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Review

A global perspective on e-waste recycling

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ABSTRACT

Electronic waste (e-waste) is one of the relatively fast-growing solid waste streams, with an annual growth rate of 3%–5%. Although international policies have been formulated to better limit the global transboundary movement of hazardous waste, the existence of illegal trade and "informal" recycling has exacerbated the global recycling of e-waste. At present, residents in many low-income areas are still illegally and unscientifically disposing of e-waste to profit from it. The toxic and harmful substances produced affect the global ecological environment through the geochemical cycle. In this review, we provide a systematic overview of the status quo of e-waste recycling globally. E-waste is placed into a framework, grouped by product type, quantity, composition, environmental health risk, and global impact. Management measures, legislative policies, current disposal, and transboundary movement are summarized at international, regional, and national levels, illustrating the status and challenges of e-waste collection and disposal. Techniques such as physical dismantling, component recycling, metal extraction, and re-utilization of non-metallic materials are described, which can have long-term impact on the ecosystem. We advocate that the global sustainable recycling of e-waste be supported by regional cooperation, legislative management, technology development, and eco-friendly design. This study provides a global solution for the recycling of e-waste.

1. Introduction

Waste electronic and electric equipment (WEEE) (Perkins et al., 2014) is now the world's fastest-growing solid waste stream, as a result of the explosive demand and shorter product cycles (Heacock et al., 2016; Hossain et al., 2015; Li et al., 2015; Zhang et al., 2012). In 2019, nearly 53.6 million tons (MT) of e-waste was generated globally, a 21% growth compared to 5 years ago (Baldé et al., 2017). Despite this growth, only 17.4 wt% of e-waste was collected and recycled (Forti et al., 2020), which means that the valuable metal and high-value recyclable materials in the e-waste were abandoned instead of being recycled (Cucchiella et al., 2015; Ikhlayel, 2018; Vats & Singh, 2014).

Unlike conventional solid wastes such as household waste, e-waste has the dual attributes of hazardousness and resourcefulness (Ilankoon et al., 2018; Oswald & Reller, 2011). From the perspective of resource utilization, the metal and non-metal compositions contained in e-waste are highly recyclable (Dave et al., 2016; Tesfaye, Lindberg, Hamuyuni, Taskinen, & Hupa, 2017; Tiwari and Dhawan, 2014), especially precious metals, of which the grade is dozens or even hundreds of times higher than that of crude ores (Ashiq et al., 2019; Cui & Zhang, 2008). E-waste contains up to 60 different types of metals, such as copper, gold, silver, palladium, aluminum, and iron (Debnath et al., 2018). It is estimated that as of 2017, the value and reserves of waste materials in e-waste are as follows: Iron/steel of 16,500 kt (9 billion Euros), copper of 1900 kt (10.6 billion Euros), aluminum of 220 kt (3.2 billion Euros), gold of 0.3 kt (10.4 billion Euros), silver of 1.0 kt (0.58 billion Euros), and plastics of 8600 kt (12.3 billion Euros) (Baldé et al., 2017). The recycling cost of metal from e-waste is far below the mining of crude ore (Chancerel et al., 2009; Vidyadhar, 2016), which means that e-waste recycling is an energy-saving and environmentally-friendly approach (Anand et al., 2013; Khaliq et al., 2014; Thakur & Kumar, 2020). The total economic value of the recyclable resources contained in e-waste is as high as 57 billion USD, which is higher than the gross domestic product of most countries in the world (Forti et al., 2020).

However, there are a variety of heavy metals such as lead, mercury, and cadmium, and persistent organics such as polychlorinated biphenyls and brominated flame retardants (He et al.,

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2017; Quan et al., 2014; Wu et al., 2015, 2016). If handled illegally, such hazardous substances will cause serious harm to the global eco-system and human health (Quan et al., 2015; Tang et al., 2010; Wang et al., 2011; Zeng et al., 2016). The increasing pollution and damage to the environment are the price paid to the upgrade of electronic products (Akram et al., 2019; Gaidajis et al., 2010; Zeng et al., 2017). The e-waste from high-income countries, where disposal cost is high and eco-friendly regulations are strict, is often passed onto low- and middle-income countries illegally (such as China, India, Ghana, and Nigeria) for recycling (Petridis et al., 2020; Shinkuma & Huong, 2009; Wong, Wu, et al., 2007). The industrial infrastructure and recycling technology, however, tend to be informal in those countries, with workers adopting crude methods to recover the valuables from the e-waste, resulting in negative and irreversible impact on local, regional, and even global ecological environment (Awasthi et al., 2016a; Christian, 2017; Terazono et al., 2006; Wong, Duzgoren-Aydin, et al., 2007). Considering the huge volume and rapid growth rate of e-waste, there must be an understanding of the impact and potential hazard of e-waste recycling, and a discussion of sustainable e-waste management and recycling technology to form a comprehensive solution for e-waste (Awasthi et al., 2019; Ecroignard, 2008; Gaidajis et al., 2010; Widmer et al., 2005).

This review provides a comprehensive overview of the status quo of e-waste globally. First, the characteristics of e-waste are introduced from the aspects of quantity, product type, composition, and global impact. Subsequently, the management measures, legislative policies, current disposal, and transboundary movement in different countries are examined from international, regional, and national levels to outline the situation of e-waste collection and disposal. For recycling, the application of techniques such as physical dismantling, component classification, metal extraction, and non-metal reutilization, and the potential hazards of e-waste to the environment and organism are concluded. Finally, targeted measures are proposed to sustainably promote the global recycling of e-waste (Khajuria et al., 2022; Zeng et al., 2022).

2. Definition and composition

At present, there is no global definition on e-waste, with its definition varying amongst countries and regions (Kumar et al., 2017). The Organization for Economic Cooperation and Development defines any electrical appliance that has reached the end of its useful life cycle as e-waste (Suja et al., 2014). According to United States Environmental Protection Agency, e-waste includes bulk electrical appliances, small electrical appliances, and consumer electronic products (Kahhat et al., 2008). There are specific laws governing e-waste recycling in Japan, such as *Resources Effective Utilization Promotion Law*, *Home Appliance Recycling Law* and *Small Electrical and Electronic Products Recycling Law*. The law applies to 34 types of electronics, ranging from big devices like TV sets to small ones like cellphones (Bo & Yamamoto, 2010). China's *Administrative Measures for the Prevention and Control of Environmental Pollution by Electronic Waste* defines e-waste as waste electronic and electrical equipment and their parts and components generated in daily life, as well as products or equipment that are prohibited by laws and regulations from being produced or imported. The *Disposal Catalog of Waste Electrical and Electronic Products (2014 Edition)* of China increases the number of WEEE from 5 to 14 types, including televisions, refrigerators, washing machines, air conditioners, microcomputers, range hoods, electric water heaters, gas water heaters, fax machines, cellphones, standalone telephones, printers, copiers, and monitors (Duan et al., 2016). At present, the most widely accepted definition of e-waste is Europe's *Waste Electrical and Electronic Equipment (WEEE) Directive*, which defines e-waste as waste electrical and electronic equipment, including all parts, sub-parts and consumables that are used as products when discarded (Shittu et al., 2021). The attribute definition of e-waste given in this directive is clear. *WEEE Directive* is recognized as the e-waste management law with the most widely applicable product range in the world today, and it has become the best practice for defining the concept of e-waste. *WEEE Directive* implemented by Europe in 2003 defines the categories and specific products of e-waste, including 10 categories of electrical and electronic equipment. After two amendments, WEEE's classification is implemented according to the new directive (Table 1), which almost covers all Electrical and Electronic Equipments (EEEs) (Mihai et al., 2019).

