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REVIEW ARTICLE

# Trends of electronic waste pollution and its impact on the global environment and ecosystem

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**Abstract**
Electronic waste (e-waste) is used for all electronic/electrical devices which are no more used. Conventionally, waste management policies are desfig

handle the traditional waste. Although e-waste contains toxic materials, however, its management is rarely focused by policy makers; therefore, its negative impact on the global environment, ecosystem, and human health is aggravated. The review outlines the categories of e-waste materials, major pollutants including ferrous/non-ferrous metals, plastics, glass, printed circuit boards, cement, ceramic, and rubber beside, some valuable metals (such as copper, silver, gold, platinum). Toxic elements from e-waste materials, released in the air, water, and soil, include arsenic, cadmium, chromium, mercury, and lead, causing pollution. Although their roles in biological systems are poorly identified, however, they possess significant toxic and carcinogenic potential. It is therefore critical to monitor footprint and devise strategies to address e-waste-linked issues from manufacturing, exportation, to ultimate dumping, including technology transmissions for its recycling. This review traces a plausible link among e-waste condition at a worldwide dimension, its fair settlement procedures to keep it secure and carefully monitored when traded. Their fate in the three spheres of the earth, i.e., water, soil, and air, impacts human health. The strategies and regulation to handle e-waste generation at the global level have been discussed.

**Keywords** E-waste · Toxic waste · Heavy metals · Human health · Global environment · Ecosystem · Contamination



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## Introduction

The increasing use of electronic devices like computers and mobile phones and their short lifespan has led to the production of huge volume of electronic waste (e-waste) globally. Electronic waste is used commonly for all electronic/electrical apparatuses which are no more used (Thompson 2019). e-waste is expensive and has an emerging scope of electronic gadgets, ranging from major home appliances (coolers, air conditioners (ACs), freezers, mobile phones, sound systems) to personal computers (PCs) that have been disposed of by the users. Materials of international cycles require the 3R principle (reduce, reuse, recycle) to control the secondary resource trans-boundary movement which is increasing in Asian countries that have rapid economic growth (Chao et al. 2016). The important thing is to control environmental pollution at source, such as raw material in the industry and other related resources, in efficient ways (Cucchiella et al. 2014). The estimated world plastic production was 0.27 billion tons, with European Union (EU) production (0.05 billion tons) and demand (0.049 billion tons), and approximately 0.0028 billion tons of this plastic production is used for electric and electronic equipment (EEE) in 2014 (Plastics Europe 2017). In 2013, the estimated use of EEE was 17.4 kg/individual in EU countries (Eurostat 2017).

Mostly for damaged appliances which use electricity, the words e-waste and waste electrical and electronic equipment (WEEE) are used for this type of waste (Zhang and Xu 2016). However, WEEE represents both types of waste non-electronic goods (oven and refrigerators) and electronic waste (PCs, TVs, and mobiles) but e-waste materials simply represent the electronic goods (Reddy et al. 2018). Due to advances in computing technology, there is difficulty in differentiating WEEE from e-waste, as some goods are generally not categorized as electronic (Yan et al. 2015). e-waste generation has increased on a regular basis due to the incessant growth of computing devices. Approximately one billion computers were damaged during 2008 and 2012 ([illegible]adou and Lovegrove 2008).

e-waste is not comparable with the industrial and municipal wastes because a different physical and chemical nature exists ([illegible] 2016). Moreover, an e-waste material contains hazardous substances as well as valuable waste (Sepulveda et al. 2010; Cucchiella et al. 2015). To save the environment and human health, there is need to recycle e-waste materials. Through recycling, there is possibility in recovering some valuable metals such a copper, silver, gold, and platinum (Ackah 2017). In Fig. 4, the e-waste recycling process and recovery of valuable materials are presented. Recycling processes have high energy requirements and serious environmental consequences. Because of the high cost of labor and strict eco-friendly legislation, most developed countries transport hazardous materials to developing countries instead of recycling or dumping in landfills (Dias et al. 2019).

The export of e-waste proceeds through underground activities, legitimate gaps, and by states without having any confirmed agreement. The negative impacts on the environment of e-waste dumping are drawing amassed consideration from a political figure, NGOs (like Greenpeace), and mainstream researchers (UNEP 2009). e-waste cannot manage according to policies of conventional waste management; it is only applicable to handle the traditional waste types because e-waste contains toxic materials which have negative impact on the environment and health of living organisms (Işıldar et al. 2018). Huisman and Magalini (2007) studied that we can recover 97–98% of very precious metals through recycling of e-waste materials. The avoided environmental impacts of raw material generation at the initial stage, WEEE disposal, and recycling are also studied by Dias et al. (2018). The impacts of raw material generation at initial stages are not negligible as compared with WEEE waste recycling (Nelen et al. 2014). It was estimated by OECD (2008) annual production of municipal waste is [illegible]36 tons and e-waste annual production is 1–3%, in other words 0.02–0.05 billion tons (UNEP 2010).

In 2010, mobile telephones and computers add 5.5 million tons into e-waste (Cobbing (2008)), which are increased up to 9.5 million tons in 2015. Approximately 8% of municipal waste included e-waste in developed countries (Widmer et al. 2005). Yearly e-waste generation relays on the average lifespan, no. of total units in check, and mass of the electronic device. Three years is the common lifespan of computers. Ovens and computers have greater lifespans (10–12 years) as compared with the proportion of WEEE (Johnson et al. 2018). The lifespan (years) and mass (kg) of different household appliances are shown in (Fig. 3c). The annual generation of e-waste is 9 kg per person in Switzerland and 14 kg per person in Europe (Sinha-Khetriwal et al. 2005). In the USA, the annual e-waste generation is 2.7 million tons (2005) (Cobbing 2008) and China generates 2.5 million tons (Liu et al. 2009). In 2007, Thailand and India produced only 0.1 and 0.33 million tons respectively (Cobbing 2008).

The existing record shows that the worldwide annual e-waste production was 13.9 tons/year. Russia, Latin America, and Africa are not included for the last 4 years. In developed countries, the annual e-waste generation is 11.7 million tons, which has similar amount with respect to the above calculation. According to a 6-year-old data, again, worldwide production of e-waste materials will be considered higher. Considering refrigerators in electrical items, the mass of WEEE similarly will be greater (Johnson et al. 2018). Regulating the intended numbers of 14 million tons annually for 20% progression in gross domestic product (GDP) in the previous 5 years gives 17 million tons worldwide. Most of the computer substance of e-waste is produced in the developed states (Cobbing 2008; Barsalou and Picard 2018), and agreeing to United Nations Environment Programme's calculations, the worldwide e-waste generation is 0.02–0.05 (UNEP 2010).

Figure 1 shows the global population of all continent countries and their contribution towards e-waste generation in kilograms tons (kt) in 2016 (Balde et al. 2017).

