Electronic waste considerations in the Middle East and North African (MENA) region: A review

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A R T I C L E   I N F O

A B S T R A C T

Waste Electrical and Electronic Equipment or e-waste is a waste stream that has multiplied profoundly in recent years. Currently, many researchers focused on the study of e-waste. The Middle East & North Africa (MENA) is a region with similar geographical features, has a high young population, and is economically diverse. The area has seen unprecedented population growth in the last 50 years. This paper presents a review of the reported works in the field of e-waste in the MENA region. It aims to shed light on the various aspects of e-waste in the MENA region. The various methods of estimating the quantities of e-waste, how it is presently managed in the MENA, the impacts of e-waste, and the regulations compliant with MENA are covered in the review. The e-waste stream is beginning to attract attention in certain countries of the MENA in recent years. As a step to this, there are various mathematical models developed to estimate the quantity of e-waste effectively. The prime component of e-waste is mobile phones, which have penetrated very deeply into all regions of the world. The health hazards caused by e-waste stem primarily from heavy metals and halogenated plastics in them. The review found that the health impacts caused by informal e-waste handling in MENA countries are not given due attention and are not covered in the literature. Regarding the regulations on e-waste disposal, countries need to implement these regulations to control e-waste penetration effectively.

Contents

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Abbreviations

Ag	Silver
AHP	Analytic Hierarchy Process
Al	Aluminum
ALF	Artificial Lysosomal Fluid
Ar	Argon
As	Arsenic
Au	Gold
Ba	Barium
Be	Beryllium
Br_2	Bromine
Cd	Cadmium
CE	Consumer Equipment
CFC	Chloro Fluoro Carbons
Cr (VI)	Chromium VI
CRT	Cathode Ray Tube
Cu	Copper
DP	Dechlorane Plus
EE	Electrical and Electronic
EEE	Electrical and Electronic Equipment
EU	European Union
FR	Flame Retardant
Ga	Gallium
GDP	Gross Domestic Product
Hg	Mercury
HQ	Hazard Quotient
HS	Harmonized System
IT	Information Technology
LCA	Life Cycle Assessment
LCD	Liquid Crystal Display
LHA	Large Household Appliances
MCA	Multi Criteria Analysis

MFA	Material Flow Analysis
Ni	Nickel
Niobium	Nb
PAH	Polycyclic Aromatic Hydrocarbons
Pb	Lead
PBB	Poly Brominated Biphenyls
PBDE	Poly Brominated Diphenyl Ethers
PCB	Poly Chlorinated Biphenyls
Pd	Palladium
POP	Persistent Organic Pollutants
Pt	Platinum
PV	Photo Voltaic
PVC	Poly Vinyl Chloride
Sb	Antimony
Sb_2O_3	Antimonous Oxide
Se	Selenium
SELF	Simulated Epithelial Lung Fluid
SHA	Small Household Appliances
Ta	Tantalum
TBBA	Tetra Bromo Bisphenol A
Te	Tellurium
Tl	Thallium
UNEP	United Nations Environment Program
UNU	United Nations University
USD	United States Dollar
USEPA	The United States Environmental Protection Agency
V	Vanadium
WEEE	Waste Electrical and Electronic Equipment
Zn	Zinc
ZnS	Zinc Sulfide

1. Introduction

With increasing consumer demands, technology is growing rapidly, making electronic devices obsolete quickly. This has led to the reduced life span of electrical and electronic products over the last two decades (Duman et al., 2019). The overall global economic development is the most vital factor related to the consumption of electrical and electronic equipment (EEE). Technology growth is inevitable and enhances living standards. Globally, the consumption of EEE is growing at an alarming rate of 2.5 million tonnes annually (Forti et al., 2020). As is the case, when technology finds an update or a slightly better version of an existing product is released, a significant segment of products become outdated. Waste electrical and electronic equipment (WEEE), referred to as e-waste throughout this article, involves a wide range of damaged, discarded, outdated electrical and electronic devices, mostly with battery systems. It includes mobile phones, tablets, computers, accessories, television sets, refrigerators, and air conditioners. They are considered by the users as waste and have no intention of reusing them (Duman et al., 2019; Forti et al., 2020). In other words, e-waste refers to all items of EEE and its parts that the owner discards as waste without the intent of reuse (UNU, 2014; Kaya, 2016). For analysis purposes, EEE is classified by type of activity, similar internal constituents, weight similarities, and similar features towards the end of useful life. Together they are 54 categories, and these 54 types can be grouped into six major types, namely, cooling and freezing equipment, screens and monitors, lamps, large electrical equipment, small electrical equipment, and small I.T. and communication equipment, see Fig. 1 (Alghazo and Ouda, 2016; Vanessa et al., 2018).

Worldwide, e-waste is a rapidly growing waste stream, with a value of 53.6 million tonnes in 2019 and anticipated to reach 74.7 million tonnes in 2030 (Awasthi et al., 2022). Compared to a value of 44.4 million tonnes in 2014, the expected value in 2030 shows that the quantity almost doubles within 16 years. The technology growth and corresponding e-waste contribution have grown rapidly but the collection and management systems are lagging and have not come up in pace with its production and usage (Parajuly et al., 2020).

E-waste combines valuable resources and toxic substances that call for careful manipulation (Kusch and Hills, 2017; Parajuly et al., 2020). Chemical compounds and heavy metals find their way to electrical and electronic products as they
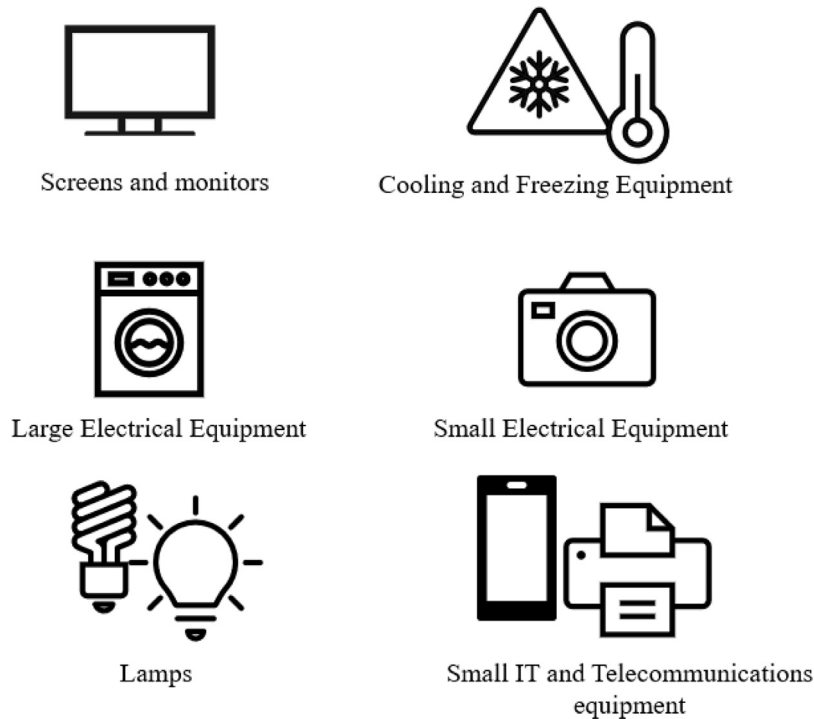
Fig. 1. Illustration of six major categories of e-waste.

Table 1
Various heavy metal usage in the electrical and electronic (EEE).

Element	Items/Use in EEE	Reference
Mercury (Hg)	Fluorescent lamps, switching relays, thermal relays	Ni et al. (2014), Albatrni et al. (2021) and Al-Ghouti et al. (2022)
	Used in pigments	Han et al. (2019)
Cadmium (Cd)	Serve as a plasticizer to impart stability	Morf et al. (2007)
Lead (Pb)	Serve as a plasticizer to impart stability	Morf et al. (2007)
	Used for metal joints	Han et al. (2019)
	Used as solder for printed circuit boards	
	Cathode ray tubes (CRT)	Duan et al. (2016), Woo et al. (2016), Tansel (2017) and Bakhiyi et al. (2018)
Chromium (Cr VI)	Increase anti-corrosion properties of metal casings	Han et al. (2019)
	Used in pigments	Han et al. (2019)
Copper (Cu)	Used in wires	
Nickel (Ni)	Used as part of alloys that make stainless steel used in parts of EEE	Han et al. (2019)
Arsenic (As)	LCD	Duan et al. (2016), Woo et al. (2016), Tansel (2017) and Bakhiyi et al. (2018)
Tin (Sb)	Used as flame retardant	Han et al. (2019)

are used to give various desired product features. Table 1 presents various heavy metal usage in EEE, and subsequently in e-waste.

Additionally, the elements present in abundance in the printed circuit board are Cu, zinc (Zn), Aluminum (Al), and Pb, and it also contains Ni, Cd, Selenium (Se), Arsenic(As), Barium (Ba), Cr, Silver (Ag) and Hg (Demim et al., 2013; Priya and Hait, 2018). High concentrations of Cu, Ni, Pb, and Sb have been found in the e-waste of printed circuit boards (Li et al., 2011). Apart from the heavy metals, compounds like Antimonous oxide (Sb_2O_3) and Bromine (Br_2) containing organic compounds are applied to printed boards for flame retarding properties (Morf et al., 2007).