The chemical composition of e-waste is very complex, usually including steel, iron, polymer plastics, non-ferrous metals, glass, wood, plywood, printed circuit boards, concrete, ceramics, and rubber, etc (Betts, 2008). Among them, iron and steel account for about 47 wt%, plastics ~21 wt%, copper ~7 wt%, glass ~5 wt%, and others (Zeng et al., 2018). Valuable metals, such as nickel, copper, lead, zinc, cobalt, precious metals (gold, silver, palladium, rhodium, and others), and rare earth elements (samarium, europium, yttrium, gadolinium, dysprosium) are the main economic driving force for recycling e-waste (Tesfaye, Lindberg, & Hamuyuni, 2017; Yang et al., 2021). For example, 143 kg of copper, 0.5 kg of gold, 40.8 kg of iron, 29.5 kg of lead, 2.0 kg of tin, 18.1 kg of nickel, and 10.0 kg of antimony can be usually separated from 1 ton of waste printed circuit boards (Kolias et al., 2014). Non-metallic materials such as engineering plastics and glass fibers are also of considerable value through secondary use (Rajagopal et al., 2017; Sahajwalla & Gaikwad, 2018). In general, the dominant polymers in WEEE were found to be polystyrene, acrylonitrile-butadiene-styrene, blends of polycarbonate, high-impact polystyrene, and polypropylene (Ma et al., 2016). The glass fiber is mainly composed of metal oxides, such as alumina, potassium oxide, sodium oxide and calcium oxide., etc., which are generally present in the resin laminate of the circuit board (Khan et al., 2022). In addition, e-waste is a hazardous industrial waste because it contains several types of persistent substances, such as tetrabromobisphenol A and decabromodiphenyl ether (Breivik et al., 2016; Herat, 2008; Zeng et al., 2016). In this study, we propose an element-level perspective to better understand the composition of e-waste (Fig. 1). The composition of e-waste is complex, with dozens of constituent elements, all of which bring direct challenges to the recycling of e-waste. Based on the function of the element and the applied materials, E-waste can be divided into common metals, precious metals, rare elements, rare earth elements, plastics/biomass, added elements, and glass fiber/concrete. The elemental composition of plastics and biomass is mainly carbon, hydrogen, and oxygen. As an added element, fluorine, chlorine, and bromine can often constitute polyvinylidene fluoride, polyvinyl chloride, and brominated flame retardants to play a flame-retardant or binding effect, but these added elements increase the environmental risk of plastic recycling. Low-value components such as glass fiber and concrete mainly contain elements such as aluminum, silicon, calcium, sodium, and potassium, etc. These elements are often used for construction materials or landfill disposal due to their low added value after extracting high-value components.

3. Generation scale

The total amount of global e-waste continued to increase from 2014 to 2019 (Fig. 2(a)) (Shittu et al., 2021). In 2014, 44.4 MT of e-waste was produced. Five years later, that is, in 2019, the data has soared to 53.6 MT. From the perspective of per capita e-waste generation, the number has been growing yearly globally

Table 1
Definition and types of e-waste in WEEE.

No.	Type	Products
1	Temperature regulating equipment	Refrigerators, freezers, equipment that automatically transfers cold, air conditioners, dehumidifiers, heat pumps, oil-containing radiators, and other temperature exchange equipment that uses non-aqueous liquids
2	Displays, monitors, and any display device that is bigger than 100 cm^2	Monitors, TVs, liquid crystal display photo frames, monitors, laptops
3	Lamps	Straight tube fluorescent lamps, compact fluorescent lamps, fluorescent lamps, high-density discharge lamps—including high-pressure sodium lamps and metal halides, low-pressure sodium lamps, light-emitting diodes
4	Large equipment	Washing machines, dryers, dishwashers, cooking equipment, electric stoves, electric hot plates, lamps, equipment that reproduce sounds and images, musical instruments (excluding wind instruments in churches), sewers, mainframe computers, large-scale printers, photocopiers, large slot machines, large medical equipment, large monitoring instruments, large electrical appliances that automatically deliver products and coins, photovoltaic solar panels
5	Small equipment	Vacuum cleaners, carpet cleaners, electrical appliances for sewing, lamps, microwave ovens, ventilators, electric irons, electric ovens, electric sewing machines, electric kettles, clocks and watches, electric shavers, electric scales, electrical appliances for hair and body care, calculators, radios, digital cameras, image recorders, high-fidelity equipment, musical instruments, equipment that reproduce sounds and images, electric toys, sports equipment, computers for cycling, diving, running, throwing, etc., smoke detectors, heating controllers, thermometers, small power tools, small medical equipment, small monitoring instruments, small appliances that automatically deliver products, and small devices with photovoltaic solar panels
6	Small IT and communication equipment (outside length not exceeding 50 cm)	Mobile phones, global positioning system, portable calculators, routers, personal computers, printers, telephones

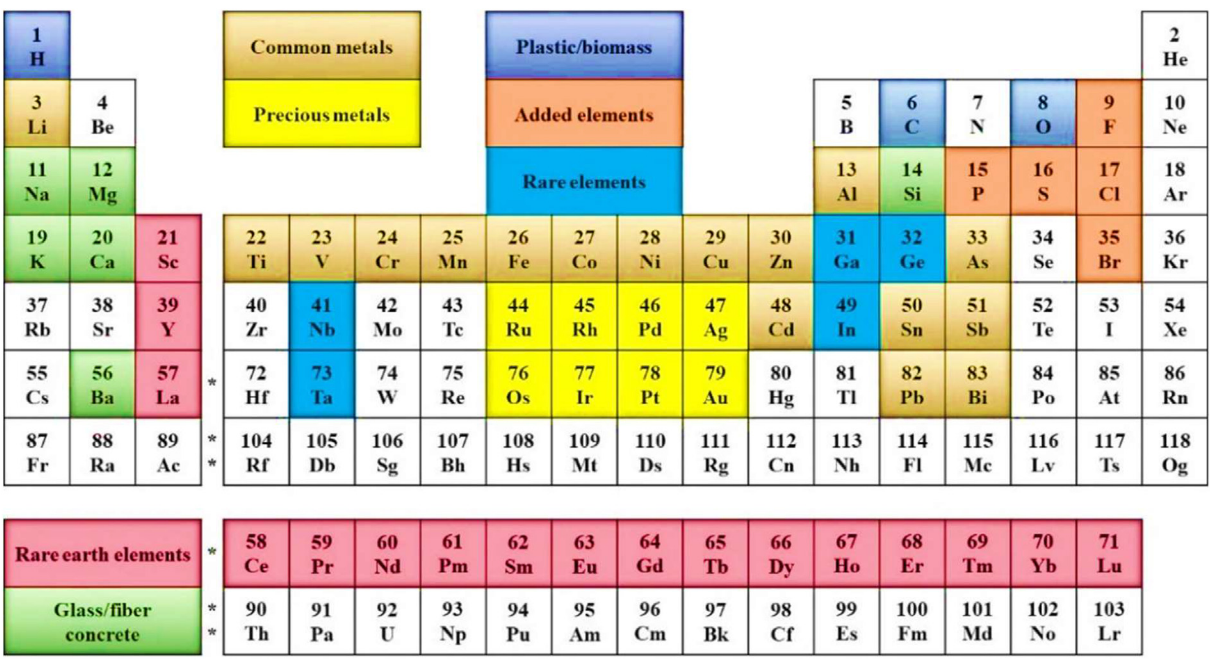

Fig. 1. Element-level view of e-waste composition.

(Fig. 2(b)). In 2014, the global per capita generation of e-waste was 6.4 kg/person. Five years later, this value has increased to 7.3 kg/person. In the waste category and classification composition of products in e-waste, large-scale equipment, small-scale equipment, and temperature control equipment rank in the top three (Fig. 2(c)). Types that grow fast include temperature control equipment (20.1 wt%), large equipment (24.4 wt%), electric lights (1.7 wt%), and small equipment (32.5 wt%). In contrast, small electronic communication equipment shows a slower increase (8.8 wt%). In 2019, only 17.4 wt% was officially recycled, and the rest of the flow is not clear (Fig. 2(d)). In 2019, only 17.4 wt% was officially recycled, and the rest of the flow is not clear (Fig. 2(d)). In 2019, Asia produced the most e-waste at approximately 24.9 MT, followed by the Americas (13.1 MT) and Europe (12.0 MT), while Africa and Oceania produced 2.9 MT and 0.7 MT, respectively (Fig. 2(e)). The amount of e-waste generated per capita in Europe (16.2 kg) ranks first in the world, followed by Oceania (16.1 kg) and the Americas (13.3 kg). Asia and Africa are much lower, at 5.6 kg and 2.5 kg, respectively (Fig. 2(f)) (Baldé et al., 2017; Forti et al., 2020). From a per capita perspective, the amount of e-waste generated in Europe and Oceania is much higher than that in other continents.

4. E-waste regulation and trade

We summarized e-waste management policies and measures from international, continental, and national levels, and reviewed the flow of illegal e-waste trade.