With the evolution of new technologies and emerging economies of the world, the complexity and volume of e-waste will be altered tremendously. In recent years, GDP of a country is directly or indirectly linked to the total number of computers because to function the primitive economies is required. e-waste generation is increasing on a regular basis due to emerging economies and development of the world (Breivik et al. 2016). It is difficult to estimate the production of e-waste according to economic growth and population of any country, but purchasing power parity (PPP) defines the World's populace as a function of capital, linked with e-waste production and distribution of computers per person. Worldwide, 75% of rich people have computers, and there is a good relationship between computer's numbers and economic status of rich people (Cordova-Pizarro et al. 2019). The yearly expansion of e-waste is growing at a rate of 3 to 5% in Europe, linked with GDP growth up to 2.6% during 2005–2008. Figure 3a shows estimation of e-waste of different countries by 2020. So, in the next decade, China, Eastern Europe, and America will be higher producers of e-waste if the total numbers of computers represent all e-waste (Hischier et al. 2005). e-waste production was directly associated with the advancement of technology. New devices are introduced due to the advancement of short cycles of hardware. In the previous decade, the lifetime of a central processing unit (CPU) decreased from 6 to 3 years (Babu et al. 2007). The normal masses of PC (25 kg) are demonstrative of a computer and have a cathode ray tube (CRT) screen, and express the greater part of the wide lifespan of PCs in the e-waste. The average weight of a desktop will be reduced with the advent of liquid crystal display (LCD). Nowadays, 1–3-kg notebook computers and laptop reduced the damaged computer average masses (Micklethwait 2009a).

On account of netbooks, calculating rule and related potential e-waste generation has been moved from end consumer to distant processing "clouds," reinforced by warehouses of common equipment, which might be situated in a different state (Micklethwait 2009b). There is a gap of data on e-waste production from these processing warehouses. The e-waste production rate is expanding due to massive assets, and shorter advancement cycles might be balanced by miniaturization and re-appropriating of process influence. e-waste materials are directed in immensely unusual means, equally under policies and physical treatment, worldwide. Developed countries really have tried hard to manage the e-waste materials and make cost-effective ways to lessen the production of e-waste (Zeng et al. 2017), but in spite of this fact, the major part of e-waste materials still remains un-recycled in European and North American countries (Barba-Gutierrez et al. 2008). To prevent dioxin release from the disassembling process of electronics, special cleanup technologies are developed (Lu et al. 2015).

In modern systems, in developing countries, for which China, India, Pakistan, and Nigeria can be taken as examples, plastic cables are commonly burn to recover the Cu and this is considered as the least expensive means to recover Cu (Adesokan et al. 2016). Valuable metals of circuit board parts



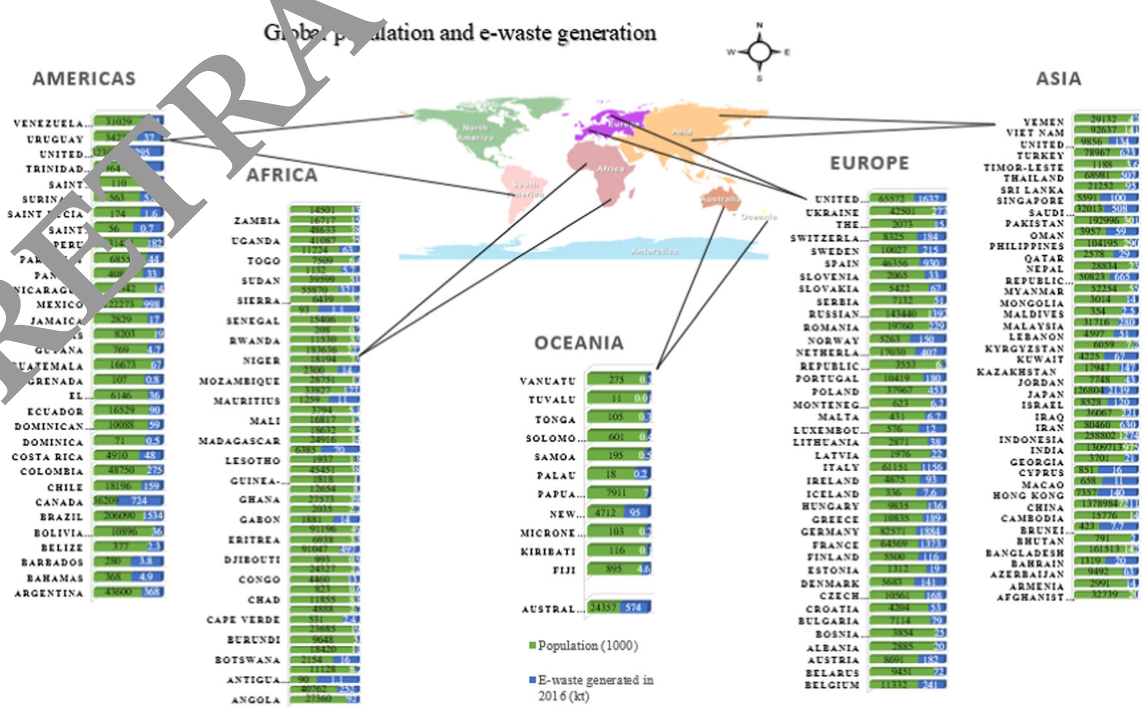


**Fig. 1** Global population and e-waste generation (Balde et al. 2017)

are drained during an acidic wash and the utilized acid along with the metal parts leached down and dumped into the ground or water bodies—a common practice in underdeveloped and developing countries (Robinson 2009). The nearby inhabitants might be unaware of the hazard from the dumping of toxic metal–contaminated waste. The official strategies and administrative rules of waste dumping in developing countries are much different from those of the developed world. However, importing e-waste materials is banned in developing countries, as the recycling of the waste by developing countries is costlier than the low-cost dumping of the waste by developed countries (Mehta 2019).

Pakistan, at present, has no standard or correct information on e-waste production. Abbas (2011) indicated that there are 0.1 billion cell phone users in Pakistan. Pakistan has no controls/management, particularly focusing on the e-waste generation in spite of the fact that the National Environment Policy has taken actions against it since 2005. The Ministry of Environment of developing countries ensures the conservation, protection, and organization of hazardous e-waste materials. There is no appropriate system to handle e-waste materials at the domestic level. In this way, individuals have to develop techniques to dispose e-waste materials at the local level. At this level, many people take part in the disassembling of e-waste materials, extracting the metals, and separating them, and by this means, they earn their living. In Pakistan, open dumping and burning of e-waste are common practices (Umair et al. 2015; Iqbal et al. 2017).

The purpose of this review article is to describe the e-waste condition at worldwide dimension, as far as settlement endeavors made to keep it where it might be securely dealt with, and its fate when traded, by giving account on the quantity of e-waste produced, categories of e-waste, major pollutants, and the effect of pollutants on human health and their fate in water, soil, and air. Developing countries are gathering approaches and frameworks to take a look at the strategies and regulation to handle e-waste generation at the global level. Ecological and human beings' effects of lethal material discharge are noted. Recommendations are considered, as well.