An economically divergent region, countries with a common tradition and culture, countries at different stages of economic advancement, and blessed with varying natural resources — This sums up the Middle East and North Africa (MENA) (Barkhordari et al., 2019). The MENA region's total population has increased fivefold since the 1950s, from just

under 110 million in 1950 to 569 million in 2017. Absolute population numbers are expected to double to over 1 billion by the end of this century (Cava et al., 2011). The population is directly related to e-waste generation (Boubellouta and Kusch-Brandt, 2021). The region has seen significant economic development thanks to a century of exploiting hydrocarbons as its primary asset. Since the 1950s, the MENA region has experienced an exceptional "youth bulge" with the rapid increase in the total population. The relative size of youth in the overall population remains high for the foreseeable future (Cammett et al., 2015). Electronic gadgets and technology devices attract youth and the young generation. For example, in the MENA region, internet users have increased tenfold from 2000 to 2010, exceeding 100 million users, and the penetration of mobile phones, which is a major part of e-waste, is over 100 percent (Cava et al., 2011). This points to the increasing amount of e-waste predictable for the region. The MENA countries, according to the united nation list, are Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Occupied Palestinian Territory, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, United Arab Emirates, Yemen (OHCHR, 2021).

This review presents all the works of literature done on the subject of e-waste in MENA countries. It aims to analyze the literature existing for different countries of the MENA on the e-waste subject. At present, to the best of our knowledge, there is no work that consolidates all the literature pertaining to e-waste in the region. In the work, e-waste classification is presented based on various criteria and the chemical constituent of the e-waste is then presented. The various models to quantify e-waste used in various countries of the MENA are presented and analyzed. The work will help the researchers, policymakers and organizations to get insight into the subject of e-waste in the countries of MENA.

2. Methodology

The methodology for this review was carried out as follows: (i) Current e-waste generation rates for the global and MENA regions were collected from United Nations documents. (ii) The literature studies reviewed focused on e-waste in the countries of the MENA. The e-waste quantification methods, the present situation of e-waste management disposal, and e-waste regulations in these countries were studied. The approaches suggested for better handling of e-waste were also analyzed. (iii) The impacts of e-waste were also considered in the MENA region.

Scopus was used as the database to collect the relevant works of literature on the subject. The keywords used were "Electronic waste (with the name of the countries added individually to it) and e-waste (with the name of the countries added individually to it)". Relevant experience from other countries is presented to help discuss the acceleration of e-waste recycling in the MENA region. Where available, this study presents data for the most recent years. The article proceeds as follows: It first presents a classification of e-waste and then moves to put forward the current global trend in e-waste. The further sections deal with the e-waste in the MENA countries, which includes the methods to quantify e-waste, how the e-waste in MENA is presently being managed, what better approaches have been put forward, and various better strategies employed to tackle the e-waste problem.

3. E-waste classification

The list of electrical and electronic products in the world market is vast, whereby it is a strenuous task to group them into realistic and feasible categories. Many categories can be made to classify e-waste, and each is influential in forming the basis of e-waste statistics (Vanessa et al., 2018). The same type of functions, the similar kind of internal constituents, and the similarity in attributes towards the end of life are the factors considered while developing a system of classifying e-waste (Forti et al., 2020). Products within a category are assumed to have similar weight and lifetime, making it easier to analyze the same type of products quantitatively. Moreover, environmentally relevant e-waste products or large devices for which much data is potentially available must be assigned a separate classification (Vanessa et al., 2018). This has led to the development of 54 keys that fulfill this criterion. This classification was developed during the study of the different standards, as discussed by Wang (2014). The keys are called United Nations University (UNU) keys and are made in such a way that the product groups have similar average weights, internal constituents, and attributes towards the end of life and duration of their life. This is helpful to categorize e-waste statistics systematically (Vanessa et al., 2018). Other possible classifications are:

E.U.- 6 Categories: Fig. 1 represented the classification based on 6 Categories of EEE set out to ANNEX III of WEEE Directive 2012/19/E (Baldé et al., 2017). The EU-6 products can be converted using the UNU keys of the above classifications. Since the lifetimes of UNU keys are similar, they can be used to analyze e-waste generated. It can be linked to the available product codes, such as harmonized system (H.S.) codes. This way, it is much easier to account for the material flow data of EEE and e-waste as the material composition of UNU keys is homogeneous (Vanessa et al., 2018).

When considering the constituents in e-waste, e-waste is a vast reservoir of substances such as precious elements, hazardous materials, and inert substances, forming a complex chemical structure in these devices (Arya and Kumar, 2020; Kaya, 2021). E-waste contains more than 1000 substances and widely falls under hazardous and non-hazardous groups (Pinto, 2008). Primarily, it consists of ferrous metals, non-ferrous metals, plastics, glass, wood, plywood, printed circuit boards, concrete, ceramics, rubber, and other items. 50% of the e-waste comprises iron and steel, followed by plastics — 21%, non-ferrous metals — 13%, and other constituents. Metals like copper and aluminum belong to the ferrous metals group, and precious metals like silver, gold, and palladium are non-ferrous metals. Elements like Pb, Hg, As, Cd, Se, hexavalent chromium (Cr VI), and flame retardants beyond threshold quantities in e-waste are classified as hazardous
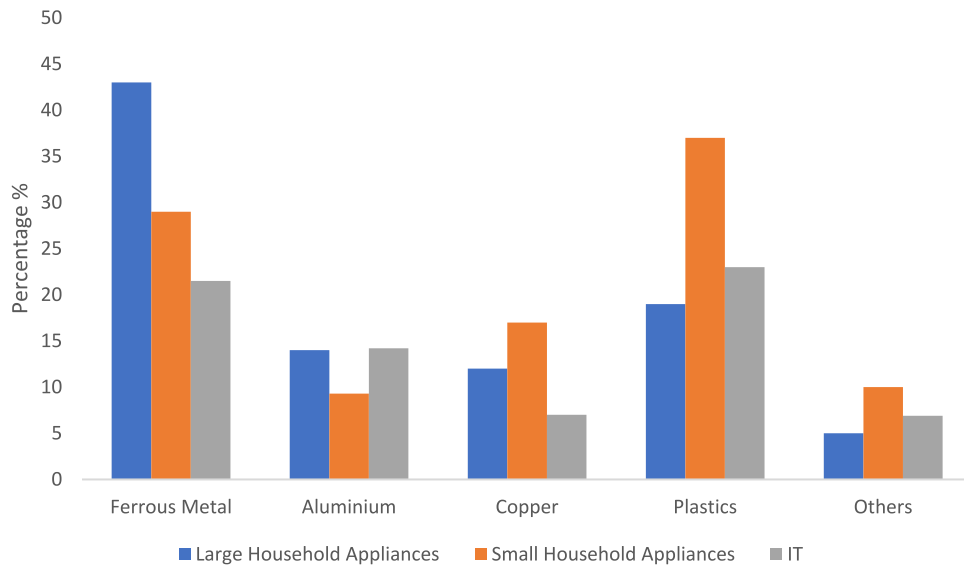
Fig. 2. Percentage of valuable elements in EEE (Arya and Kumar, 2020). (Reprinted with permission from Elsevier).

waste (Schulte et al., 2013). Pb is associated with skin damage, nausea, headache, and gastric and duodenal ulcers. Cd affects the respiratory system and kidneys and causes bone problems. Li causes neurological system defects and the flame retardants in e-waste cause hormonal disorders. The halogenated compounds can cause cancer and liver damage (Abdelbasir et al., 2018). Refined plastic is used in electronic devices to add strength, flame retardancy, impact resistance, and toughness. Examples of these are polycarbonate (P.C.) with acrylonitrile butadiene styrene (ABS) and engineered plastic (e.g., polyphenylene sulfide (PPS). They were made by adding other flame-retardant materials like talc, calcium carbonate, or glass fiber. A study on soil samples in China found them in 10 soil samples (Chai et al., 2020). The deserted dismantling sites, which are now not used for e-waste operations, continue to be a hotspot for microplastic pollution in China (Chai et al., 2020). In the EEE, valuable elements like Al, Cu, Co, Fe, Mn, Sn, Ni, Ge, Ga, In, and V are found in large household appliances (LHA) and small household appliances (SHA). They are mainly found in printed circuit boards, cables, cooling fans, heat sinks, connectors, cathode ray tubes, and power supplies (see Fig. 2). The information and communication technology equipment contain higher amounts of precious elements like Pa, Au, and Ag, and they are at percentage values of 0.0003%, 0.0016% and 0.0189% (Vadoudi et al., 2015; Mmereki et al., 2016; Arya and Kumar, 2020; Andeobu et al., 2021)

The quantities of precious metals in the e-waste are higher than their natural ores. Generally, mined ores of gold and palladium contain less than 10g/tonne of precious metals (Chancerel et al., 2009). The percentage of major toxic elements in various EEE is as follows: LHA: Pb 1.6%, Cd 0.0014%, Hg 0.00038%, brominated plastics 0.29%; SHA: Pb 0.57%, Cd 0.0068%, Hg 0.000018%, Brominated plastics 0.75%; IT equipment: Pb 6.3%, Cd 0.0094%, Hg 0.0022%, Brominated plastics 0% (Vadoudi et al., 2015; Arya and Kumar, 2020). As a fire retardant, polybrominated diphenyl ethers (PBDEs) are a compound used to satisfy strict flammability standards. The BDEs, its Penta, and Octa forms are also listed as POPs in the Stockholm convention of 2009.

E-waste is an urban mine, as indicated by the presence of these precious, valuable, and other elements, which can bring out functional secondary materials if appropriately recycled. Studies show that the value of raw materials in e-waste generated in 2019 equals approximately 57 billion USD (Forti et al., 2020). Potential hazardous elements and the appliances in which they occur are presented in Table 2. The concentration of precious elements in the e-waste (printed circuit boards) s are 1400 g/tonne for Au;14 g/ tonne for Pt;118 g/ tonne for Ga, 370 g/ tonne for Pd compared to their values in primary ores, which are 9 g/ tonne Au, 3 g/ tonne Pt, 100 g/ tonne Ga, 5 g/ tonne Pd (Chancerel et al., 2009; Arya and Kumar, 2020). Heavy metals are considered dangerous to human health and the environment when found in concentrations higher than permissible levels (Black et al., 2014).