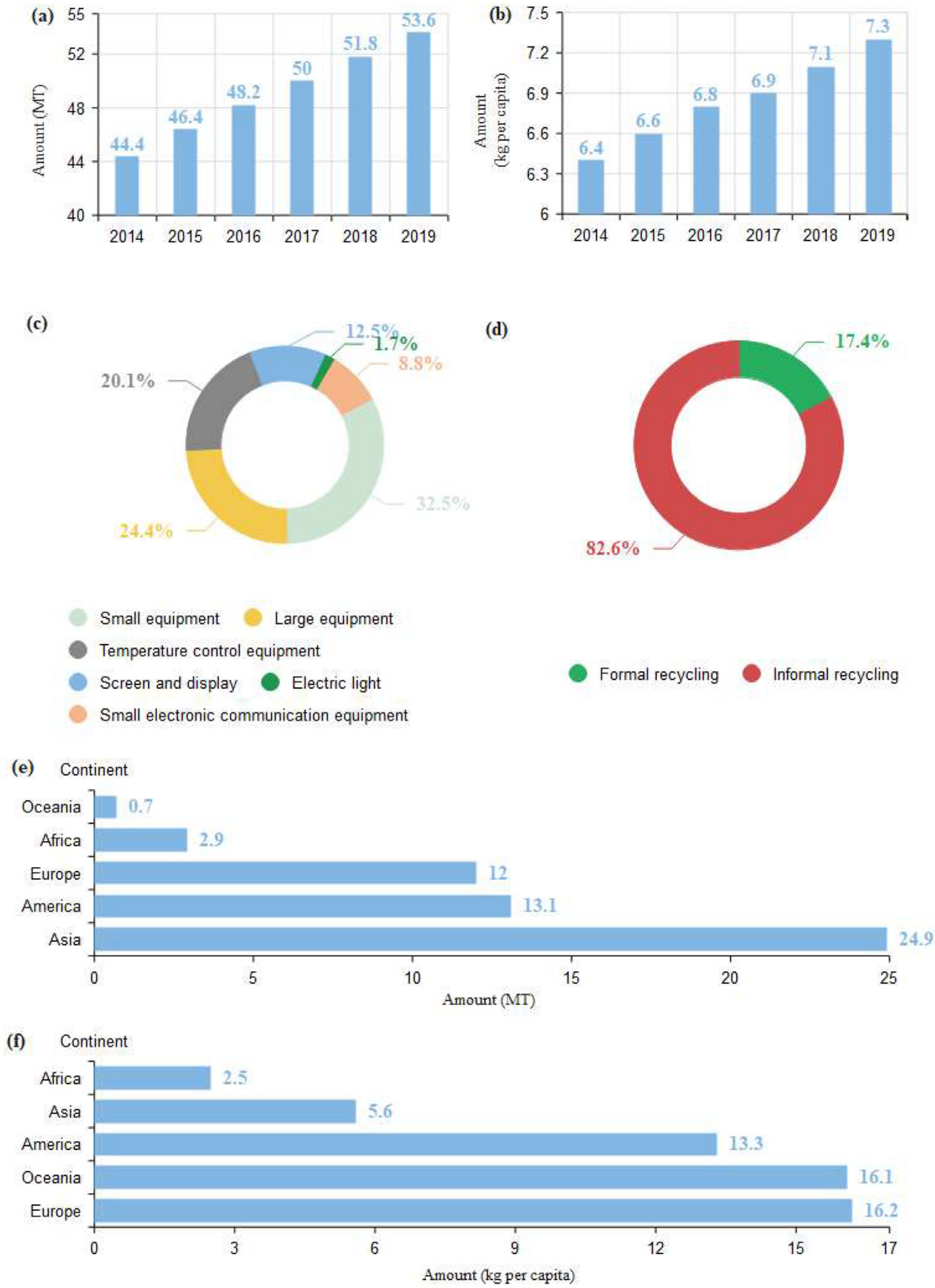

Fig. 2. Global generation data of e-waste. (a) Global generation of e-waste (2014–2019); (b) Per capita generation of e-waste (2014–2019); (c) Categories of e-waste; (d) Ratio of formal recycling of e-waste to informal recycling; (e) Amount of e-waste generated in each continent (2019); (f) Amount of e-waste generated per capita in each continent (2019). The statistical data we use in this study is up to 2019. Due to the epidemic, the statistical agency (the United Nations University (UNU) and the United Nations Institute for Training and Research (UNITAR), the International Telecommunication Union (ITU), and the International Solid Waste Association (ISWA)) did not update the generation data of e-waste after 2019. The data source comes from *The Global E-waste Monitor 2020* (Forti et al., 2020).

4.1. Policy and legislation

A number of legislative bodies have attempted to regulate the transboundary movement of hazardous substances, including e-waste, as their international trading poses threat against global environment and human health (Nnorom & Osibanjo, 2008). Multilateral environmental agreements and international conventions aimed at regulating the transport of waste include the *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal* (1989), and *Stockholm Convention on Persistent Organic Pollutants* (2001). Article 11 of the *Basel Convention* allows parties to sign bilateral, multilateral, or regional agreements on the transboundary movement of hazardous waste. Therefore, three regions, including Africa, Europe, and the South Pacific, have formulated agreements on such waste transfer, especially on e-waste, such as Africa's *Bamako Convention* and *Durban Declaration*, Europe's *Aarhus Convention* and *WEEE Directive*, and the South Pacific's *Waegani Convention*, all of which were signed as regional conventions on the regulation of the transfer of hazardous waste.

The differences in the definition of e-waste and the legislation governing the e-waste are significant among countries (Table 2). There is no federal regulation on e-waste in the United States, since there is no consensus on the recycling mechanism of e-waste yet, but e-waste as an issue has solicited attention from the United States Environmental Protection Agency (Kahhat et al., 2008). The United States Environmental Protection Agency has established *R2 Certification* in 2009, and *e-Stewards*, which is designed to regulate the e-waste recycling industry, in 2010. Various states in the USA have rolled out their own laws on e-waste management since 2003. 24 states and New York City have introduced their own laws on e-waste management, all aiming to recycle e-waste, and forbid or prevent its landfill (Namias, 2013; Schumacher & Agbemabiese, 2019). At the beginning of the 21st century, Europe began to implement unified laws and regulations on the recycling and use of e-waste, such as the *WEEE Directive* (2003), the *Restriction of Hazardous Substances Directive* (*RoHS Directive*) (2006), the *Energy-Using Product Eco-Design Directive* (*EuP Directive*) (2007), the new *WEEE Directive* (2012), and *WEEE Label of Excellence* (*WEEELABEX*) (2011). As of now, a sorted recycling system has been established by Europe and shared by consumers, sellers, and producers. All Europe members are required to establish a system ensuring that

Table 2
Comparison of different e-waste laws.