## e-waste categories

The identification and categorization of e-waste materials are difficult for proper controlling of e-waste (Birloaga and Veglio 2018). Krause and Townsend (2015) cite the description of e-waste as: "hardware which rely on electrical streams or electromagnetic systems to work appropriately and the electronic device for producing, exchanging and estimation of electric circuits for use with a power supply range not beyond 1000 Volts for alternating current and 1500 Volts for direct current." Based on the mentioned definition, e-waste material contains PCs, TVs, cell phones, iPods, fluorescent lights, printers, toys, etc. (Zeng et al. 2015). This also covers all parts and major appliances that are utilized domestically and commercially. Figure 2 shows the categories and contribution of e-waste as characterized by the EU (ADEME 2010).

## Major pollutants in e-waste

As per the Association of Plastics Manufacturers in Europe (APME), e-waste is a diverse mixture made out of ferrous, non-ferrous, ceramic, and plastic materials. E-waste is classified according to the manufacturing material and contains > 1000 different constituents, which fall into two categories, (i) toxic and (ii) non-toxic substances. Extensively, it incorporates ferrous/non-ferrous metals, plastics, glass, printed circuit boards (PCB), cement, ceramic, rubber, etc. (Wang et al. 2011; Wang and Xu 2014). E-waste includes around 50% of Fe and steel taken after plastics (21%), non-ferrous metals (13%), and different elements. Non-ferrous metals comprise trace metals, for example, Cu and Al, and valuable metals, e.g., silver, platinum, gold, and palladium (Fig. 3b). The elements like As, Cd, Cr, Hg, Pb, and Se and fire-resistant e-waste are characterized as toxic waste and e-waste materials are classified into distinct classes, i.e., (i) heavy metals, (ii) halogens, (iii) radioactive elements, and (iv) different elements depending upon their quantity in the electrical gadgets (Yamane et al. 2011).

Trace earth metals are metals which are not generally known in light of the fact that they are less used in the production section and are basic to high-tech appliances (Hurst 2010). Both trace and valuable metals are viewed as basic parts of the current innovation and their non-accessibility would make a few applications impossible. As indicated by the US Department of Energy (2011), trace earth metals are fundamental in laptops, cell phones, and weapon industries (cruise missiles, reactive armors, and detector systems). There is value of these metals in green techniques, for example, wind mills, hybrid motor automobiles, and as a catalytic agent in oil processing plant. The wide utilization of these metals in recent innovation has therefore produced an increased demand and wide generation of all such toxic metals. The main part of mining in the supply of electronic and modern gadgets cannot be ignored. Rademaker et al. (2013) reported that despite the influence of mining in the stream of basic crude elements, the impression of the mining cannot be overlooked for these metals. Moreover, Schluep et al. (2009) demonstrated that mining needs an extensive land space with activities that have a negative impact and contaminate the water, air, and land. Besides, the exploitation of resources is related to the introduction of radioactive components to the environment, and also has adverse impacts on humans (Rademaker et al. 2013). According to Schluep et al. (2009), the extraction of trace and valuable metals enhances the $CO_2$ emission. The researchers reveal that the

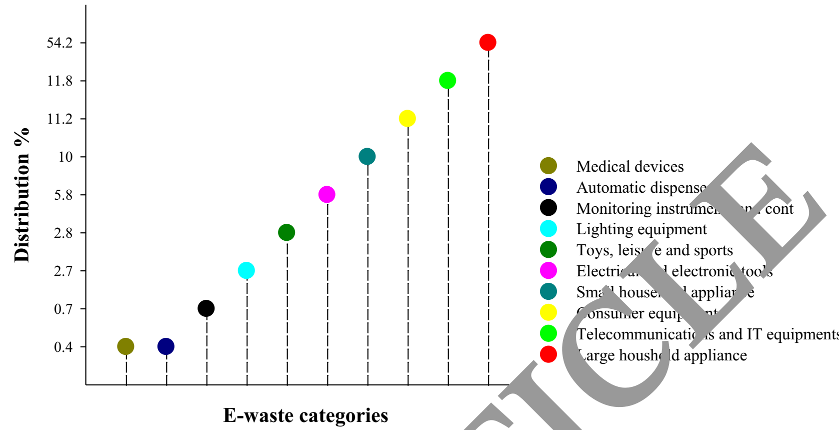


**Fig. 2** e-waste categories and its contribution at global level (ADEME 2010)



production of a ton of gold, platinum, or palladium produces $CO_2$ emissions of almost 10,000 tons.

With the depletion of trace and valuable metals, increase in the land destruction, and contamination to water and air because of mining, the considerations have been made to overcome the situation by administration of WEEE. With present-day electrical and electronic gadgets, containing up to 60 distinct elements from which some are important and some are lethal, this material should be taken under priority (Jinhui et al. 2013). Rademaker et al. (2013) revealed that various countries have set up procedures to maintain the particular and worldwide supplies of these metals by the country in order to diminish their reliance on China, taken as a leading provider of trace metals. These methodologies incorporate the proposition of effective e-waste material reprocessing (Fig. 4).

In the USA, more than 0.5 billion PCs are discarded in 1997, and 0.13 billion mobile sets were disposed of bringing about around 65,000 tons of waste in [illegible] (UNEP 2009). In 2010, mobiles are discarded around 0.61 billion in Japan, which contain 40 toxic and non-toxic substances. An estimate by Schluep et al. (2009) demonstrates that from a huge amount of cell phones without batteries, effective recycling can recoup Au (0.34 kg), Ag (3.5 kg), and Pb (0.14 kg). The stream of this e-waste generation could be highly toxic to human health if not considered appropriate. Hurst (2010) concurs that e-waste might be a major root of rare and valuable metals. This gives a contrasting option to mining as well as guarantees among others a consistent supply of metals and effective, reasonable, and low-cost management of e-waste materials.

During the recovery of e-waste in both developing and developed states, the basic raw ingredients are recovered during recycling but are not analyzed yet (Bengtsson 2011). Generally, WEEE is the combined assembling of many metals, some of which are exceptionally toxic, i.e., the creation of semiconductors, circuit board, disk drives, and monitors is highly chemically toxic (Tsydenova and Bengtsson 2011). The CPU comprises heavy metals like Cd, Pb, and Hg and PCBs have substantial metals, like Sb, Ag, Cr, Zn, Pb, Sn, and Cu. In WEEE, Pb is predominantly utilized in CRTs in screens, Sn-Pb binds, PCB, cabling, and luminous tubes (Buchert et al. [illegible]).

e-waste additionally has brominated fire retardants (BFRs, for example, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDEs) which are utilized in PCB, connectors, covers, and cables. Many studies recommended that BFRs have negative impacts on humans, thus be constrained or exchanged together (Ghosh et al. 2015). Interaction to PBDEs by the individuals employed in e-waste reprocessing industries has been considered by many researchers across the world (Tue et al. 2010; Zhang et al. 2019). Additionally, PBDEs are found in nature around some e-waste recycling areas. An investigation of the occurrence of PBDEs in the air, ash, dust, soil, drinking water, and residue in e-waste recovering areas in China and India discovered a high amount of PBDEs beyond the levels in urban or industrial area. Toxins in e-waste materials are commonly packed in plastics, PCBs, batteries, and LCDs (Kumar and Shah 2014).