The table indicates that electronic devices and goods contain potential elements that can be recycled and brought into use.

4. E-waste generation

E-waste is a class of solid waste that can be and need to be recycled effectively. As of 2019, 9.3 million tonnes is the amount of e-waste has undergone formal collection and recycling, just 17.3% of the total produced. It grew by 1.8 million tonnes from 2014, which leads to the inference that it showed an annual growth of 0.2 million tonnes. Thus, it is evident

Table 2

Hazardous elements and their occurrences in electrical and electronic appliances.

Source: Adapted from Pramila et al. (2012), Wang (2014), Pira et al. (2018), Li and Achal (2020), Parthasarathy (2021) and Ankit et al. (2021).

Substance	Occurrence	Toxicity
Halogenated compounds		
PCB (Polychlorinated biphenyls)	Condensers, Transformers, T.V. enclosures,	Dysfunction of thyroid, Thyroid problem, Nervous system development.
TBBA (Tetra Bromo-Bisphenol-A)	Used in cable insulation, plastic parts with flame retardant properties such as in television sets, materials of the screen in cathode ray tube devices, cases of devices	Disorder of the endocrine system, impairment in learning and memory functions of the fetus.
PBB (Polybrominated biphenyls)		Reproductive development, neural system, Hormone, thyroid
PBDE (Polybrominated diphenyl ethers)		Reproductive development, neural system, Hormone, thyroid
Chlorofluorocarbon (CFC)	Refrigeration units for foams use thermal insulation in devices	
PVC (Polyvinyl chloride)	Electrical insulation for cables	
Heavy metals and other metals		
As	LED use Gallium Arsenide	Skin alterations. Affects the nervous system, causes diabetes, cancer-causing
Ba	Getters in CRT	High blood pressure, cardio issues, gastric issues, brain, nerves, liver, kidney.
Be	Boxes of Switching units, which use rectifiers	Can cause pneumonia and affect the lungs, and heart.
Cd	Rechargeable Ni–Cd batteries, fluorescent layers in cathode ray tubes screens, printer inks and toners, photocopying machines	Affects kidney, and renal toxicity, bones, possibly reproductive damage, and lung emphysema
Pb	CRT screens, batteries, printed wiring boards, solders	Neural development of children. Blood hemoglobin. Kidney damage. Toxic to the nervous system
Li	Li-batteries	Skin, Respiratory issues, eyes
Hg	Fluorescent lamps, some alkaline batteries, and mercury wetted switches	Affects the nervous system, Behavioral damages, Blood hemoglobin, Renal defects, Neurotoxic,
Ni	Rechargeable Ni–Cd batteries or Ni–MH batteries, electron gun in CRT	Cancer-causing, lung embolism, respiratory failure, congenital disorder, bronchitis, asthma
Se	Older photocopying machines (photo drums)	Balding, Weak nails, Heart issues, kidney effects, nervous system dysfunctions.
ZnS	Interior of CRT screens, mixed with rare earth metals	Blood hemoglobin, nervous system
Others		
Toner Dust	Toner cartridges for laser printers/copiers	Respiratory problems, Oxidative stress, genotoxic
Americium	Medical equipment, fire detectors, active sensing elements in smoke detectors.	Carcinogenic
Asbestos	Older appliances such as electric heaters, coffee pots, toasters, and irons	Respiratory problems, lung fibrosis

that recycling activities are way behind compared to the growth rate of e-waste (nearly 2 million tonnes annually). The collection and recycling data can be shown in Fig. 3 for the different continents (Forti et al., 2020; Andeobu et al., 2021).

More than 82% of the e-waste worldwide is still not documented or recycled. This raises concerns about where they end up. This large stream of hazardous waste can negatively impact the environment. High GDP countries generally have the infrastructure (Boubellouta and Kusch-Brandt, 2021) for e-waste recycling, and in these countries, only around 8% of the e-waste is thrown off carelessly in dust bins which then finds its way to landfills or is incinerated. This 8% typically includes small-sized appliances and IT equipment (Forti et al., 2020). There is also an option for the discarded products to be reused and refurbished; hence, they get shipped as used goods/second-hand goods to low or middle-income developing countries (Li et al., 2013; Arya and Kumar, 2020). A notable quantity is shipped illegally in the guise of goods to be reused or sometimes exported as scrap material during this shipping. The transboundary movements of e-waste range from 7%–20% of the e-waste generated (Ilankoon et al., 2018). Another fate of e-waste is combining the unrecorded domestic and commercial e-waste with plastic and metal streams. In such cases, effective recycling does not occur, and recovery of all valuable materials does not occur. In middle- and low-income countries, there is no fully developed e-waste management infrastructure, and in some cases, it is absent completely (Forti et al., 2020).
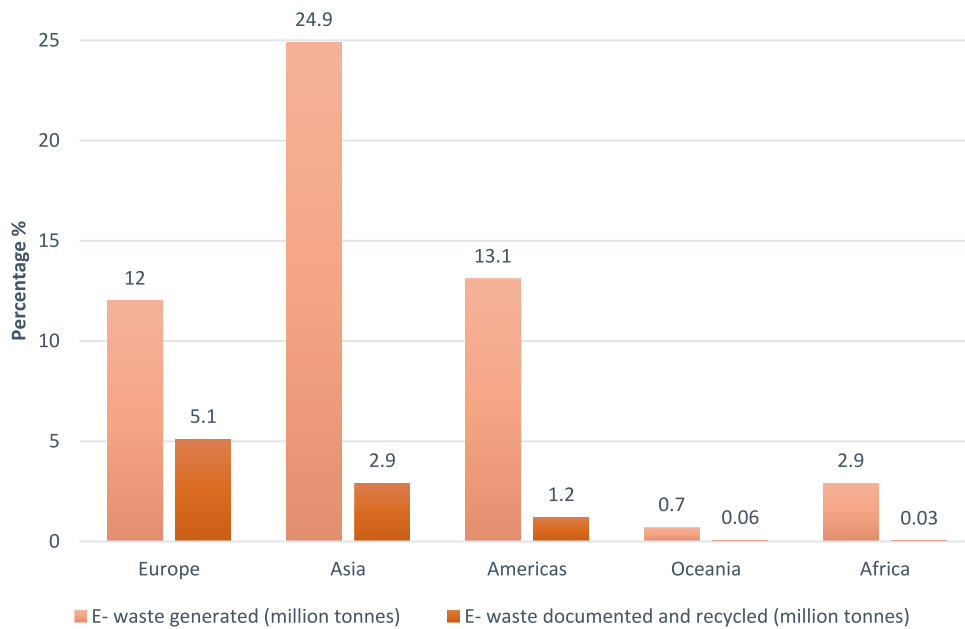
Fig. 3. Percentage of e-waste collected and recycled globally.

The total e-waste generated in 2019 in the MENA countries is presented in Fig. 4 (Forti et al., 2020). For any country, there exists a strong correlation between e-waste generation and gross domestic product (GDP) (Shamim and K, 2015; Kusch and Hills, 2017; Awasthi et al., 2018).

For example, a study in China confirms this relation; e-waste generation from 2001–2012 increased in accordance with the increase in per capita GDP. The generation of e-waste follows a doubling trend concerning the urbanization rate. In developing countries, an increase in urbanization and income levels causes an increased demand for electronic products (Lu et al., 2015). Though the study involved China, it helps to understand the relationship between GDP and e-waste generation, which was also put forward in a work by Kumar et al. (2017).

5. Discussion on e-waste in MENA countries

This section deals with the e-waste situation in MENA countries. Countries considered in the discussion are Algeria, Bahrain, Egypt, Iran, Iraq, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, United Arab Emirates, and Yemen (OHCHR, 2021). The number of articles published on e-waste from the MENA countries is indicated in Fig. 5. The articles ranged from 2011 to 2021, and the low number of publications indicates that e-waste is not yet given due attention in these countries. During the study, it was found that there is a limitation in data related to e-waste for the MENA countries.

5.1. E-waste quantity estimation

This section deals with the various works to estimate the total e-waste generated in the MENA countries. A country-wise data has been presented in the section. The first step in understanding the severity of the e-waste problem is to get an account of the quantity produced. It is crucial to further suggest and implement methods to handle it effectively and in an environment-friendly manner. The various works on this topic of quantification put forward various mathematical modeling tools that can be used to estimate e-waste.