Country/ Region	Names of laws	Year of promulgation/Implementation	Management directory
Japan	*Resources Reuse Promotion Law* was amended as the *Resources Effective Utilization Promotion Law*	Promulgated in 1991, revised in 2000, and implemented in 2001	Personal computers (including cathode ray tube (CRT) display or liquid crystal display), small secondary battery (closed nickel-cell storage battery, closed nickel-hydrogen storage battery, lithium secondary battery, and small sealed lead storage battery)
	Home Appliance Recycling Law	Promulgated in 1998, and fully enforced in 2001	Televisions (CRT or LCD), air conditioners, refrigerators and freezers, washing machines and dryers
	Small Electrical and Electronic Products Recycling Law	Implemented in 2013	Wired and wireless communication equipment, radios and television receivers, photographic and audio equipment, etc. A total of 28 categories
Republic of Korea	*Resource Conservation and Recycling Promotion Law*	Promulgated in 1992, revised in 2002, and implemented in 2003	Batteries (mercury, silver oxide, potassium, nickel-cadmium, manganese, and nickel storage batteries), fluorescent lamps
	Recycling Law of Electrical and Electronic Products & Automobile Resources	Promulgated in 2007, and implemented in the end of the year	TVs, refrigerators, washing machines (household), ACs (excluding automobile ACs), personal computers (including monitors and keyboards), etc. A total of 27 categories
European Union	*Waste Electrical and Electronic Equipment Directive* (*WEEE*)	Promulgated in 2003, and implemented in 2004	Large and small household appliances, IT and telecommunication equipment, user equipment, lighting equipment, electronic and electrical tools, toys, leisure and sports equipment, medical equipment, monitoring and control tools, vending machines
	Restriction of Hazardous Substances Directive (*RoHS*)	Implemented in 2006	Large and small household appliances, IT and communication equipment, consumer products, lighting equipment, electrical and electronic tools, toys, leisure and sports equipment, medical equipment, testing and control equipment, vending machines. A total of 11 categories
	Eco-Design Directive (*EuP*)	Approved in 2005, officially announced in the same year, and became applicable to all member countries in 2007	Heating and hot water equipment, electric motor systems, lighting equipment for homes and service industry, household appliances, office equipment for homes and service industry, ventilators and ACs, etc.
	Waste Electrical and Electronic Equipment Directive (New *WEEE*)	The *WEEE Directive* was revised in the end of 2008, and announced in July 2012	Photovoltaic panels were added to the 4th category from 2012 to 2018. The new directive applies to all electrical and electronic products since August 15, 2018
	WEEELABEX standard (*WEEE LABel of EXcellence*)	Formulated in 2011	Ten types of e-waste such as CRT displays, tablet displays, temperature exchange equipment (compressors) and fragile materials such as lamps
USA	*R2 Certification*	Formulated in 2009	Cathode ray tube and its stripping, circuit board (batteries, mercury-containing parts, and lead should be removed in advance), batteries, mercury-containing materials, and PCB-containing materials
	e-Stewards Certification	Formulated in 2010	On-site disposal safety of hazardous waste electrical and electronic products and other problematic parts and materials (such as the crushing of mercury)
China	*Administrative Measures on the Control of Electronic IT Product Pollution* (China's *RoHS*)	Promulgated and implemented in 2006	Electronic radar products, electronic communication products, radio and television products, computer products, household electronic products, electronic measuring instrument products, electronic products of special purposes, electronic component products, electronic application products, and electronic material products, etc.
	Administrative Measures on the Prevention and Control of E-Waste Environmental Pollution	Promulgated in 2007, and implemented in 2008	Lead-acid batteries, cadmium-nickel batteries, mercury switches, cathode ray tubes and PCB capacitors, etc.
	Regulations on the Management of the Recycling and Disposal of Waste Electrical and Electronic Products (China's *WEEE*)	The first catalog promulgated in 2009, and implemented in 2011	The first catalog: TVs, refrigerators, washing machines, room ACs, and microcomputers. A total of 5 categories
		The second catalog (2014) promulgated in 2015, and implemented in 2016	14 categories including TVs, refrigerators, ACs, washing machines, vacuum cleaners, computers, printers, fax machines, photocopiers, and telephones, etc.

consumers return e-waste for free. Collection infrastructure shall be constructed based on regional population density to guarantee the effectiveness and availability of e-waste (Horta Arduin et al., 2019; Patil & Ramakrishna, 2020). Japan has promulgated and implemented special laws and regulations on the recycling and use of e-waste as early as late 20th century. There are two ways for home appliances to be recycled in Japan, by electronics dealers and by the government at designated locations. Recycled home appliances are transported to designated locations where they are then transported to manufacturers or other companies entrusted to dispose of waste home appliances. E-waste disposal in Japan is paid by consumers who must pay for the transport and disposal, while the funds go from consumers directly to the handling company (Yoshida & Yoshida, 2014). Special laws and regulations on the recycling and use of e-waste have been promulgated, revised and implemented in Republic of Korea since late 20th century, such as *Resource Conservation and Recycling Promotion Law* and *Recycling Law of Electrical and Electronic Products & Automobile Resources* (Doan et al., 2019). They apply to big appliances to small equipment, and then further to automobiles, indicating a gradually improved management system. The management list has expanded to 29 types of electrical and electronic products as of now. Republic of Korea's e-waste management, which is mainly built on the *Recycling Law of Electrical and Electronic Products & Automobile Resources*, has structured a whole-process management system from preventive measures on product design and manufacture, to sales and reuse, and then post-management after recycling. With the extended producer responsibility, a dealer in Republic of Korea is obliged to recycle and bear the cost when a consumer buys and returns the product; while daily discarded e-waste is recycled and handled by regional government or civil department, and the cost is shared by residents and government finance. For e-waste legislation in China, the *Administrative Measures on the Control of Electronic IT Product Pollution* was promulgated in 2006; the *Administrative Measures on the Prevention and Control of E-Waste Environmental Pollution* in 2007; the first and second revisions of the *Regulations on the Management of the Recycling and Disposal of Waste Electrical and Electronic Products* in 2009 and 2015, respectively; and the *Technical Policy for Pollution Prevention and Control of Waste Electrical and Electronic Products* in 2015 (Lu et al., 2015; Yu et al., 2010). At present, the most effective policies in China are based on the extended producer responsibility, highlighting the producer's responsibility to recycle and dispose of e-waste, while consumers may benefit from the recycling (Zeng et al., 2013, 2017).

To solve the increasing problem of e-waste and utilize the generated e-waste, many countries have passed e-waste legislation. The number of countries that have adopted national e-waste policies has increased from 61 in 2014 to 78 in 2019, yet still far from the goal set by the International Telecommunication Union, an international organization within the United Nations system responsible for coordinating global telecommunications networks and services, which is 50 wt% (Forti et al., 2020). The main problem in most e-waste legislative countries is weak law enforcement and low efficiency. The lack of legal responsibility and limited knowledge of e-waste collection and recycling statistics make it impractical to measure the effectiveness of existing e-waste legislation. As the e-waste legislation in various countries is not uniform, it is difficult to monitor the recycling of e-waste on a global scale (Ahirwar & Tripathi, 2021). Common challenges faced by various countries nowadays include limited capacity and ability of responsible institutions, ineffective implementation of legal instruments, poor participation of stakeholders, and lack of specific definitions, legal instruments, policies or strategies (Forti et al., 2020).

4.2. Illegal trade

At present, there is a serious regional imbalance in the recycling and disposal of e-waste globally (Lepawsky, 2015). A massive amount of e-waste is being scrapped in high-income countries/regions every year, yet only little processed domestically (Bisschop, 2012). The rest goes to middle- and low-income countries/regions in Asia, Africa, Central America, and South America, resulting in legal, environmental, political, economic, and moral issues (Bisschop, 2016; Petridis et al., 2020). The e-waste outflow areas are generally high income and middle-income countries/regions, such as the USA, Western Europe, Japan, Republic of Korea, and Australia. The receiving countries/regions of e-waste are generally low-income countries/regions such as China, India, Brazil, and Africa. The rest of the e-waste goes to low-income countries/regions in Asia, Africa, Central and South America. In 2019, 12.0 MT of the e-waste generated in Europe, only about 5.1 MT was collected (Shittu et al., 2021). The main driving forces of e-waste trade include: precious metal content, high treatment risk yet low transport cost, and usually low risk of being caught (Bisschop, 2013; Palmeira et al., 2018). E-waste is often traded secretly, and the trading volume is at least above 19 billion USD per year (Petridis et al., 2020). Standards for the import/export of e-waste differ in different countries, creating obstacles for crackdown on illegal trading and leading to a boom in e-waste smuggling (Awasthi et al., 2019; Lepawsky, 2015). The United States is also one of the developed countries that has not yet joined the *Basel Convention*. According to the US law, cathode ray tubes in computer monitors and televisions are currently the only type of electronic waste that is expressly prohibited from export, while the export of most other electronic waste is not subject to legal restrictions. The US Government Accountability Office found in 2008 that 43 companies contained e-waste containers being exported, and 80% of them were destined for Hong Kong, China. Some e-waste categories, including waste circuit boards, CRT glass, and lead-acid batteries, etc, have been listed as hazardous categories and their transboundary movements are put under control by the *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal* (Gibbs et al., 2010; Lee et al., 2018; Wang et al., 2016). Even though it has been deterring e-waste from being dumped across borders to a certain extent, the goal is still far from being achieved, and illegal smuggling and dumping activities are still active (Illés & Geeraerts, 2016). Research conducted by the European Union and the United Nations clearly shows that African countries, especially West African countries, have become e-waste dumping grounds of high-income countries. Due to imperfect policy frameworks and regulations, low- and middle-income African countries cannot calculate the amount of e-waste from other countries. Although many African countries have signed international treaties dealing with waste transportation, due to lack of regulations and poor enforcement, illegal e-waste recycling and import activities have never stopped. These areas have also become the most poisoned areas of e-waste current (Ilankoon et al., 2018; Schluep et al., 2012). In recent years, the Chinese government has taken a series of measures to improve the import standard of solid waste. Since January 1, 2018, China has banned the import of 24 solid wastes, including waste plastics and waste slag, significantly reducing the types and quantities of imports. This provides a new solution to prevent the cross-border entry of electronic waste (Qu et al., 2019).