## Health impacts

Constant dumping of WEEE, in developing countries, the innovation received to reuse the waste, is unrefined and is carried out physically in the backyard of the recycling facility. Heavy metals, like Pb and Hg, can harm the central nervous system. Lead, specifically, adversely affects the mental health of children and also may harm the circulatory, renal, and reproductive systems (Grant et al. 2013). Mercury can harm the renal system and its contact with pregnant ladies can influence the fetal growth. At the point when in contact with water, it changes over into the more toxic form, methyl mercury, and would contaminate the food chain/food web. Barium, Be, and BFRs may cause major human health disorders (Hennebert and Filella 2018). Impacts of e-waste on human health are described in Table 1.

Many human health risks are related to e-waste pollution. The health impacts result from various environmental

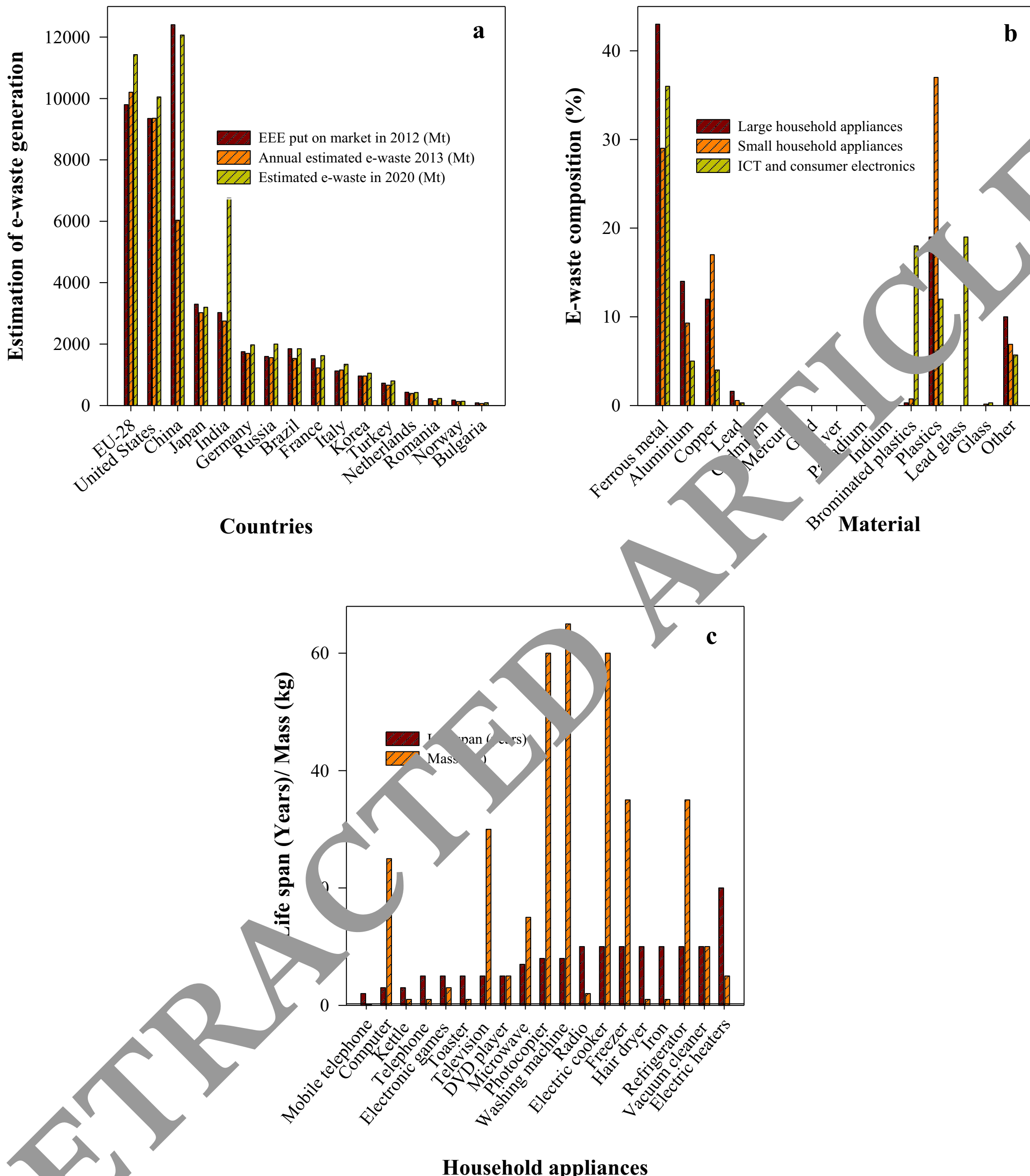




**Fig. 3** **a** Estimation of e-waste generation. **b** e-waste composition. **c** Lifespan of household appliances

exposure pathways. The closer the human to the recycling facility, the more the chance of having health disorders. The possible human health risk from e-waste exposure is higher for female and kids. Similarly, pregnant ladies and children are at higher risk to have health disorders by e-waste (Mamtani et al. 2011). However, every individual working in the recycling facility is at high risk. Children are most directly associated with e-waste recycling as indicated by the International Labor Organization; they are indirectly exposed to toxins in their homes by the contamination of clothes, shoes, and other items. This can be termed as home exposure, mainly hand-to-mouth conduct ordinary in toddlers that may ingest harmful substances, which results in long-term low-level exposure (Agyei-Mensah and Oteng-Ababio 2012; Nasim et al. 2011, 2012). Likewise, it is fundamental to address the contamination of the environment by improper e-waste reusing, and they are dumping on the ground harmful metals that can develop in the soil. This can cause a negative impact on health for the most part as a result of the chemical lipophilicity which is the capacity of the substance to break up in the lipids and oils in the human cell membranes (Kwon et al. 2019).

