waste production, helping to engage in timely intervention and decision-making to better meet the sustainable circular economic goals [46]. Another study used regression analysis to estimate the volume of E-waste created across the Indian industrial sectors in order to establish a regulatory framework [47]. Moreover, the distribution delay model was employed to forecast mobile phone End-of-Life in the Czech Republic [48]. Aside from this, another study attempted to anticipate the amount of E-waste generation in the USA by utilizing the material flow analysis (M.F.A.) approach. This method was used to anticipate the future E-waste of thirteen E.E.E.s. Historical and future sales records are required to apply this model and the life span assumption [49].

Furthermore, the M.F.A. approach was used with a logistic model to anticipate the number of outmoded P.C.s [49]. Additionally, grey modeling was applied to estimate E-waste generation in Botswana [50]. Another study used a different technique by employing discrete grey modeling to quantify the quantity of E-waste created by electronic products like televisions, mobile phones, and PCs in the Indian environment. The forecast was done using a discrete grey model that incorporates the Fourier transform and exponential smoothing techniques [51]. Grey modeling has been used also to estimate the amount of E-waste collected in Turkey [52]. This demonstrates that grey modeling may yield valuable insights even with small, limited datasets. The reliable accuracy of the models varies from one scenario to another and based on the characteristics of the databases. For instance, grey forecasting models are renowned for providing accurate predictions whenever used with small-sized datasets. Among several prediction models, the univariate grey forecasting model GM (1.1) and its improved variants have become popular due to their improved accuracy. In addition, higher precision grey models are often attained by adjusting the model’s parameters [53].

8. E-Waste Inventory

E-waste management also demands the tracking of the in-outflow of electronic products for developing strategies, infrastructure, and a sustainable supply chain network, including the economic, social, and environmental aspects. Hence there is a need for a dynamic and extensive database. This can be achieved through the development of a detailed E-waste inventory. In this regard, a study has been carried out in India on the development of an E-waste prediction and inventory model for households in Pune city. The model provided segregation, transportation, tracking, and data storage for use regarding the cooperative functionalities available and reducing hazardous waste. Thus, it offered sustainability, reliable solutions, and new economic propositions for the stakeholders and end-user engagement [54]. A study carried out in Pakistan declared the development of an inventory to be imperative for developing countries as it is in these areas that E-waste generation is in a state of fluctuation and increasing tremendously. They also showed the current expansion of E-waste production, which clearly demands proper E-waste handling and disposal [55]. In India, two suggested methods are E-waste inventory determination through a questionnaire-based survey, and a Cloud-based model. The consumer buying capacity and life span detail the utilization of E-waste inventory to provide the in-out flow of e-products which is then linked with E-waste generation. This facilitates smart E-waste inventory. There is also the data available on e-product buying and selling, which can be further utilized in decision-making and strategy development [56].

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