5.1.1. Algeria

In Algeria, a questionnaire was used to collect data for modeling the quantity of e-waste. The questionnaire dealt with the lifetime of computers and monitors from purchase to end-of-life disposal (Hamouda and Adjroudi, 2017). This was the first of its kind work in Algeria, and the work focused only on the count of desktop computers, laptops, CRT monitors, and flat panel displays generated in the country. With the result of the questionnaire survey, the Carnegie Mellon model and market supply (distribution delay model) were the two models used for the quantity estimation. In the first part, using the Carnegie Mellon model, the count of the reused, stored, and discarded items were estimated. Whereas in the market supply model, the import data of the country were combined with obsolescence rates to get the quantity of e-waste generated. The main difficulty faced was the lack of response to the questionnaire received. The survey found that
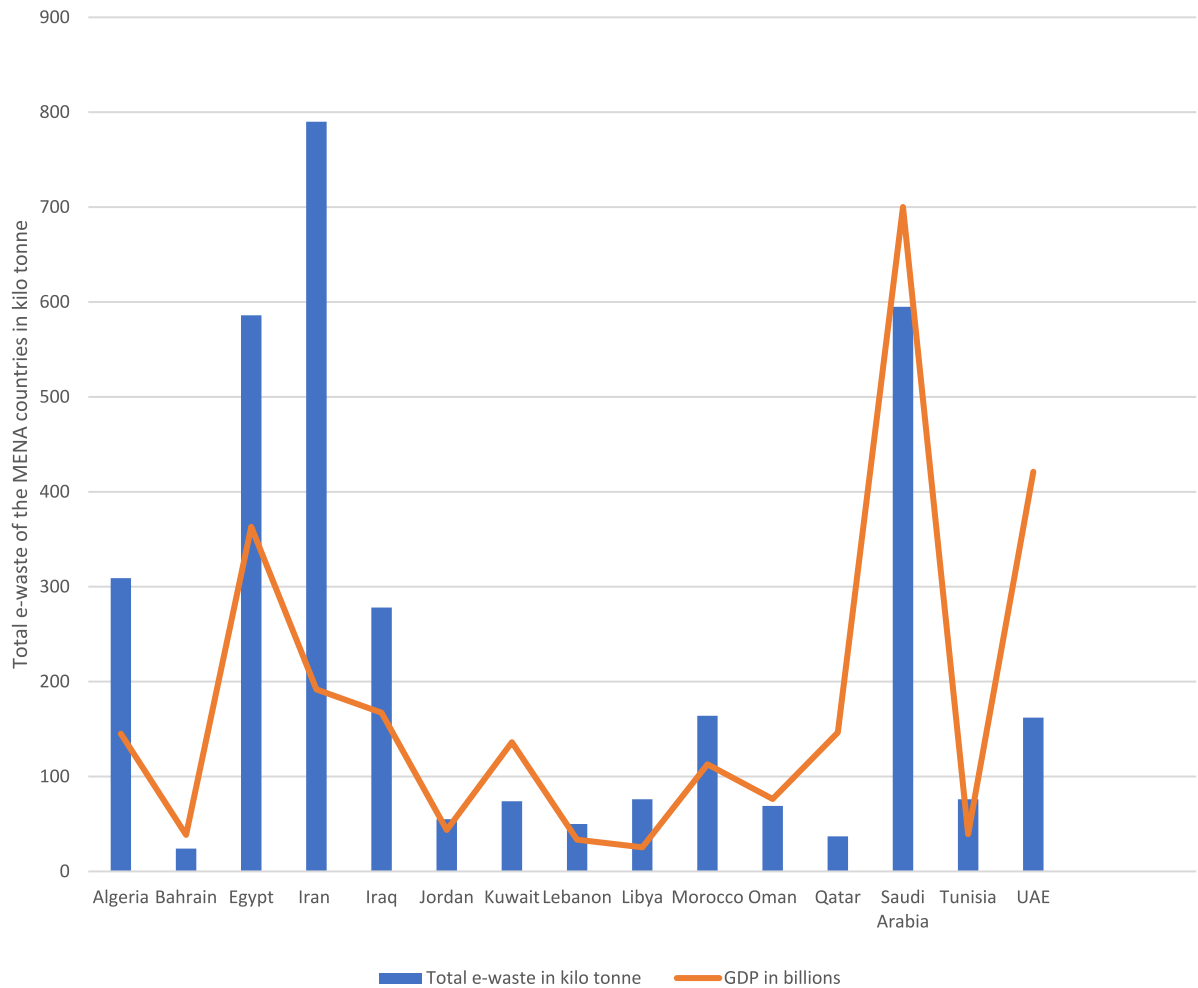
Fig. 4. GDP and the total e-waste for MENA countries. GDP data from Worldbank (2022) and the e-waste data from Forti et al. (2020).

the obsolescence of technology was the main reason for discarding the devices and not their functional obsolescence. The group explicitly mentioned that the drawback associated with managing e-waste in MENA is the lack of specific regulations to manage this type of waste. However, there are laws about solid and hazardous waste in general. Another critical issue raised by the group is the lack of accurate information on the amount and types of e-waste generated, which other authors reported as well (Fraige et al., 2012; Ikhlayel, 2016; Ikhlayel and Tasaki, 2015; Hamouda and Adjroudi, 2017).

In another work to forecast the amount of e-waste in Algeria, a logistic growth model was introduced, according to which the computer penetration rate follows a logistic curve. The Gompertz model and a bass model were also utilized in the work. The model predictions showed that by 2030, the in-use stock of PCs would be one PC for five persons (0.22). The model predictions were validated by taking the modeled value for the year 2010 for the in-use stock of PCs, which was found to be 3,118,508 PCs. This was very close to the value of 3,000,000 provided by the madar research report for 2010 (Hamouda et al., 2016, 2017).

5.1.2. Egypt

In Egypt, the end-of-life (EoL) mobile phones were estimated. Mobile phones are the most rapidly growing electronic device in developing countries. End-of-life mobile phones refer to mobile phones that were not usable further. The group found that the EoL mobile phone count would increase to 130 million by 2025. They also estimated the precious metals that could be recovered from the EoL mobile phones. The projected potential of gold recovery from EoL mobile phones was 3 tonnes, and silver will be 31 tonnes cumulated in 2025. The number of mobile phones was taken from the subscriber count of the registered subscriber identity module (SIM) cards. A 10% deduction was taken for SIM cards with only data access, dual sim operating mobile phones, out-of-use sim cards, and temporary connections for travelers in Egypt (Shakra and Awny, 2017). This was done to get an approximate correct count of the active mobile users.
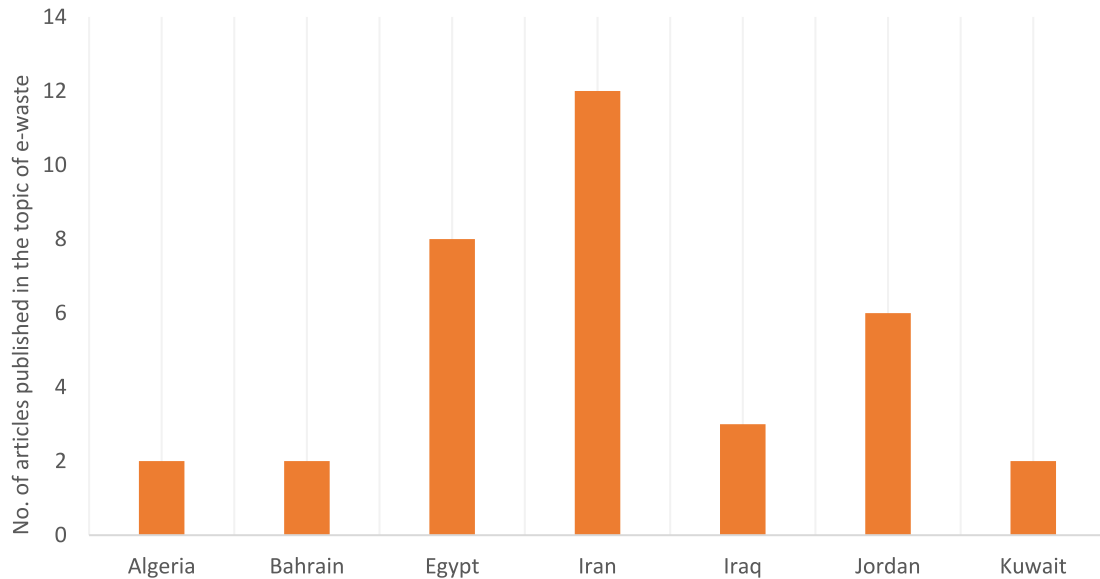
Fig. 5. The number of articles on e-waste from the MENA countries from 2011 to 2021.

5.1.3. Iran

Iran, like other countries, experienced a massive rise in WEEE owing to the increased number of businesses and domestic users (Taghipour et al., 2012). The work dealt with estimating EoL mobile phones and computers. A similar approach was taken to estimate EoL mobile phones by considering the number of active users from telecommunications companies. For assessing the count of computers, import data between 1999 and 2011 were used. The time series multiple life span model was then used to estimate the reused devices, the number of recycled devices, and the landfills each year. This was made feasible by collecting data from 1000 users to get an idea of the life span of the devices. Using the questionnaire survey enabled us to understand that the average life span of a computer was five years for the first user and three years for the second user. The time series multiple models help find a device's extended life after it becomes obsolete. The model considers the total amount of reuse for a specific year, the amount of storage by the first and second users, the total amount recycled by the first user, and the total amount of land filled by the first and second users (Rahmani et al., 2014). A logistic equation enables a forecast of future e- waste from mobile phones and computers. The logistic model has roots in ecology and was used in population growth modeling (Yu et al., 2002). In terms of technological devices, these models can help to understand the diffusion characteristics of electronic devices and can indicate their growth, inflection, and saturation (Dwivedy and Mittal, 2010). The growth models indicated there will be 50 million obsolete computers by 2040 and 90 million obsolete mobile phones by 2035 (Rahmani et al., 2014). In contrast to the more abundant electronic devices of mobile phones and computers, a lighting device, namely Compact Fluorescent Lamps (CFL), was estimated in a work in Iran. CFLs present a significant advantage in terms of greenhouse gas emissions. However, Hg and Pb present in them are hazardous substances that need to be disposed of carefully. In Tehran and Tabriz in Iran, a multi-layer perception (MLP) artificial neural network model was used to predict CFL generation rates from 2010 to 2020. Estimating the generation rates for 2013–2020 reveals that it would be in the range of 163.621 to 174.431 million pieces of CFL annually. The study also concluded that the level of Hg in CFLs is 78.4 mg per lamp (Taghipour et al., 2014). The work contradicted the earlier works in determining the Hg levels with values of 87.73 mg per lamp (Santos et al., 2010) and 85.76 mg (Rey-Raap and Gallardo, 2012). In the same country of Iran, this same MLP model and the gradient descent algorithm model were used in another work to forecast the e-waste production and the data for eight electronic devices. The eight electronic products considered and their typical lifetimes (in brackets) are: personal computers P.C. (3 years), laptops (3 years), television (5 years), radio and tape recorders (10 years), mobile phones (2 years), photocopier (10 years), printers (5 years), video recorders and video projectors (5 years). The quantity of these devices was estimated based on their internal production data and import data from 2005–2010. The MLP model indicated that these eight devices accounted for 115,286, 112,914, and 115,151 tonnes per year for 2008, 2009, and 2010 respectively. From 2008–2010, TVs, with 42.42%, were the highest in proportion. These eight electronic devices in the years 2008, 2009, and 2010 contributed to 115.3, 112.9, and 115.2 kilo tonnes of e-waste (Taghipour et al., 2012).