A research conducted in Tsinghua University in Beijing, China, studied the health impacts on the individuals linked

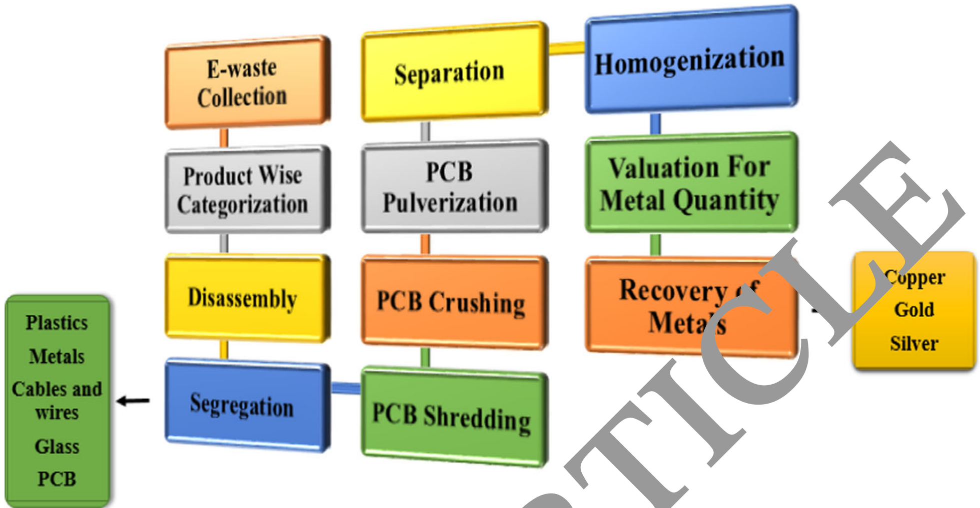


**Fig. 4** e-waste recycling process and recovery of valuable materials

with e-waste reprocessing networks. It showed that while disassembling e-waste materials, above 90% of the metals and other contamination exposure in individuals are from the nutritional pathway. Individuals can retain and bio-accumulate toxins in body tissues. Moreover, the nutritional intake of PBDEs, PCBs, and polychlorinated dibenzodioxins (PCDD/Fs was estimated from three recycling areas from shellfish, fish, eggs, meat, and others. The investigation found that the inhabitants of Guiyu intake nine times more than the limit value proposed by US EPA. Moreover, levels of PBDEs in breast milk were predicted for 6-month-old offspring near e-waste areas and noticed to be 57 times more than the guideline values proposed by the US EPA (Liu et al. 2019). The most elevated measurements were 2240 ng/day/kg BW which was higher than the US EPA–recommended dose. The PCBs were determined to be 242.61 ng/day/kg BW from food and water samples in Taizhou. In addition, in Guiyu, essentially taking an individual nutritional intake from seven types of fish, the dimension was 264 ng PCBs/day/kg BW. Newborns in Taizhou appeared to be ingesting 25–100 times more PCBs than the WHO recommendations (Sthiannopkao and Wong 2013). In spite of dietary intake as a major pathway, contaminated air can even now adversely affect the health. Children breathe in general twice the harmful toxins compared to adults (Song and Li 2014). In Guiyu, it was evaluated that 80% of the kids fall ill as a result of the contaminated air. The WHO expresses that heavy metals, for example, Cd and Pb, can be harmful for child's growth and development and may cause neurological disorders. Laborers seemed to have typically 1900 ng/day PCBs, which were five times greater than nearby inhabitants of Guiyu who were likely to have high levels of other pollutants. Beside the uptake of harmful e-waste synthetic substances via inhalation, exposure to soil and dust is at critical levels. The PCDD was 1200 times more in Taizhou w.r.t dust and soil ingestion. Moreover, Guiyu announced comparable levels for adult and kids (Song and Li 2014).

An investigation explored the impact of PBBs, PCBs and PDBEs, on the cancer patients' inhabitants of e-waste reprocessing area. The PHAHs containing PBBs, PCBs, and PBDEs are dangerous and can bio-accumulate in the environment (Ramoni and Zhang 2013). These toxins may cause endocrine disruption and are probably known to be cancer-causing elements. There has been an increasing possibility of lung and liver cancer in individuals living inside and close to e-waste reprocessing regions. The e-waste pollution, from determining contaminants, for example, PBDEs, PBBs, PCBs, and PCDD/Fs, should be routed to diminish the environmental outcomes as well as decrease the negative human impacts due to the accumulation of toxins in tissues (Zhao et al. 2009).

## Impacts of e-waste on the environment

The occurrence of lethal elements in e-waste materials was seen from the most recent two decades. There are inadequate laws worldwide for sufficient administration of e-waste materials. The vast improvement of e-waste and the inadequacy of enactments have unsuitable administration frameworks in developed and developing countries, prompting noteworthy impacts on nature. Organization of e-waste by reusing and by dumping in landfills seemed to make a tremendous loss of environmental viability (Wong et al. 2007a; Nasim et al. 2016; Nasim et al. 2018; Asad et al. 2017; Aziz et al. 2017a; Fahad and Bano 2012; Fahad et al. 2013; Fahad et al., 2014a, b; Fahad et al. 2015a,b; Fahad et al. 2016a,b,c,d; Fahad et al. 2017; Hafiz et al. 2016; Awais et al. 2017; Muhammad Hafiz et al. 2017; Naeem et al. 2017; Noman et al. 2017; Saud et al. 2013; Saud et al. 2014; Saud et al. 2016; Saud et al. 2017; Shah et al. 2013; Qamar et al. 2017; Zahida et al. 2017; Adnan et al. 2018; Arif et al. 2017; Aziz et al. 2017b; Ghulam et al. 2017; Bakhat et al. 2018; Kamarn et al., 2017; Yang et al. 2017; Zahida et al. 2017).