5. E-waste recycling

Technology development and material recovery are extremely important links in e-waste recycling. In this section, we describe the global disposal of e-waste, the technologies that have been successfully applied, the extraction of metals, and the utilization of non-metallic materials plastics.

5.1. Treatment status

In 2005, under the *WEEE* and *RoHS Directives*, the European Union stipulated those producers, importers, and distributor were responsible for the cost of recycling and disposal of e-waste. *WEEE Directive* requires producers to bear the final disposal costs of electronic and electrical products, while consumers are exempted from any fees (Billinghurst, 2005). Most of European Union's e-waste recycling and processing systems adopt government supervision, and third-party non-profit organizations are authorized to coordinate, organize, and monitor (Levinson et al., 2008; Salhofer, 2017). There are currently more than 500 active e-waste treatment and disposal companies. The e-waste in the US is recycled by municipal departments, dealers, recyclers, non-profit organizations or environmental protectors, producers or industry organizations, and government partnership programs (Petridis et al., 2020; Wagner, 2009). Most producers are involved in e-waste recycling through the National Electrical Manufacturers Association or the United States Trade Representative. There are over 2000 companies involved in the treatment of e-waste across all 50 US states (Kahhat et al., 2008; Kollikkathara et al., 2009). Japan's e-waste treatment has gone through three stages: from collecting non-metals to mixing regular wastes for recycling, and then to the rapid rise of standardized treatment after 2001 (Chaudhary & Vrat, 2018). In 2008, the number of TVs, washing machines, refrigerators and ACs being treated in a standardized manner accounted for 55 wt% of the total production, while the rest went to used market or overseas (Yoshida & Yoshida, 2014). Currently, there is already a complete industry chain in Japan from e-waste collection, transport to handling. The recycling rate and number of resources have been significant increased. The scale of standardized treatment continues to expand, and the mechanized level of treatment machines keeps improving, all of which lead to a surplus in the e-waste treatment capacity in Japan (Bo & Yamamoto, 2010). Guided by the market and government, e-waste in China mainly enters the used electronics market, or goes to handling businesses and/or individual workshops (Wang et al., 2013). Since the introduction of the *Regulations on the Management of the Recycling and Disposal of Waste Electrical and Electronic Products*, however, individual workshops where waste was manually dismantled are disallowed. Now, most of them are certified companies. Regardless most e-waste recycling companies are still unable to achieve full recycling due to scattered recycling channels (Lu et al., 2015; Wei & Liu, 2012; Yu et al., 2010). At present, China has formed an extended producer responsibility system centered on the waste electrical and electronic product disposal fund and has established a comprehensive environmental management system for electronic waste in line with China's national conditions. By allowing manufacturers of electrical and electronic products to pay the fund, a waste electrical appliance disposal fund was established to subsidize the recycling and processing costs of waste electrical and electronic products. It became the first development in the world to implement the extended producer responsibility system through the establishment of a waste electrical appliance disposal fund. With the encouragement of the Waste Electrical Appliance Treatment Fund, the overall competitiveness of waste electrical appliance processing enterprises has continued to increase, and the recycling and processing industry has achieved sustainable development. The coordinated efforts of multiple government departments will manage the entire life cycle of the production, circulation, recycling of electrical and electronic products. Chinese government has strictly carried out the review of the dismantling and handling of enterprises to crack down on illegal dismantling and dismantling, which has effectively guaranteed the safety of funds (Wang et al., 2020; Xu et al., 2021).

5.2. Disposal processes

Disposal processes of e-waste mainly include: safe dismantling, separation and enrichment, material regeneration, energy recovery, and pollutant treatment (Fig. 3) (Li et al., 2017; Ruan & Xu, 2016). Safe dismantling: At present, dismantling is mostly done manually with the help of tools since electronics cover a long list, and the component vary hugely in structure, making the parts unable to be automatically dismantled (Ostroukh et al., 2018); Separation and enrichment: Toxic and harmful parts are removed, and the rest is crushed, before the waste is treated by equipment with one or multiple separation and enrichment techniques (such as separation by magnetic force (Ruan & Xu, 2016), gravity (Huynh et al., 2020), airflow (Zhang et al., 2019), or eddy current (Ruan et al., 2014)); Then, higher-content single-component materials are obtained, such as non-ferrous metals or engineering plastic (Islam et al., 2020); Material regeneration: Separated materials can be manufactured into new functional materials or products, such as metal alloy or wood-plastic product, after necessary processing (Kaya, 2016; Sahajwalla & Gaikwad, 2018); Energy recovery: Materials not suitable for recycling generated from the process of dismantling, separation and regeneration can be used as fuel or incinerated directly to generate energy (Chandrasekaran et al., 2018); Pollutant treatment: Pollutants generated in the process of dismantling, separation or regeneration shall be appropriately treated in a bio-safe way based on the attributes of pollutants (Wei & Liu, 2012). After scrapped electronic and electrical products are collected and transported, they are transferred to a qualified dismantling factory. After safe disassembly, the useful parts are sorted and recycled. Discarded parts are transformed into new saleable products through metallurgy, smelting and plastic modification. Combustible components such as plastics and resins are burned for energy recovery, while the emission of persistent organic pollutants must be controlled.

In the complete chain of e-waste recycling, the overall process is as follows (Fig. 3(a)): Electronic wastes such as televisions, washing machines, refrigerators, air conditioners, etc. first enter the dismantling workshop of the factory through collection and transportation. E-waste is disassembled, crushed, and sorted in the workshop to separate and enrich the materials of different components such as steel, plastic shells, circuit boards, etc. In this process, the components storing hazardous materials are disassembled, stored, and supervised. The metals in the separated recyclable parts are extracted by pyrometallurgy and hydrometallurgy. Plastics are transformed into new value-added products through modification. Plastic, wood, and biomass materials can be decomposed through energy recovery processing. At the same time, pollution control of the pollutants in the flue gas is needed to avoid the impact on the soil, atmosphere, and groundwater (Kang & Schoenung, 2005; Yoshida et al., 2016; Zeng et al., 2015).

5.3. Metal recycling

As the main economic driving force for e-waste recycling, the recovery technology of valuable metals can be described as: mechanical and physical technique, pyrometallurgy, hydrometallurgy, and bio metallurgy, etc (Debnath et al., 2018; Nithya et al., 2021; Vidyadhar, 2016; Wang et al., 2022b; Xiu et al., 2022). The first three techniques are more widely applied in terms of maturity and industry scale (Hsu et al., 2019; Islam et al., 2020). The mechanical treatment of e-waste is a separating method by the differences in