5.1.4. Iraq

Iraq, a highly populated country, is home to industries related to petroleum refinement and people's income/living standards depend on Iraqi oil prices (Arif, 2014). The increased income has resulted in increased electrical and electronic

Table 3

E-waste generation quantities from different estimation methods (Ikhlayel, 2016). (Reprinted with permission from Elsevier).

Method	Mobile	Laptop	Desktop	TV	Refrigerator	Washing machine	Total	Per capita (kg/person/year)
C& U	0.2	1.2	0.3	0.7	0.9	0.8	4.1	3.0
Time step	1.4	0.8	0.9	0.9	0.7	1.1	5.8	3.3
Simple delay	0.8	0.8	1.1	0.8	0.8	0.7	5	3.0
Mass balance	1.4	0.8	1	1.3	0.7	1.3	6.5	3.7
Approximation 2	1.5	1	1.1	1.1	1.5	1.3	7.5	4.8
Modified method 1	1.2	0.9	1.2	1.1	1.1	0.9	6.4	3.8
Modified method 2	1.2	1.5	1.4	1.1	1.1	0.9	7.2	4.0

products within the country. In the city of Dohuk, there is more than one T.V. set in every household, and every household owns refrigerators, air conditioners, personal computers, and mobile phones. This has resulted in increased e-waste in the city. A study investigated the households' perception, knowledge, and attitude to the environment and, in particular, e-waste management. Most electrical and electronic appliances were replaced within two-thirds of their lifetime (Arif, 2014). The study found that 64% of the residents were unhappy with the local environment and 70% of respondents were ready to take up environmental responsibility, and 40% of households were prepared to sort their waste and segregate them separately. The group suggested that the informal recycling of e-waste is not a good option because most informal recycling activities are ineffective as only a small percentage of materials get recovered, and many valuable materials are lost during the recovery. Moreover, these informal handling results in occupational health risks to the people concerned. The study suggested better material design of electronic devices and also redesign of equipment, where a particular part of equipment can be replaced instead of dumping the whole equipment when it becomes damaged (Arif, 2014). The term informal refers to all e-waste handling activities that are not done professionally. In Iraq, in another work, geographic information systems (GIS) were implemented to locate the percentage of electronic waste in the country with respect to various locations. Baghdad tops the ten cities with an e-waste generation list, where the government and public sector generate 71% of the e-waste. On the other hand, individual households generate about 16% (Ridha et al., 2020).

5.1.5. Jordan

GIS was employed in a similar study in Jordan on household electrical and electronic equipment quantification through a survey of 15,883 households in 12 governorates (Hamdan and Saidan, 2020). The survey data were modeled using ArcGis mapping. Extrapolated findings revealed that 13 kilo tonnes had been turned into e-waste and discarded by all households in 2018 in the 12 governorates in Jordan. On average, there were 3.72 items of EEE devices per household, giving rise to 5.72 kg of EEE per household. The per capita value of e-waste generation in Jordan, as per the study, was 1.33 kg which was low compared to other MENA countries. Of the total e-waste generated, 58.4% is dumped off, 16.6% is given to others, selling off the e- waste amounts to 10.7%, sound recycling activities take up 6.8%, and other practices come to 7.4%.

Saidan et al. estimated the present and future value of e-waste in Jordan contributed by five significant types of devices: cell phones, PC, TV, refrigerators, and washing machines. They indicate a total value of 16,874 tonnes in 2015, which was a 1.81% increase from the previous year. The study analyzed only the sales data of these devices and the yearly e-waste generated. The e-waste from the three appliances, washing machines, refrigerators, and TVs contributed significantly to the total e-waste in Jordan, with shares of 35.9%, 31.8%, and 22.2%, respectively. The study was based on a questionnaire survey and had the limitation that the intermediate phases in the life period of the electronic devices could not be counted. As per the survey, the majority, around 56%, would prefer to sell obsolete devices to factories, waste traders, and second-hand shops (Saidan and Tarawneh, 2015).

In another work in Jordan, various methods of estimating e-waste were examined in Jordan as a case study. The five methods compared were the consumption & use (C&U) method, time step method, simple delay method, mass balance method, and approximation 2 method. The consumption and use method had the drawback of underestimating the amount of e-waste, but it was a simple method suitable for developing countries. It was ideal for fully saturated markets, for which the simple delay method and approximation 2 methods are also applicable. The time step and mass balance methods apply to saturated and unsaturated markets. The results from the various models used in estimation were analyzed and are as shown in Table 3. The per capita values varied from 3 to 4.8 kg/year for Jordan and e-waste generated in Jordan accounts for 1.24% of municipal solid waste (MSW) (Ikhlayel, 2016).

5.1.6. Morocco

In Morocco, the number of computers in households is increasing by 20% per year as of 2007 (Schluep et al., 2008; Laissaoui and Rochat, 2008). The e-waste from computers was estimated to be 5000 tonnes from the household sector, 13,000 from the private sector, and 500 tonnes from the public sector, totaling 18,500 tonnes. Mass flow analysis was used in the estimation, and the survey study indicated that a significant part of the computers, around 75%, was only a year old, indicating young stock. As the economy of Morocco shows promising growth, e-waste is expected to grow further.
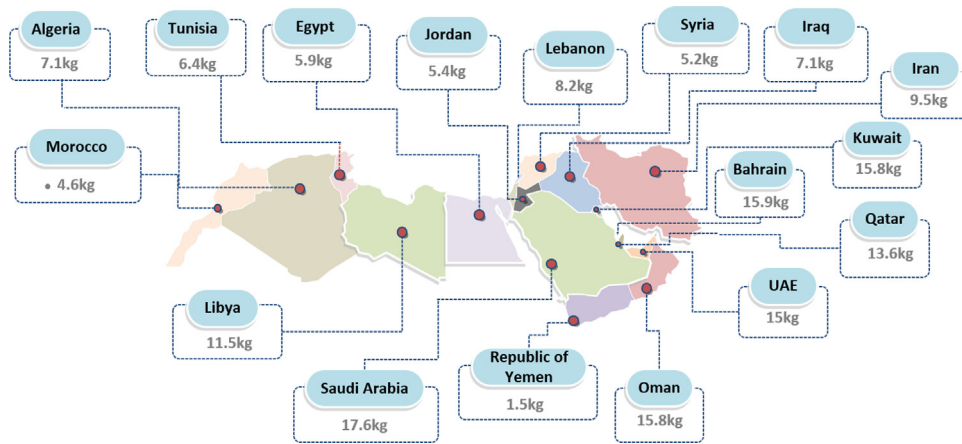
Fig. 6. Per capita values of e-waste in the MENA countries.

5.1.7. Kuwait

Cell phone contributed waste constitutes a principal share of e-waste in Kuwait, and an efficient assessment of the production rate of e-waste in this segment was done. The number of clients in the leading telecommunication service providers was taken in the estimation. The models used to predict the growth of e-waste were statistical analysis software packages and analysis of variance.

Cell phones were used as a measure of e-waste as it represents a significant share of e-waste in Kuwait as it is the densest telecom market in the world (Faisal, 2015; Al-Anzi et al., 2017). The prediction of the growth percentage of customers was an indicator of the e-waste generation. The e-waste production accordingly was 3 kilo tonne per year with an average increase of 12.7% (Al-Anzi et al., 2017). Model predictions were carried out for each telecom provider, and the regression value was close to unity (Al-Anzi et al., 2017).

The section presented the various works done in the countries of MENA to quantify e-waste. A crucial point to highlight is the lack of information from other countries than the ones mentioned. This points to the fact that e-waste, with its seriousness, needs to be considered in greater light and reiterates the importance of conducting a detailed study on the e-waste of the region. The quantification of e-waste is a challenging task, as is presented by the various works. Real value reports, in some cases, also validate the various models aimed at predicting the e-waste quantity and the models. This indicates the success of the models used. Not all studies make a comparison with the real existing data. Most of the works reported focus only on certain e-waste components, mainly mobile phones, PCs, laptops, and the like.

The various models present various methods by which e-waste quantification can be done. For most of the models, a questionnaire survey helps to understand the number of electronic devices per person or household. On the other hand, in some cases, the import data or sales data of electronic devices are used. The models are then developed to predict the future quantity of the specific electronic device. The logistic growth model that has roots in ecology provided results which are in good agreement with the reported value of in-use stock for PCs. The multi-layer perception model used in Iran showed a 77% success rate with the import values compared. In the comparison of various models carried out in Jordan, it is seen that approximation method 1 and approximation method 2 give nearly the same results. But the consumption and use method gave values that differ greatly. It can be concluded that the choice of the best model to predict the quantity of e-waste may not be possible; however, it should be chosen cautiously according to the market conditions and the availability of data. Only one work showed a different e-waste component that belongs to the lighting field. There need to be more studies that deal with other types of equipment and electronic appliances. Compared to the models, the technique of using the telecommunication subscribers to get the count is a straightforward method and one that can be applied to all countries to get a basic knowledge of the number of mobile phones in the country. Though inaccurate, this can be used to get primitive data concerning the e-waste from mobile phones, which constitutes a major share of the e-waste. Using a questionnaire survey shows that the response is limited in most cases, and this is not feasible to represent a country as a whole. Using GIS mapping to identify the area-wise density of the e-waste presents a good way to identify the locations that need an immediate alert.