**Table 1** Different types of e-waste pollutants, occurrence, and their impacts on human health

| Pollutants | Occurrence | Impacts on human health |
|---|---|---|
| Arsenic (As) | Semiconductors, diodes, microwaves, LEDS (light-emitting diodes), solar cells | Soluble inorganic arsenic is acutely toxic and intake of inorganic arsenic over a long period can lead to chronic arsenic poisoning. Effects, which can take years to develop, include skin lesions, peripheral neuropathy, gastrointestinal symptoms, diabetes, renal system effects, cardiovascular disease, and cancer (WHO, 2010a) |
| Barium (Ba) | Electron tubes, filler for plastic and rubber, lubricant additives | Short-term exposure causes muscle weakness and damage to the heart, liver, and spleen. It also produces brain swelling after short exposure (Osuagwu and Ikerionwu 2010) |
| Cadmium (Cd) | Batteries, pigments, solder, alloys, circuit boards, computer batteries, monitor cathode ray tubes (CRTs) | Has toxic, irreversible effects on human health and accumulates in the kidney and liver (op. cit.). Has toxic effects on the kidney, the skeletal system, and the respiratory system, and is classified as a human carcinogen (WHO, 2010b). |
| Chromium (Cr) | Dyes/pigments, switches, solar | Respiratory tract irritants can cause pulmonary sensitization. Increase the risk of lungs, nasal, and sinus cancer. Severe dermatitis and usually painless skin ulcers. Increased risk of respiratory system cancers. Indicated that reversible renal tubular damage can occur. Severe liver abnormalities. Caustic and irritating the gastrointestinal mucosal tissue. Cardiovascular collapse. Hematological toxicity. DNA damage, gene mutation, sister chromatid exchange, chromosomal aberrations in a number of targets, including animal cells, in vivo and animal and human cells in vitro. |
| Cobalt (Co) | Insulators | Hazardous in case of inhalation and ingestion, and is an irritant of the skin. Has carcinogenic effects and is toxic to the lungs. Repeated or prolonged exposure can produce target organ damage (Material Safety Data Sheet 2005) |
| Copper (Cu) | Conducted in cables, copper, ribbons, coils, circuitry, pigments | Very hazardous in case of ingestion, in contact with the eyes, and when inhaled. An irritant of the skin and toxic to the lungs and mucous membranes Repeated or prolonged exposure can produce target organ damage (Materials safety data sheet 2005) |
| Lead (Pb) | Lead rechargeable batteries, solar, transistors, lithium batteries, PVC (polyvinyl chloride)stabilizers, lasers LEDs, thermoelectric elements, circuit boards | Causes damage to the central and peripheral nervous system, blood system, and kidneys and affects the brain development of children (Osuagwu and Ikerionwu 2010) A cumulative toxicant that affects multiple body systems, including the neurological, hematological, gastrointestinal, cardiovascular, and renal systems (WHO, 2010c) |
| Lithium (Li) | Mobile telephones photographic equipment, video equipment (batteries) | Extremely hazardous in case of ingestion as it passes through the placenta. It is a hazardous and an irritant of the skin and eye, and when inhaled. Lithium can be excreted in maternal milk (Material safety data sheet 2005) |
| Mercury (Hg) | Components in copy machines and steam irons; batteries in clocks and pockets calculators, switches, LCDs | Harmful effect on the nervous, immune, and digestive systems, lungs, and kidneys and may be fatal corrosive of the skin, eye, and gastrointestinal tract, and may induce kidney toxicity. Neurological and behavioral disorders, mild, subclinical signs of central nervous system toxicity. Kidney effects have been reported, ranging from increased protein in the urine to kidney failure. |
| Nickel (Ni) | Alloys batteries relays semiconductors pigments | Allergic reaction (skin rash and etc.), stomach aches, and adverse effects in their blood (increased red blood cells) and kidneys (increased protein in the urine). Chronic bronchitis, reduce lung function, and cancer of the lung and nasal sinus. |
| Polychlorinated biphenyls (PCBs) | Transformers, capacitors, softening agents for paints, glue, plastic | Possible cancer, effects on the immune system, nervous system, and endocrine system. It accumulates in the fat-rich tissues of almost all organisms (bio-accumulation) |
| Phthalates | Used to soften plastics | Disrupts the endocrine system, reproduction, fertility, and birth and has developmental effects. Also has organ system toxicity and is linked to liver cancer and effects on the brain, nervous system, and immune system (Environmental Working Group n.d.) |

**Table 1** (continued)

| Pollutants | Occurrence | Impacts on human health |
|---|---|---|
| Silver (Ag) | Capacitors, switches (contacts), batteries, resistors | Very hazardous in case of eye contact, ingestion exposure can result in death. Repeated exposure can deteriorate health by an accumulation in one or many human organs (Material safety data sheet 2005) |
| Zinc (Zn) | Steel, brass, alloys, disposable and rechargeable batteries, luminous substances | Contact with eyes can cause irritation; powdered (University of Oxford, 2005); if inhaled, causes cough, and if ingested, abdominal pain, diarrhea, and vomiting are common (ICSC database n.d.) |
| Antimony (Sb) | CRTs, printed circuit boards, etc. | Very hazardous in the event of ingestion, hazardous in the event of skin and eye contact, and inhalation. Causes damage to the blood, kidneys, lungs, nervous system, liver and mucous membranes (Material safety data sheet 2005) |
| Beryllium (Be) | Motherboards of computers | Carcinogenic (causing lung cancer), and inhalation of fumes and dust can cause chronic beryllium disease or berylliosis and skin diseases such as warts (Osuagwu and Ikerionwu 2010) |
| Dioxins | Created when electronics are burnt in open air | Highly toxic and can cause chloracne, reproductive and developmental problems, damages in the immune system, interfere with hormones, and cause cancer (WHO, 2010a) |
| Gallium | Integrated circuits, optical electronics, etc. | Hazardous in case of skin (may produce burns) and eye contact, ingestion, and inhalation. Severe overexposure can result in death. Toxic to lungs and mucous membranes. Repeated or prolonged exposure can produce target organs damage (Materials safety data sheet 2005) |
| Indium | LCD screens | Can be absorbed in the body by inhalation or ingestion. Is irritating to the eyes and respiratory tract may have long-term effects on the kidneys. Environment effects have not been investigated and information on its effects on human health is lacking; therefore, utmost care must be taken (ICSC database n.d.) |
| Chlorofluorocarbons (CFCs) | In older fridge and coolers | Found to destroy the ozone layer and is a potent greenhouse gas. Direct exposure can cause unconsciousness, shortness of breath, and irregular heartbeat. Can also cause confusion, drowsiness, coughing, sore throat, difficulty in breathing, and eye redness and pain. Direct skin contact with some types of CFCs can cause frostbite or dry skin (US National Library of Medicine n.d.) |
| Polyvinyl chloride (PVC) | Cabling and computer housing plastics contains PVC for its fire-retardant properties | Produces dioxins when burnt; causes reproductive and developmental problems, immune system damage and interferes with regulatory hormones (Osuagwu and Ikerionwu 2010) |
| Tin | Lead-free solder | Causes irritation in case of skin and eye contact, ingestion and inhalation. Can cause gastrointestinal tract disturbances, which may be from irritant or astringent actin on the stomach (Materials safety data sheet 2005) |
| Polybrominated diphenyl ethers (PBDEs) | Plastic housing of electronic equipment and circuit boards to reduce flammability | High lipophilicity, high resistance to the degradation processes. Hepatotoxicity and behavioral effects have been demonstrated. BFRs in general have been shown to disrupt endocrine system functions and may have an effect on the levels of thyroid-stimulating hormone and cause genotoxic damage, causing high cancer risk (Tsydenova and Bengtsson) |

## Atmospheric contamination by e-waste

Large volumes of e-waste materials are presently transported worldwide to recycle in developing countries utilizing manual procedures in the backyard of homes consequently that contaminate the air in these areas. Such activities have harmful impacts on individuals working with the recycling network. For example, Gauteng (South Africa), Guiyu and Taizhou (China), Accra (Ghana), Karachi (Pakistan), and New Delhi (India) are huge e-waste spots and at this place, high contamination is radiated from the recycling of waste (Tsydenova and Bengtsson 2011; Asante et al. 2012).

The significant metal discharge includes As, Cd, Ni, Cr, Hg, and Pb. Natural contamination discharged included PAHs, PCBs, and BFRs, for example, PBDEs and PCDD/Fs, generated by the thermal procedures of recycling. The PBDD/Fs may exist as an impurity in PBDEs, due to PBDE weathering, production, and recycling of fire retardants (Frazzoli et al. 2010). It is clear from the investigations that whole biological systems are being contaminated by these lethal elements (Table 2).