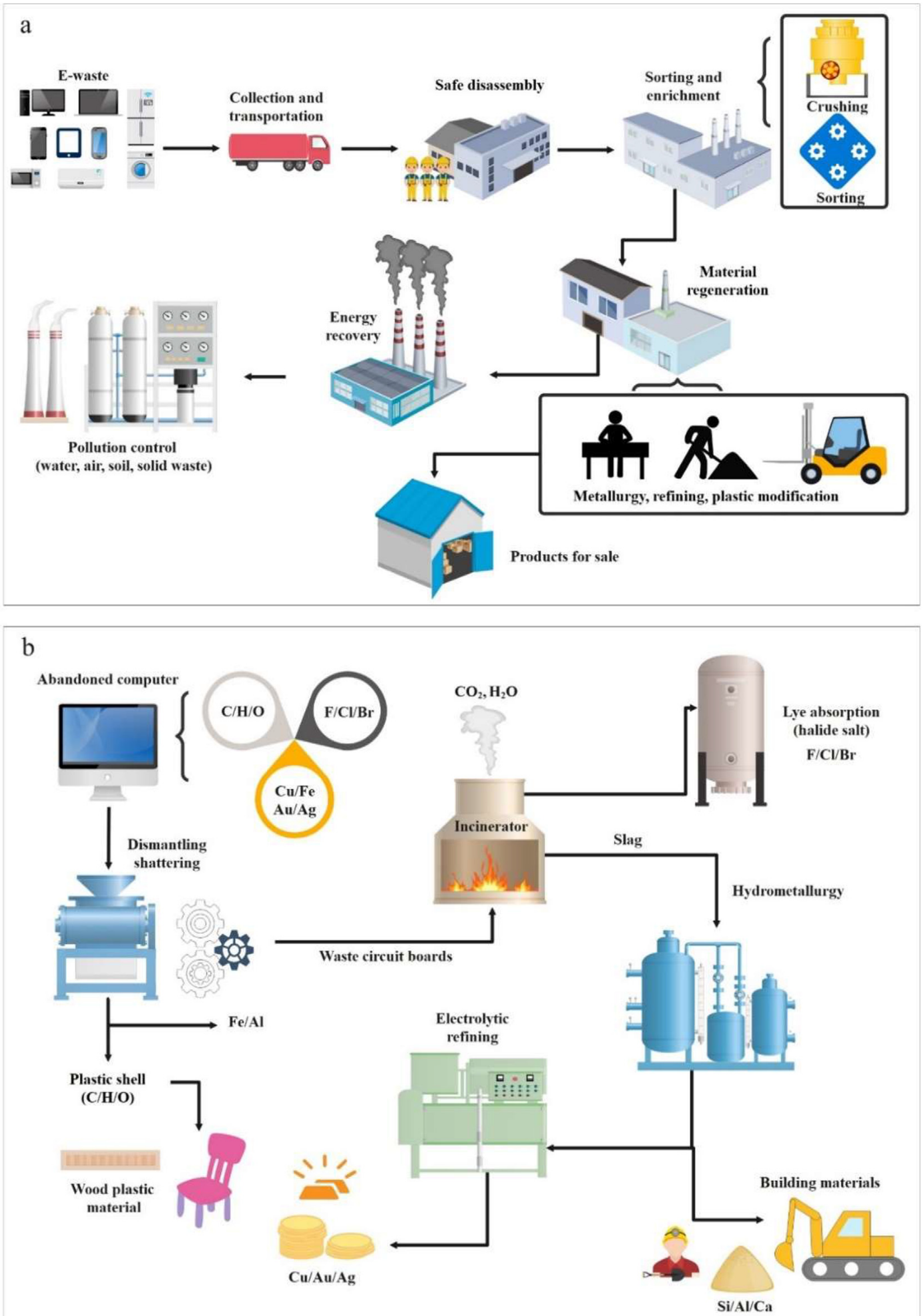

Fig. 3. The overall and individual (waste printed circuit boards) disposal process of e-waste (a) e-waste recycling process, (b) element recovery perspective.

the physical attributes of components, including dismantling, crushing, and separation (Li et al., 2007; Sarvar et al., 2015). Separated materials such as metals, plastics and glass after subsequent treatment may be used for regeneration (Khanna et al., 2020). Such treatment is of low cost and easy operation, and avoids secondary pollution, making it a hot spot in the industry (Nekouei et al., 2018; Otsuki et al., 2020). Pyrometallurgy is a method of incineration, smelting, sintering, and melting of e-waste to remove plastics and other organic components to enrich metals (Ebin & Isik, 2016; Khaliq et al., 2014). It is simple to operate, but the operating temperature often requires a high temperature of 300–1000 °C, and sulfur oxides, and the reaction consumes higher level of energy and the incineration of organic matter may result in hazardous fumes containing benzene series, dioxin (Shuey & Taylor, 2005; Wang et al., 2017). Hydrometallurgy involving placing the crushed e-waste particles into acid or alkaline solution, separating and producing different high-grade metals through processes such as extraction, precipitation, replacement, ion exchange, filtration and distillation (Ashiq et al., 2019; Tuncuk et al., 2012). Compared to pyrometallurgy, hydrometallurgy can be operated at room temperature and pressure, exhausts less emissions, and has higher metal separation efficiency, as well as prominent economic values (Liu et al., 2020). But it consumes more chemical reagents, includes complicated techniques, and produces a large amount of acidic wastewater that is difficult to dispose (Kamberović et al., 2009). Bio-metallurgy recycles by exploiting microbial activities to leach metals into solution (Zhuang et al., 2015). Bio-metallurgy is known for simple process, low cost and easy operation (Hennebel et al., 2015). However, compared with the reaction time of several hours in pyrometallurgy and hydrometallurgy, bio-metallurgy often requires several days of reaction time, which becomes a disadvantage in the application of bio-metallurgy (Ilyas & Lee, 2014). Due to the complexity of the structure and composition of waste electronic and electrical products, it is difficult for a single technology to realize the recycling and utilization of resources. For the recycling of electronic waste, physical crushing, pyrometallurgy and hydrometallurgy often need to be combined to design a comprehensive product recycling plan based on the characteristics of different materials.

Taking the smelting of copper in waste printed circuit boards as an example, pyrometallurgy is very different from hydrometallurgy. During the pyrometallurgical process of copper, the waste printed circuit boards are thrown into a furnace at a high temperature of 1000 °C, and oxygen is continuously supplied as a combustion-supporting agent. Brominated epoxy resin in waste printed circuit boards is converted into high-temperature fuel gas such as carbon dioxide and water. The released hydrogen bromide gas is absorbed by the lye. Copper, gold, and silver exist in high-temperature smelting residues, and the selective leaching-extraction of copper and precious metals can be achieved by using electrodeposition (Li et al., 2018; Wang et al., 2017). Here we provide an element-level flow understanding of e-waste disposal (Fig. 3(b)). The main components of waste printed circuit boards are calorific value elements (carbon, hydrogen, and oxygen), added elements (fluorine, chlorine, and bromine), precious and base metals (copper, iron, gold, and silver) and low-value elements (aluminum, silicon, and calcium). After crushing and sorting, the plastic components can be converted into wood-plastic materials through cross-linking and modification. Waste printed circuit boards are thrown into the incinerator for calorific value recovery. Carbon, hydrogen, and oxygen are converted to carbon dioxide and water. Fluorine, chlorine, and bromine are recovered after being absorbed by the lye. Copper, gold, and silver are recovered as products through hydrometallurgy and electrodeposition. The worthless residues are mainly aluminum, silicon, and calcium, which can be used for construction materials and landfill disposal. Discarded computers contain a variety of different plastics (C/H/O) that can be converted into wood-plastic materials. Metals (Cu/Ag/Ag) are transformed into saleable products through pyrometallurgy and hydrometallurgy. The halogen atoms (F/Cl/Br) are absorbed by lye after the heat treatment to generate the halide salt products. Low value-added elements (Ca/Al/Si) either enter the landfill or are converted into building materials. In the hydrometallurgical route of copper, waste printed circuit boards need to be converted into powder by mechanical crushing first. Under the action of inorganic acid sulfuric acid and oxidant hydrogen peroxide, copper is dissolved and converted into copper sulfate. Copper in solution can be finally recovered by electrodeposition.

Metal recycling activities are an important link in e-waste recycling (Kaya, 2022). A number of emerging technologies such as supercritical fluid (Li & Xu, 2019), molten salt (Amietszajew et al., 2016), electrochemistry (Ashiq et al., 2020), and mechanochemistry (Ou et al., 2015), have been developed to achieve eco-friendly extraction of valuable metals, in order to alleviate the impact of metal recycling on the environment. These recycling technologies driven by light, electricity, heat, and force can often achieve unexpected experimental results to achieve selective extraction of target metals. For example, driven by mechanical force, zero-valent copper in waste circuit boards can react with the co-grinding reagent potassium persulfate to convert into copper sulfate products. After the reaction is end, only water washing is needed to realize the leaching, extraction, and recovery of the copper sulfate product in the ball mill product. The metal recovery technology based on mechanochemistry avoids the use of acid and alkali and reduces the production of waste liquid, becoming a supplement to hydrometallurgical technology (Liu et al., 2019; Wang et al., 2022a). But because of limited technical maturity and supporting industries, metal recycling from e-waste is still dominated by pyrometallurgy and hydrometallurgy now.