5.2. Present situation of e-waste disposal in MENA

Increased consumption of e-waste in the region is attributed to enhanced technologies, high income, and economical prices of the EEE. Of the MENA countries, considering the global average of 7.5 kg in 2019, the per capita value is higher for the nine countries in the group, as indicated in Fig. 6.

For most countries, a formal e-waste sector does not exist in the MENA region. No NGOs or private entities are controlled by the government that serves the environment-friendly treatment of e-waste and provides suitable conditions

for its workers (Hamouda and Adjroudi, 2017). However, some related activities are to be found about some management schemes that have been started to find their way in the region and will be presented in this section.

In Algeria, the e-waste is collected along with household and bulk waste, and the informal sector carries out e-waste recycling activities. Their activities include collecting from dumping sites or companies that discard e-waste. The industry is also active in refurbishing, dismantling, and recovering precious metals (Seitz, 2014). This has the significant drawback of not having any environmental standards and causes the hazardous materials to diffuse to the various phases of the environment (Ashfaq et al., 2019).

In Bahrain, only a few recycling companies exist, and the industry is mainly limited to separating iron-containing metal scraps (Alghazo and Ouda, 2016). Bahrain has no e-waste disposal or treatment facility in the Kingdom, and the e-waste is thus exported to other countries where it could be given due consideration and properly recycled and elements recovered in ways suitable to the environment. The status of the e-waste procedures and the effectiveness of the procedures for e-waste adopted by the Bahrain Public Commission is in an early stage and needs to be developed (Maderazo and Pineda, 2017). This conclusion is based on the responses from individuals within the commission and the general public who used the recycling facilities.

Similar to Bahrain, considering other GCC countries, the e-waste of these countries is mainly exported. This is because proper e-waste and battery scrap management systems are not available in the area. In total, exports of e-waste and batteries went to a higher level from a 2012 value of 33,603 to a value of 52,098 tonnes in 2014, which indicates a Compound Annual Growth Rate of 24.5%. Among the GCC countries, a major share of exports was from UAE at a value of 30,086 tonnes (57.7%) of the region's trade, followed by Kuwait at 18,737 tonnes — 35.9% in 2014, according to a market overview by Research Wing (2017). Considering the e-waste values of Qatar, increased from 26,683 tonnes in 2010 to 37,000 in 2019 (Forti et al., 2020; Research Wing, 2017). Few companies take up recycling activities like the Al Haya Enviro (2017), which deals with e-waste like computers, monitors, fax machines, printers, TVs and other electronic appliances (Al Haya Enviro, 2017).

Whereas in Egypt, the network of e-waste recycling is through a line of compilers, merchants, and recyclers. The formal sector deals with only a small portion of the generated e-waste, leaving most of the e-waste to be dumped. Neither the government nor the private sector has an official e-waste management policy (Abdelbasir et al., 2018). The recycling of e-waste takes place through selling collected devices and equipment in five main markets spread around Cairo in the poor and populated areas (Shakra and Awny, 2017; Tarek and El-Haggar, 2019). According to reports prepared by the Ministry of Environmental Affairs, e-waste recycling in Egypt was around 1% in 2014 (Lamiaa, 2014). The leading telecommunication companies that carry out the formal recycling methods of e-waste in Egypt, Orange [Formerly Mobinil], Vodafone, Nokia, Raya trade company, and Resala, have taken steps to take back and officially recycle mobile phones in Egypt. Another unusual step is the actions by "RecycloBekia". They dismantle, sort, and sell electronic waste to China and Germany. The initiative has a web portal, and to increase the participation of the general public in handing over e-waste, reward points are awarded, which can be used in other web portals (Shakra and Awny, 2017).

In Iran, the people's awareness of e-waste and its impacts were measured by a survey in Nowshahr city to check for the existing e-waste disposal methods. It was found that the understanding of the city's authorities in matters related to e-waste was low, and as such, they have not been provided with the necessary knowledge on the correct disposal of e-waste (Simiari et al., 2020). Another work by Taghipour et al. (2012) pointed out that the classification of e-waste was often unprofessional and not systematic. It is done by laborers in servicing shops, persons handling solid waste in municipalities, or those illegally separating waste at landfill sites. This is particularly true for the city of Tabriz. Small companies with primitive technology are involved in the recycling of e-waste, either legally or illegally (Taghipour et al., 2012). The municipalities dispose of a large share of the e-waste together with domestic waste.

In Iraq, a study using a questionnaire survey pointed out that a high percentage (95% of 87 respondents) throw their e-waste in public waste containers, and only 14% know the degree of e-waste risks to the environment and health (Ridha et al., 2020).

The section presented the various methods currently in practice for e-waste disposal in the region. Informal handling of e-waste is very common. It is mostly mixed with solid wastes and dumped off. The e-waste in some countries is exported, where it can be given due care and efficient recycling. In many cases, the e-waste gets transferred from households to informal handlers with no recycling facility or knowledge of its components. Neither is the recovery of the valuable elements taking place nor is the proper discard of the hazardous substances. This informal handling also exposes the persons dealing with it to dangerous health hazards. The multinational companies involved in e-waste, like telecommunication companies, taking up recycling activities is a good turning point in the region.

5.3. The adverse health effects of e-waste

The impacts caused by the e-waste constituents, mainly the toxic heavy metals, are discussed in certain literature related to MENA. The amount of Pb present in a TV screen is around 1 kg, and a computer screen has twice the magnitude of Pb in T.V. The source of the heavy metals in the landfills is a large share of 70% coming from e-waste. The solder used in printed circuit boards and panels of glass causes damage to the nervous system; it affects brain growth in young kids. The Cd in resistors and semiconductor devices is accumulated in the kidney, causing damage to the neural system. The Barium (Ba) present in CRTs is known to affect muscle functioning and causes damage to the heart, liver, and spleen.

The wires used in computers impair the reproductive system and affect immunity. The inks used in printers can cause harm to the respiratory systems and cause cancer as they contain heavy metals. Motherboards of computers contain Be, which, when entered into the human body, causes skin diseases and is carcinogenic (Dawood, 2019). The various types of organic pollutants used in the EEE to impart flammability standards caused oxidative stress, neurotoxicity, and endocrine disruption. Air inhalation from indoor areas is one of the major ways by which it enters human bodies (He et al., 2017). A study on the impacts of e-waste on human DNA was carried out by (Khlaif and Qumsiyeh, 2017) to assess the individuals in the Idhna village in the Hebron district of Palestine. Comet Assay was used for evaluating DNA damage, and chromosome aberrations were tested using conventional techniques. The findings reveal an average of 4.83 aberrations/cell/subject compared to a value of 0.75 for an individual in control areas. The analysis was carried out on 46 non-smoker individuals who had direct exposure to e-waste. The examined individuals were engaged in the workshops that deal with the informal handling of e-waste were residents of the village. The control samples analyzed were individuals who were living 40 km away from the village. The comet assay also showed there is a significant difference between exposed and control samples for DNA damage (Khlaif and Qumsiyeh, 2017).

A work by Friedlander et al. showed a long-term exploratory analysis of an e-waste incineration site in East Jerusalem. The local climatic and mineralogical factors surrounding the e-waste recycling facilities strongly control the chemical dispersion of trace elements. A geopolymer-like material combining ash from the incineration areas and the mountain soils were formed. The work by the group was able to affirm that the possibilities of very fine particulate matter, exposure to incineration smoke, or direct physical contact with ash/dust from e-waste burning are the possible ways by which heavy metals exposure can happen. The concentration of the heavy metals at a distance within 10 m from the edge of the incineration equipment is less than the recommended USEPA values. However, the formation of a geopolymer-like substance similar to biochar leads to the conclusion that the geology of the area is essential in the context of e-waste disposal (Friedlander et al., 2019).

The environmental impacts of six electronic appliances under five e-waste management scenarios were evaluated in Jordan. These scenarios are sanitary landfilling, recycling of metals, recycling of materials, recycling of precious metals, and the incineration of printed circuit boards. The six appliances considered for the study were laptops, mobiles, CRT TV, LCD TV, refrigerator, and washing machine. Of the five e-waste management methods using a landfill is the worst of all methods and should not be followed. Integrated waste management (IWM) processes should be carried out, which involve recycling precious metals, and non-metals and the incineration of the plastic and hazardous content using the energy recovered from the incineration process itself (Ikhlayel, 2017). A novel study analyzed technology critical elements (TCE) concentrations of Ga, Thallium (Tl), Niobium (Nb), Tellurium (Te), Tantalum (Ta), Ge, Indium (In) possibly leached from e-waste and plastic materials into the seawater, wastewater and absorbed by marine organisms. The concentration in fish was found to be 0.13 ng/g, which indicates bioaccumulation. The study was carried out on samples collected from 5 sites in Kuwait Bay (Bu-Olayan and Thomas, 2020). An important addition to this part is that the influence of e-waste exposure is persistent even after the dismantling sites have been closed. This is seen in the work done by Li et al. (2020). The waste impacts are apprehensive and are linked to the risk of lung cancers due to the high concentration of Ni in the blood caused by exposure to e-waste. This correlated positively with telomere length and mitochondrial DNA copy number which indicates the carcinogenic nature and was observed even two years after the e-waste dismantling sites were shut (Li et al., 2020).