To assess the air quality, a large portion of the investigations is from these areas which exhibit significant effects of e-waste dumping and reprocessing, and reports show serious air contamination from brominated and chlorinated substances and toxic metals near e-waste reprocessing areas in China. Elevated levels of metals containing Cr, Cu, and Zn were identified in 1038, 1161, and 483 ng/m$^3$, individually, and 4 to 33 times greater than those in other Asian countries (Deng et al. 2006). The PBDEs related to $PM_{2.5}$ and TSP were identified at 62.1 and 124 μg/m$^3$, individually; however, the high contamination levels of PBDEs were 58 to 691 times higher in Guiyu than those in other areas (Deng et al. 2007). The air contamination in Guiyu is high due to e-waste reprocessing units. Large amounts of Bi, Co, Cr, Cu, In, Mn, Pb, Sb, and Sn were found in the atmosphere near reprocessing territories in India (Ha et al. 2009). Furthermore, the level of PBDEs in the indoor air of an e-waste store room was 46 to 350 pg/m$^3$; however, in outdoor air, it was 8–150 pg/m$^3$ in Thailand (Muenhor et al. 2010), lower than PBDE concentrations in China.

## Groundwater contamination by e-waste

The major source of groundwater is rain or water from freshwater bodies present on the upper surface and then moved through minor spaces present in soil particles. Groundwater contamination happens when toxic materials are dissolved or mixed in the water (Akram et al., 2017a, b). On the other hand, when these freshwater sources interacted with contaminated soil while saturating the ground, it can end up contaminated and can transfer the contaminants from the soil to the groundwater. Groundwater can likewise end up in contamination when dissolved substances leach down from the soil to the groundwater (Akram et al. 2018a, b).

Regarding the impacts of e-waste materials on groundwater, Wang and Guo (2006) discovered a measurable concentration of lead in water that arises during the reprocessing process in Guiyu. The contents of Pb (0.4 mg/l) were eight times greater than the permissible level for water in Guiyu. Wong et al. (2007b) announced that the high levels of hazardous metals in Liangjian and Nanya Rivers contrasted with those of the Guiyu and reported that the Guiyu ground streams have more metal content than those examined on the surface. Subsequently, recycling practices can appear to



**Table 2** Selected toxic substances associated with recycling e-waste and their presence in the surrounding environment

| Environment | Toxic substances | Country/region | References |
|---|---|---|---|
| Soil | PBDEs | Guiyu, China | Wang et al. (2011) |
| | | Taizhou, China | Cai and Jiang (2006) |
| | PAHs | Guiyu, China | Leung et al. (2006) and Yu et al.(2006) |
| | | Taizhou, China | Shen et al. (2009) and Tang et al. (2010) |
| | PCDD/Fs | Guiyu, China | Leung et al. (2007) |
| | | Taizhou, China | Shen et al. (2009) |
| | PCBs | | Shen et al. (2009) and Tang et al. (2010) |
| | As, Cu, Cr, Cd, Hg, Pb, and Zn | | Tang et al. (2010) |
| | Ag, Bi, Cd, Co, Cr, Cu, In, Hg, Mn, Mo, Pb, Sb, Sn, Tl, V and Zn | Bangalore, India | Ha et al. (2009) |
| Water | As, Cd, Cr, Cu, F, Fe, Hg, Mn, Ni, Pb, Zn, Ag, Al, As, Be, Ca, Cd, Co, Cr, Cu, Fe, Li, Mg, Mn, Mo, Ni, Pb, Sb, Se, Sr, Ti, V, and Zn | Guiyu, China | Wang and Guo (2006) |
| | | | Wong et al. (2007b) |
| Air | PBDEs | Guiyu, Guangzhou, Hong Kong, China | Deng et al. (2007) |
| | | Guiyu and Chendian, China | Chen et al. (2009) |
| | | Thailand | Muenhor et al. (2010) |
| | PAHs | Guiyu, China | Deng et al. |
| | PCDD/Fs | Guiyu and Chendian, China | Li et al. (2007) |
| | Polybrominated dibenzo-*p*-dioxins and dibenzofurans(PBDD/Fs) | Guiyu and Chendian, China | |
| | As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn | Guiyu, China | Deng et al. (2006) |
| | Ag, Bi, Cd, Co, Cr, Cu, In, Hg, Mn, Mo, Pb, Sb, Sn, Tl, V, and Zn | Bangalore, India | Ha et al. (2009) |

antagonistically affect water characteristics in Guiyu (Wang and Guo 2006).

## Soil contamination by e-waste

Soil is a pool of environmental contamination as it is typically made out of a huge number of topographical and natural materials because of weathering and degradation process, as well as particle sizes and chemical characteristics (Manfredi and Goralczyk 2013). There is a wide range of soil categories according to the organic matter content, from sandy to loamy soil and peat soils, which makes its analysis more difficult. Potential contamination of soils may happen at old e-waste landfill sites, where chemicals may have been dumped on the ground. Overabundance of heavy metals gathering in the soils is harmful to humans and other living beings (Qu et al. 2013).

Independent of the present worldwide transfer to "zero wastes," the area of landfills has been expanding equally in developing and developed countries. Whereas the holders of present-day landfills contend that modern landfills are safer to keep away the pollutants from the environment (SWANA 2004), thousands of previously constructed landfills without obstructions and contain e-waste are at higher rates. Toxins can possibly move over to soil particles and leach down and contaminate the areas near landfills (Kasassi et al. 20[illegible]8). Natural and other toxic substances in landfills deteriorate and leach over soil particles as leachate. Landfill leachate has a high concentration of inorganic substances and toxic metals. In any case, the concentration of hazardous compounds relies upon the waste attributes and phases of waste deterioration in a specific landfill (Masahiro et al. 201[illegible]).

To evaluate the possible effect of leachates from e-waste dumping is a toxicity characteristic leaching procedure (TCLP). Various electronic gadgets are based on TCLP. A TCLP test decides whether a waste possesses a physicochemical property that marks it as toxic waste. Electrical gadgets are thought to be toxicity characteristic (TC) unsafe waste, if the gadgets contain particular components greater than TC-recommended concentration, which are As (5 mg/l), Ba (100 mg/l), Cd (1 mg/l), Cr (5 mg/l), Hg (0.2 mg/l), Se (1 mg/l), and Pb (5 mg/l). Lead from CRTs in TVs and PC screens is one of many hazardous constituents that severely contaminate the environment (Townsend, 2011). Townsend et al. (2004) considered leachability of Pb, Fe, Cu, and Zn from electrical equipment—computer processing units, display screens, PCs, laser printer, videotape recorder, laptops, mouse, and remote controls—to inspect the content of substantial metals. It is reported that Pb exceeds 5 mg/l in numerous electrical gadgets including PCs, mobiles, remote controls, and smoke indicators.