5.4. Non-metallic materials

In addition to valuable metals, there are also non-metallic components such as plastic, glass, and rubber in e-waste (Yousef et al., 2017). The recycling value of plastic is second to metals. Depending on the technique, the use of non-metallic components includes mechanical regeneration, modified regeneration and resource recovery (Qiu et al., 2021). Plastic being mechanically regenerated does not change its physical and chemical properties and is the best way to achieve material recycling and reuse. It is also a common method to add one or more plasticizers, tougheners, nucleating agents, fillers and other polymer modifiers to waste plastics to convert them into recycled plastics with high added value (Li et al., 2012). Fully recovering the chemical and thermal energy of waste plastics through incineration, pyrolysis, hydrothermal liquefaction and gasification is also an effective means to reducing the amount of waste plastics (Sahle-Demessie et al., 2021). Low-value glass fiber, ceramics, and concrete in e-waste will eventually end up in landfill (Shen et al., 2018). In the initial stage of e-waste treatment, the recycling techniques mainly focus on the recycling of metals. However, with the technological development and improvement of resource mining requirements, it has now developed into a comprehensive recycling of ferromagnets, non-ferrous metals, rare and precious metals, and waste plastics (Cucchiella et al., 2015; Saldaña-Durán & Messina-Fernández, 2021).

6. Environmental impacts

This chapter describes the toxic and hazardous substances in e-waste and the related environmental chemistry and toxicological effects. Furthermore, the environmental pollutants and environmental impacts that may be generated in different stages of e-waste recycling are depicted to remind possible ecological and environmental risks.

6.1. Long-term environmental hazards of e-waste

The main threats posed to the environment and human health by e-waste come from its heavy metals, persistent organic pollutants, flame retardants, and other potentially dangerous substances

(Gong et al., 2021; Hou et al., 2020; Tsydenova & Bengtsson, 2011). The threat mainly comes from various pollution sources released to the environmental media after electronic products are destroyed in the formal and informal dismantling process. The pollutants will be released to various media in the process of treating e-waste, such as air, dust, soil and water, and further enter the body of living things through geochemical cycles and biological chains (Gaidajis et al., 2010; Heacock et al., 2016) (Fig. 4). The air medium can become a transmission medium for dust volatilization, heavy metals, and persistent organic pollutants. The sulfur and nitrogen elements, dioxins, and heavy metals in the flue gas of incineration will become atmospheric pollutants. These pollutants will accumulate, migrate, and transform into animal and plant communities and human communities through the water cycle, soil, and groundwater, and will eventually cause health hazards to life (Fig. 4). A study (Ngo et al., 2021) based on an informal e-waste treatment village in Vietnam showed that the average daily total intake of five heavy metals (Pb, Cd, Cr, Ni, and As) in children in the exposed village was 3.90 times that of the children in the reference village ($p < 0.01$). Cooked rice is the most important source of heavy metals. A report (Shi et al., 2020) on Wenling, Zhejiang, China, one of China's largest e-waste dismantling sites and a commercial grain production area, also shows that heavy metals produced during the dismantling of e-waste are one of the main sources of food pollution. Monitoring data show that from 2006 to 2016, the average concentration of Cd, Cu, Ni and Zn in the soil increased by 0.11, 11.81, 1.01 and 6.82 mg kg^{-1}, respectively (Shi et al., 2020). A report based on the Guiyu, China (2009) shows that the uncontrolled release of polychlorinated biphenyls during the recycling of e-waste was the main source of human accumulation (Song & Li, 2014; Xing et al., 2009).

The recycling of e-waste requires advanced technologies, but the resulting pollutants are difficult to control because of their complex composition and longtime (Song & Li, 2015; Wath et al., 2011). Even in the advanced dismantling process, there are issues on the concentration of heavy metals and persistent organic matter in air, soil, and water (Awasthi et al., 2016b; Leung et al., 2008; Ádám et al., 2021). For example, a study on the formal recycling of waste printed circuit boards shows that the$\sum_8$ poly brominated diphenyl ethers ($\sum_8$PBDEs) concentration in inhalable particles (PM_{10}) inside the waste printed circuit boards de-soldering workshop was 20,300 pg/m^3, and the $\sum_8$PBDEs inhalation exposure for

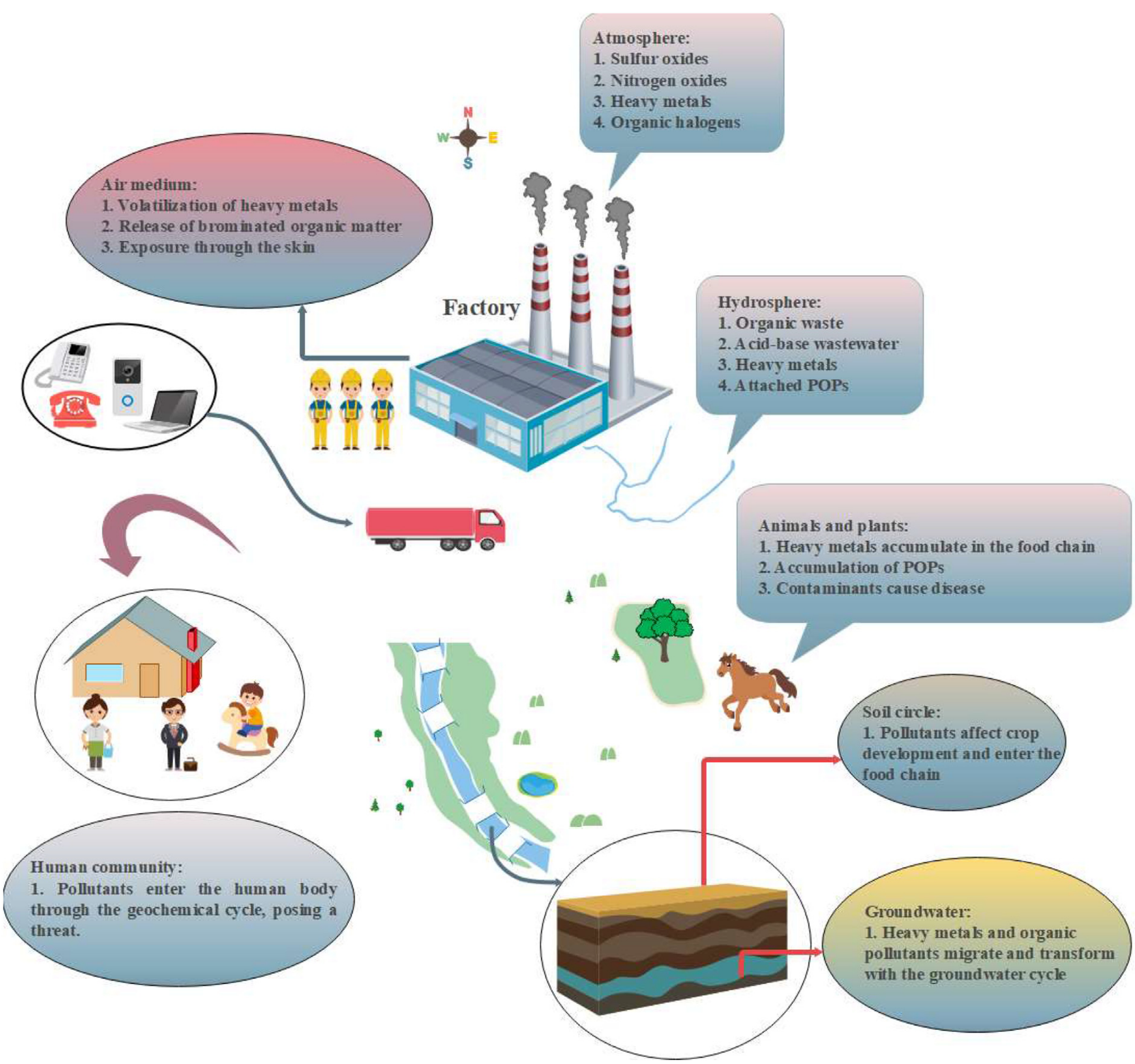

Fig. 4. Schematic of environmental and health impacts of e-waste.

the worker was 1.46 ng/(kg·day). The negative pressure hood system can reduce the exposure dose of workers, but the smoke from the range hood (including particulate matter and PBDEs) still poses a threat to the health of workers (Guo et al., 2019). An examination of flame retardants and organic phosphates in outdoor air, soil, and sewage near formal e-waste disposal facilities (regular e-waste dismantling and recycling facilities, official waste dumps and landfills, and waste incineration plants) showed although the formal e-waste facilities have adopted environmental protection technologies, the concentration of such species in the atmosphere and soil near the formal e-waste treatment facilities is still increasing (Ma et al., 2022). For example, in the official e-waste recycling facility in Norway and the official e-waste storage facility in Thailand, increased concentrations of PBDEs in the atmosphere have been observed (Morin et al., 2017; Muenhor et al., 2010). Substances that may cause long-term environmental hazards in the e-waste recycling process include suspended particulate matter from disassembly, leachate from hydrometallurgy, floating dust and bottom ash from incineration, and fumes from welding and burning, waste water from dismantling and crushing equipment, cyanide leaching and waste liquids from other chemical activities (Li & Achal, 2020; Singh et al., 2020).