When considering the impacts associated with e-waste, no significant works are reported in the MENA countries. Though the impacts of e-waste can be assumed to be similar to the studies done in other countries like China, India, and Nigeria; however, the geographical difference in location can cause changes in the distribution of the pollutant and its presence in the various phases of air, water and land and ultimately in human bodies.

5.4. Approaches for better e-waste handling in MENA

This section deals with the works where alternate improved methods for handling e-waste are presented. Egypt produces about 586 kt of WEEE per year, the largest in the North African countries. The study of a pilot project for e-waste management in Alexandria Governorate was conducted. An economic feasibility study for e-waste was conducted under achievable framework conditions, proving that positive operating results can be achieved (Mostafa and Sarhan, 2018). The reverse logistic approach to managing e-waste in Egypt is compared with that of Switzerland and inferred that Egypt could be a potential market for recycling e-waste due to the massive quantities generated (El Nakib, 2012). Optimization of the reverse logistic approach for Egypt in the e-waste sector was done using a Genetic Algorithm to achieve more efficiency (Elbadrawy et al., 2015). The work by Tarek and El-Haggar (2019) gives detailed policy recommendations and suggests frameworks for extended producer responsibility (EPR) and producer responsibility organizations (PRO).

In Iran, A mathematical model was developed to select an appropriate alternative to follow at a product's End of Life (EoL) (Raad et al., 2014). This is done with reference to EoL alternatives for parts of a PC with respect to environmental, social, and economic criteria. Each option for treating e-waste at its EoL has its consequences from an economic, social, and environmental point of view. A multi-objective mathematical model is developed to assist in decision-making. Similar to the work done in Egypt on reverse logistics, a mathematical model of a two-stage reverse logistics network was developed in Iran (Shokouhyar and Aalirezaei, 2017). The evaluation of different alternatives for e-waste collections and their processing in the city of Tehran, Iran, was done using a fuzzy analytic hierarchy process (AHP) approach (Khoshand

et al., 2019). Another study proposed EPR with advanced recycling fee-implemented for collecting and recycling CFLs (Taghipour et al., 2014). Also, the EPR implementation needs the consumers to bring back their obsolete electronic products, and the study showed that 58.7% of people would bring back used electronics even if no incentive is given (Jafari et al., 2017).

In Jordan, taking the number of laptops imported in 2011 and using mass flow analysis indicates that it is a step towards establishing a sustainable industry (Alsheyab, 2015). This is in line with the findings that e-waste is an urban mine (Chancerel et al., 2009; Forti et al., 2020). A study by Arif (2014) which used a questionnaire of the staff at a local university, led to the conclusion that 70% of residents would be willing to share environmental responsibility. Similarly to this, in Jordan, a work by Fraige et al. (2012) measured the awareness of Jordanian households of the problem of e-waste, and 6% of the respondents showed their willingness to pay for recycling based on a questionnaire survey.

Among recent advancements in Qatar are the initiatives by the Qatar Foundation (QF), which collected 4.5 tonnes of e-waste over seven days in 2019 through containers placed at its different locations across the Education city and other QF entities. The collected e-waste was segregated, categorized, and packed at a local facility from where it will be exported (Gulf news, 2019). Another positive initiative is by Al Meera Consumer goods company which saw a nationwide recycling initiative for used battery collection (Al Meera, 2019). The country of Oman has started an e-waste recycling facility which is the first of its kind, and it offers complete recycling from collection to the stage of recycling (Prabhu, 2017). With respect to UAE, as per the data by Tabarez (2020), residents of the UAE can schedule pickups from the Municipality, and the items to be recycled will be picked up by the associated body.

Better management alternatives present forward approaches like developing a sustainable industry from e-waste. This is possible by recovering the precious metals in them and is a feasible solution to manage the costs associated with recycling. The studies from the surveys indicate that the people who know about the dangers of e-waste are ready to share the environmental responsibility and are prepared to take steps for its proper handling. This is promising as it will enable the public's involvement and facilitate the better handling and recycling of e-waste.

5.5. E-waste regulations in MENA countries

This section discusses the laws and regulations pertaining to e-waste in MENA countries. Here also, a country-wise presentation is provided as per the data available. In Egypt, currently, law 4/1994 for protecting the environment and its executive regulation amended by Law 9/2009 exists but is not dealing with e-waste explicitly (Shakra and Awny, 2017), but mentioned implicitly and provides a principal framework for handling hazardous substances. There is also an Egyptian Telecommunication law, Law No. 10 of 2003, Article 46, which states that it is prohibited to import used Telecommunication Terminal Equipment for the purpose of trading (Egyptian Environmental Affairs Agency, 2022). In addition, there is Decree No 703 of 2007 controlling the regulation of the import of old computers, which states that imported computers and peripheral devices shall not have production dates exceeding 10 years (Minister of foreign trade and industry, 2005).

Iran is one among many countries with general legislation related to waste management. E-waste also comes under this legislation (Shaeri, 2012; Taghipour et al., 2014) (Waste Management Regulations of Iran, 2009). This was drafted and approved in 2004; clause 12 of the legislation demands manufacturers and importers of electrical and electronic equipment are accountable for their recycling. A fine of 0.005% of the goods manufactured or imported is to be paid and collected in a particular fund. The money collected goes for the recycling of e-waste. As per the notes to clause 12, the enterprises that do not take up the responsibility of recycling should pay the penalties. Companies that use recycled material and take back their products at the end of their lifetimes or export their products are exempt. Though these legislations exist, they are not implemented or appropriately enforced. This holds true for other provinces and cities as well. No clear policies and plans exist for the allotment of the necessary funds to establish suitable equipment and facilities to manage and recycle e-waste at the end of its useful life (Taghipour et al., 2012).

In Iraq, the Ministry of Environment of the Kurdistan Regional Government issued Law No (8) for the year 2008, and the Kurdistan Parliament approved this in the same year, which discusses hazardous substances. A paragraph in the third section of the law is dedicated to hazardous substances and the recycling of garbage. Articles numbered (34, 35, and 36) deal clearly with this issue to prevent any person or entity from manufacturing, storing, transporting, importing, or burying any material that may contaminate the environment in general except under special instructions from the ministry in coordination with the concerned authorities. Unfortunately, this law has not been activated (Dawood, 2019).

In Jordan, the used electronic and electrical equipment generated in the country can be sold domestically as no laws ban it. On the other hand, Law No. 43 of 1999 under the hazardous waste management act prohibits importing used EEE into the country. Moreover, directive No. 24/2005 on managing, transporting, and handling harmful and hazardous substances bans e-waste dumping in landfills (Tarawneh, 2013; Saidan and Tarawneh, 2015). In addition, solid waste and e-waste, including batteries, are monitored, regulated, and enforced by the ministry of the environment (MoE) as referred to in the environmental protection law No. 52 of 2006 of Jordan. This law does not address e-waste directly, but article 25 of the law states that the council of ministers shall regulate provisions, including but not limited to the management of solid waste which is delegated to the MoE (The Jordanian Ministry of Environment, Environment Protection Law, 2006).

In Bahrain, law No. 3 of 2006 of the ministerial order related to hazardous waste management classifies e-waste as hazardous waste (Maderazo and Pineda, 2017). In Qatar, the cabinet approved the draft resolution on treating and

recycling waste, including e-waste. The draft law includes a provision concerning the types of waste and materials that may be recycled, and the controls on their circulation, management, processing, recycling, or disposal at home or abroad. The draft deals with the cases of revocation or suspension of the license, the stages of waste treatment and regulation, and the conditions that must be met at waste treatment sites and facilities (Qatar News Agency Doha, 2019). In UAE, federal law No. 12 of 2018 considers hazardous wastes of various types, including those from various types of operations, the hazardous substances used in equipment or devices, medical waste from hospitals, or any other waste, which has a toxic nature. Article 2 of the law aims at controlling waste management methods and bringing the tools and systems for their safe disposal under one umbrella. This is to be achieved by implementing the best possible practice with the primary aim to protect the environment and minimize human impacts (Federal Law issued by President of the UAE, 2018).

Considering the global guidelines of which MENA countries are part of; Algeria, Egypt, Iran, Iraq, Libya, Morocco, Oman, Qatar, Tunisia, and Yemen are parties to the Basel convention, while the countries of Bahrain, Jordan, Kuwait, Lebanon, Saudi Arabia, Syria, UAE are signatories on the control of transboundary movements of hazardous wastes and their disposal (Basel Convention, 2011). The laws about e-waste specifically are present in the countries of Iran and Jordan. Other countries deal with e-waste under the category of hazardous wastes that cause harm to the environment and the people. Also, the implementation of the laws is weak. This is because e-waste is not given due attention as needed. Given the present scenario of the proliferation of technology devices, there should be specific laws to deal with e-waste explicitly and what happens to the e-waste in a country.

6. Global regulations and laws for e-waste disposal

71% of today's world population, compared to 44% in 2014, is covered under e-waste policies or regulations initiated by the countries they belong to This 71% accounts only for 78 countries of the total 193 countries of the world, which equates to the fact that more than half of the countries of the world are not yet covered by a law/regulation pertaining to e-waste (Forti et al., 2020).

Among the initiatives by the U.N. in this regard, the notable applicable ones to e-waste are as follows:

6.1. The Basel convention 1989

The objective of the Basel Convention is to safeguard human health and the surrounding environment from the negative impacts that result from the generation, management, inter-country movements, and discarding of dangerous and other waste. From the year 2002, Basel Convention commenced addressing e-waste issues. It is comprised of the effective management of e-waste to avert the illegal transport of the e-waste to developing countries and to enhance the facilities around the globe that can better control e-waste, too (United Nations Environment Management Group, 2017).