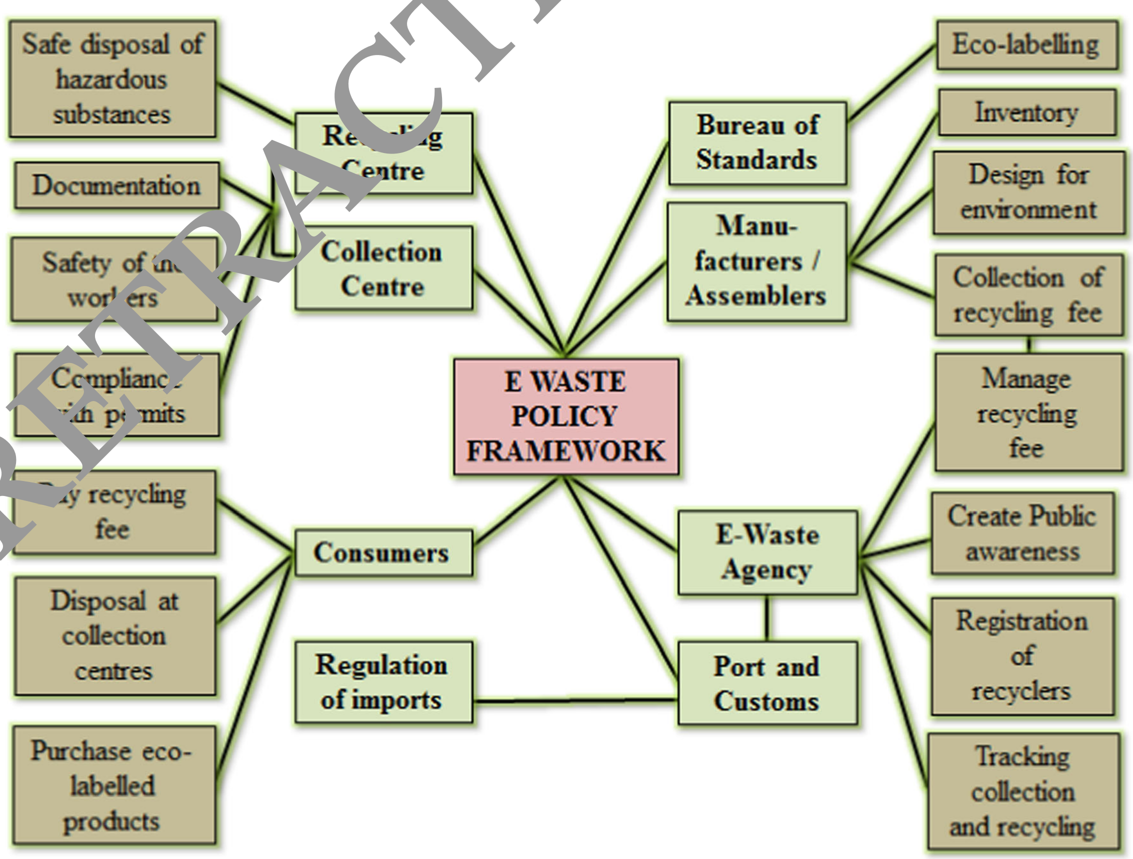


**Fig. 5** Elements of the e-waste policy framework

## e-waste management strategies

The e-waste management strategies can address issues from manufacture and exportation to ultimate dumping, including technology transmissions for the reprocessing of e-waste materials (Ongondo et al. 2011). This should consist of appropriate training, rules and regulations, and strategies for all involved (Rafia et al. 2013). Thinking about the seriousness of the issue, it is categorically essential that specific management alternatives be implemented to deal the bulk e-waste materials. Figure 5 shows an important framework for e-waste management policies, proposed for the government, the industries, and the users to manage and handle e-waste efficiently and in an eco-friendly way.

## Recommendations and conclusion

The present review confirms that the critical concentrations of possibly toxic metals discharged throughout the recycling process and accumulate in the atmosphere. The possible risks of inorganic and organic pollutants to the environment and human well-being are long term. Besides, degradation of organic contaminants will probably result in the development of metabolites which may conceivably be more harmful than the parent material. Now, it is obvious from the review that considerable attention has been given during the past decade to govern the toxic elements related to e-waste materials and their effective management and recycling practices. There are less data, in any case, regarding the effect of e-waste on human well-being and particularly its effect on the terrestrial and aquatic ecosystem. There are various ways to minimize the e-waste generated at the global level to protect the whole surrounding environment. For this, government, manufacturers, industries, electronic media, and all citizens should play their role at equal levels. These are a few points that can be used to overcome the issues of e-waste:

- Government should formulate laws for suitable controlling and management of e-waste hazardous substances and provide an organized system for the implementations the law and regulation. Clear policies should be formulated regarding risk assessment associated with the disposal of e-waste materials.
- Educational policies can play an important role to create awareness for electronic manufacturing industries and users on wise use of electronic things and also about the harmful elements present in e-waste materials and impacts on human health as well as on the whole environment (Fig. 6).
- Seminars should be conducted to develop 3R techniques in daily life.

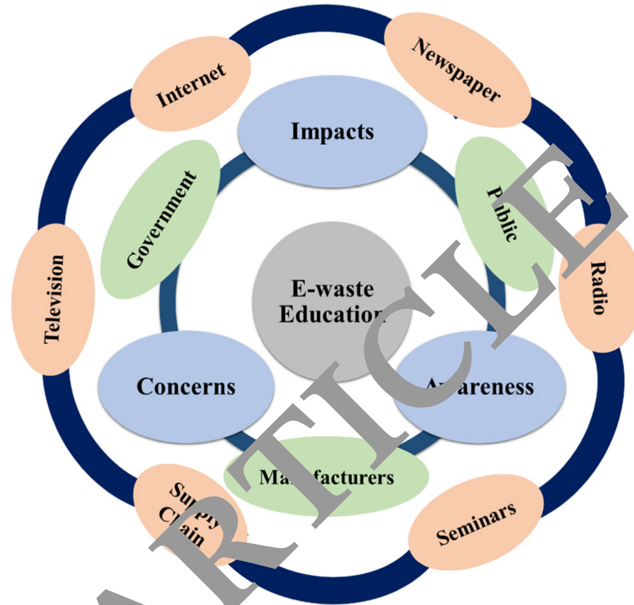


**Fig. 6** Importance of education to create awareness about e-waste

- If there is any violation of the rules, the government should take firm action against the manufacturers/consumers who do not follow the proper e-waste handling and disposal measures.
- Various NGOs are working to create awareness about e-waste in people and actively involve how to handle this issue, so the government should encourage these NGOs and other such organizations
- The hazardous e-waste substance can be minimized by making innovation in manufacturing industries and sustainable and environment-friendly designs should be used.
- Biodegradable substances (plant-produced polymers, toners, glue, gums, inks) should be used to make electronic appliances.
- The approach of responsible purchasing should be adapted and try to purchase environment-friendly electronic gadgets that have less/no harmful impacts on living organisms.
- Mostly discarded electronics have many reusable parts that can be combined with discarded machines to make new functional machines.

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