6.2. Stockholm convention on persistent organic pollutants 2001

The Stockholm Convention is a global pact that aims to safeguard human health and the surrounding environment from the persistent chemicals that stay in the environment for a long time. It also considers the substances that get distributed geographically and the ones that accumulate in the fatty tissues of humans and animals, and substances that cause harm to human health and the environment. As seen, e-waste contains many persistent organic pollutants, and the parties involved in the Stockholm Convention are required to take necessary measures to avoid the discharge of these pollutants from stockpiles and waste (United Nations Environment Management Group, 2017).

7. Mitigation methods and suggestions for improvement

E-waste is a problem that is projected to reach unprecedented levels in the coming years. Appropriate steps must be taken to mitigate its negative environmental impacts. For all the formal recycling processes to take place, a first step is needed to make sure all e-waste gets collected. Efficient take-back systems should be in a place where retailers and consumers can play significant roles, as shown below in Fig. 7 (Hakami, 2018). It is important to note that the e-waste categories of SHA, LHA, CE, etc., have entirely different environmental priorities, and the costs of take-back systems are not the same for all of them (Gregory et al., 2009).

7.1. Extended producer responsibility

Extended producer responsibility (EPR) is a technique in which the party held responsible for the cautious discarding, or the further treatment of the e-waste is the manufacturer. It is primarily an environmental law that the manufacturer should be held accountable for the products they produce and is based on pay-offs by the polluter (Hakami, 2018). EPR principles require that manufacturer takes responsibility for the entire life cycle of a product, especially for the collection, dismantling, and reuse at its end-of-life stage (Organization for Economic Co-operation and Development (OECD), 2001). EPR involves a scheme of a take-back approach where consumers return products to be reused, repaired, and refurbished under the producer's responsibility. The process removes the burden of EoL management of these goods
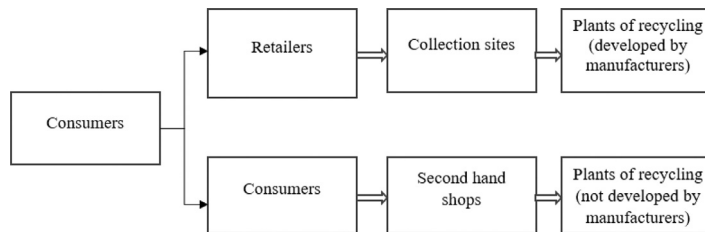
Fig. 7. Take back system representation.
Source: Adapted from Hakami (2018).

Fig. 8. Procedures in multi-criteria analysis.

from the municipalities and taxpayers to the producers (Leclerc and Badami, 2020). Developed countries apply EPR to enact regulations on e-waste recycling (Cao et al., 2016). The main objectives of EPR are to reduce e-waste generated and disposed of, the toxic contents in the waste stream, and the pollution in the product use phase. On the other side, it also increased the concept of design for the environment (DfE), which focuses on products and methods that are environment friendly (Margaret, 2003). Additionally, it urges the manufacturer to opt for better environmentally friendly elements which results in greener products, and nationwide competition with respect to trade will follow and involve an efficient and integrated system of e-waste management (Hakami, 2018).

7.2. Material flow analysis

Material flow analysis (MFA) is a method that analyzes the flow of materials from the user to the discarding locations considering both time and space (Hakami, 2018). It applies to the flow of matter ranging from chemicals, compounds, and commodities and is supported by material balancing, which represents the material conservation law (Porte et al., 2005; Agamuthu et al., 2015). Providing a connection between materials sources, pathways, intervening, and final destinations will help us to decide which methods will be suitable for environmental waste management (Steubing, 2007; Agamuthu et al., 2015; Hakami, 2018). This method can be used to mitigate the impacts associated with e-waste.

7.3. Multi-criteria analysis

Multi-criteria analysis (MCA) is another technique that aids in choosing appropriate solutions by solving complex problems. Different quantitative and qualitative aspects exist for various problems, which MCA can analyze. It applies to environmental problems, including e-waste issues, and provides suitable management methods, like choosing between economic and environmental benefits. It includes a 6-step procedure, as shown in Fig. 8.

Evaluating and comparing strategies and selecting the best strategy for a waste management system is possible only through the numeric determination of criteria that measure the entire system's operation (Generowicz et al., 2018). MCA is generally in two phases: the first is the construction of the evaluation problem, and the second is the processing of data (Eshra et al., 2021). This method can reduce or stand as a balance between economic costs and environmental impacts (Hakami, 2018).

7.4. Life cycle assessment (LCA)

This technique enables to manage and minimize the e-waste problems to a maximum extent (Hakami, 2018). LCA is a decision-making tool that evaluates environmental performance and recognizes the environmental burdens caused by a process, product, or activity (Sauve and Van Acker, 2020). LCA compares the potential positive/negative environmental impacts of different options in the evaluation and helps in the strategic decision-making process (Pokhrel et al., 2020). In this, the electronic devices are evaluated based on the technical details, design with a preference given to greener designs, and the effects on the environment. The technical design analysis enables us to think about the possible economic impacts and environmental impacts. Where electronic devices are concerned, an environmentally friendly design is best advocated. LCA is an efficient system that helps to identify the prospective negative impacts of e-waste on the environment (Hakami, 2018). E-waste stream is a rather dangerous and potentially harmful waste stream to the environment. Based on the experience of the other countries in e-waste recycling, a few recommendations for better handling of e-waste in the MENA region are suggested: (i) several collection points should be established. Parties interested can take up this activity, and their operation should be reviewed to confirm the e-waste finally reaches the authorized recycling facilities, which are licensed or certified. (ii) There should be a recycler certification system, which will bring about standardization in the field and ensure the reliability of the recyclers. (iii) Design and production, as well as the packaging of I.T. products, need to be done in an environmentally sound way with prior thought given to recycling issues. (iv) I.T. products for sale must label toxic and harmful materials contained in the product, the period of safe use, and the potential for recycling (Yang et al., 2008).

Some methods include hydrometallurgical, pyrometallurgical, and bio-metallurgical ways to treat the parts of e-waste. Hydrometallurgy involves leaching with acids and is widely used for recycling printed circuit boards. Pyrometallurgy involves incineration/smelting in a blast furnace, and this is a method to recover precious metals in an economically efficient way. Abdelbasir et al. (2018) and Kaya (2019). Bio metallurgical processes are an interesting method that involves bioleaching and biosorption. Biosorption combines physical and chemical interaction between ions and microorganisms, and bioleaching depends on the ability of the microorganism where elements are extracted by them by converting solid compounds (Abdelbasir et al., 2018).

The use of robots in e-waste recycling is a significant step towards ensuring its safe disposal. Solutions that use microbial degradation also have scope for e-waste decomposing. Steps such as bioleaching, biosorption, bioaccumulation, biotransformation, etc., can be applied to e-waste for recovery (Bagyaraj and Jamaluddin, 2017; Awasthi et al., 2019). Another suggestion is using of microbial fuel cells, which can work on the contaminants and generate energy in turn (Gangadharan et al., 2015).

8. Conclusions

E-waste is an important environmental issue that needs to be addressed very cautiously. Numerous studies depict the negative effects of e-waste disposal in water, soil, and surrounding air quality and its catastrophic impact on human lives in the vicinity of informal e-waste recycling areas.

The review enables us to conclude that e-waste is a relatively new topic of interest in the field of solid waste management in MENA countries. The primary exploration into the topic gives the impression that the needed attention has not been given to the e-waste stream though it presents a group of hazardous contaminants. In MENA countries, the vast majority of the people are less aware or ignorant of the e-waste stream and its implications, as indicated in the questionnaire surveys discussed in the review from the countries of Algeria, Iran, and Iraq. The impacts of e-waste in the countries of MENA are not subjected to a detailed study. The impacts studies of e-waste as of literature availability are largely dealt with in countries of China, Nigeria, India, Vietnam, and to less extent in the MENA region (Kurdistan, Kuwait. Jordan, and Egypt). This points to the need for detailed studies of the e-waste impacts in detail. E-waste is comparable to plastic. Like the situation of plastic, which once seemed to be a boon, now it is choking up the lakes, rivers, and soil and causing tragic damage to the planet, e-waste is expected to follow the path and take up a similar position if its recycling is not brought into formal methods and given due attention. Technology growth is unavoidable: they are imperative and oriented towards the growth of the communities and the population. The devices and accessories that support the technologies should be given considerate thought, while their disposal mechanism should be in focus right from the beginning of their production and introduction to the market.

Very recently, it is promising to notice that many countries of the MENA are taking initial steps towards better handling of e-waste, which shows it is gaining rightful importance. The review enabled us to investigate various modeling methods used in the e-waste quantification and forecast in the MENA region. The choice of a suitable model to predict the e-waste quantity is very much dependent on the market conditions, and the availability of data. Another area to be accentuated is the enforcement of the regulations pertaining to e-waste in the region. Though preliminary laws or regulations directed towards e-waste exist, countries must enforce them stringently to make them in control before things go out of hand.

CRediT authorship contribution statement

Buzaina Moossa: Investigation, Methodology, Writing – original draft. **Hazim Qiblawey:** Conceptualization, Supervision, Writing – review & editing. **Mustafa S. Nasser:** Writing – review & editing, Supervision. **Mohammad A. Al-Ghouti:** Writing – review & editing, Supervision. **Abdelbaki Benamor:** Writing – review & editing, Supervision.

Declaration of competing 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. Open Access funding provided by the Qatar National Library.

Data availability

No data was used for the research described in the article.

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