6.2. Human health hazards in the disposal of e-waste

According to statistics from the World Health Organization, there are currently approximately 2.9–12.9 million female practitioners in the world involved in informal recycling of solid waste, and approximately 73 million children (World Health Organization, 2021). The Agbogbloshie dump in Ghana is the largest e-waste dump in Africa and one of the largest in the world. It is estimated that about 250,000 tons of classified electrical and electronic waste are dumped there every year. Approximately 40,000 people live and work around the site (Feldt et al., 2014). There are three main ways of exposure to e-waste: (1) food intake; (2) breathing; and (3) soil/dust intake and direct skin contact (Li & Achal, 2020; Singh et al., 2020; Zheng et al., 2010). Risks brought to human health by e-waste include breathing difficulty, respiratory comfort, coughing, suffocation, pneumonia, tremor, neurological problems, coma and even death (Zheng et al., 2013; Zhu et al., 2021; Ádám et al., 2021). Halogenated polymers will emit halogen-containing smoke after incineration or pyrolysis, such as dioxins, furans and polychlorinated biphenyls (Fu et al., 2008; Lau et al., 2014). Such substances might trigger cancer (Labunska et al., 2014). Increased blood lead concentration will damage body's nerves, blood systems and kidneys, and affect the brain development of infants and young children (Song & Li, 2014; Thanomsangad et al., 2020). With the action of microorganisms, the inorganic mercury contained in e-waste might be converted into methyl mercury, which further damages human nerve system. Chromium compounds damage human's DNA sequence and cause respiratory diseases such as asthma. Freon leaked from air conditioner will destroy the ozone layer, causing the greenhouse effect and triggering dermal carcinogenesis. Landfill or illegal burning of brominated flame retardants and chlorinated plastics will emit highly toxic substances such as dioxins (Chipperfield et al., 2020).

Workers who work at the dismantling and treatment plant will inevitably be exposed to the toxic chemical substances in e-waste, such as dioxins, polybrominated diphenyl ethers and polychlorinated biphenyls, through breathing, dust, skin contact and oral inhalation, resulting in occupational health risks (Akormedi et al., 2013; Khan, 2018). Such work-related risks may cause physical harm and chronic diseases, including asthma, skin diseases, neuritis, eye inflammation and stomach problems (Akormedi et al., 2013; Tahir et al., 2021). The particulate matter collected from where e-waste is recycled has been shown to cause inflammation, oxidative stress and DNA damage (Ohajinwa et al., 2017; Srigboh et al., 2016). Pollutants might accumulate in adjacent farmland through transfer or conversion, so they may build up in organisms via food chain and passing on. The toxic effects of substances related to e-waste can last for decades (Nguyen et al., 2020; Yang et al., 2020). Therefore, e-waste has become a major global environmental and health issue. Its impact far exceeds the hazards of occupational exposure and endangers the health of vulnerable groups and future generations.

7. Tackle solutions

7.1. Green product design

Green design of electronic products is an effective initiative to reduce e-waste from the source. It focuses on the greening of the entire product life cycle. In the design of electronic products, modular, integrated, and intelligent technologies and high-powered, lightweight, and eco-friendly new materials should be used. Electronic products which are non-hazardous, energy-saving, eco-friendly, and easily recyclable with high reliability and long lifespan are to be designed (Li et al., 2020).

Producers need to be responsible for the green design of their products to aid in the recycling and safe disposal of electronic products. Meanwhile, they are encouraged to green the design and production of electronic products to extend their life cycle as much as possible and achieve the reduction of e-waste (Kirschner, 2022; Yi & Wu, 2021). Design principles, materials used, and construction techniques serve as the three elements of green design for electronic products. In terms of design principles, the environmental attributes of the product (disassembly, recyclability, maintainability, and reusability, etc.) need to be considered, which in turn simplifies the recycling processes for decommissioned electronic products. In terms of materials used, the use of eco-friendly materials and their recyclability are expected to draw attention. It is banned to use toxic and hazardous materials, and the variety of materials will be reduced to facilitate recycling. In terms of construction techniques, the development of green recycling process of electronic products can help to avoid the release of heavy metals and organic substances during the dismantling of electronic waste, and to reduce the use of acidic, alkaline, and corrosive reagents and chemicals.

7.2. Management strategy

It becomes a consensus that the current global regulatory framework for e-waste is ineffective. Regulatory measures based on top-level design have little effect on end-of-pipe regulation and control of e-waste. Therefore, it is extremely necessary to establish a multi-latitude, three-dimensional, and modern regulatory framework (Barapatre & Rastogi, 2022; Thakur & Kumar, 2022). Overall, a modernized framework for e-waste management requires close international cooperation among governments, recycling mechanisms that minimize adverse impacts on ecosystems and human communities, technological systems that enable businesses to profit from them, and incentives that protect the economic interests of labor.

First, the recycling of e-waste needs a sound and well-functioning top-level design system. Governments are advised to design a reasonable recycling framework based on their own economic development, urbanization, and geographical conditions. Governments need to improve the existing relevant laws and regulations, with extended producer responsibility system as an important driver, to establish a sustainable system of recycling electronic products throughout their entire life cycle. The recycling framework is required to incorporate potential environmental impacts, risk prevention measures, and extended producer responsibility systems into the current regulatory framework. Among the management measures for transboundary movements of e-waste, the extended producer responsibility system has proven to be an effective and powerful tool (Chen et al., 2022; Pan et al., 2022). Entire life cycle assessment is also considered as an effective tool for minimizing potential environmental impacts in solid waste recycling (He et al., 2021). Collection remains the primary challenge of e-waste recycling. The government can strengthen the driving force of recycling enterprises through fund incentives, while attracting the intervention of external capital, which in turn can rapidly increase the effective rate of formal e-waste recycling. This will help to solve the e-waste recycling problem at root. The inclusion of electronics manufacturers, marketing sectors, and recycling companies may lead to a well-functioning industry and substantial innovative initiatives.

7.3. Advances in collection

With the development of social needs, the types of electronic products are becoming more and more diversified. The change of product types and continuous upgrading of products also provide technical challenges for the recycling of electronic products. In general, collection, disassembly, and fine separation are the three vital aspects of electronic product recycling. Based on the rapid development of the Internet, building an e-waste recycling network with the Internet of Things as the key information flow serves as the hinge for solving the problem (Fig. 5) (Razip et al., 2022; Sun et al., 2022). We propose to build an e-waste collection system based on online/offline integration. In this system, the information of e-waste can be coded to track and monitor for visual management. Manufacturers are required to codify electronic products, and sellers need to register the electronic products sold with their identity information. Purchasers submit information about waste electrical and electronic products and receive money and credit points on a third-party platform provided by the government. Disposers offer services by accepting information online, providing offline transfers, and making profits from recycling. Through online supervision and offline financial subsidies, the government realizes the “closed-loop” management of waste electrical and electronic products.

7.4. Recycling of all components

The structure of electronic products is becoming increasingly sophisticated and complex. Thus, a single technology cannot achieve the purpose of fine separation. A large amount of valuable raw materials is lost during recycling, resulting in a waste of resources (Jadhao et al., 2022; Roy et al., 2022). Currently, substantial technologies are needed to upgrade the e-waste recycling system. The proposed full-component recycling is to achieve full-component recycling of waste electrical and electronic products. For instance, the main parts, i.e., useable and unusable components in electronic products, can be classified and separated to achieve differentiated recycling; incineration or pyrolysis can realize the fuelization of calorific value elements such as carbon, hydrogen, and oxygen in unusable parts and the enrichment recovery of metals; hydrometallurgy combined with chemical precipitation is used to extract conventional metals such as copper, tin, and lead in incineration residues; electrochemical and solvent extraction are feasible ways to achieve fine separation of rare metals such as gallium and germanium in the leachate; low-value components such as silicon, aluminum, and calcium are eventually converted into building materials (Murthy & Ramakrishna, 2022; Xiu et al., 2023).

8. Summary and future directions

The rapid growth of the global economy cannot be achieved without the contribution of electronic and electrical products. Therefore, it is proven that the global management and recycling of e-waste is a persistent battle. The problem of e-waste cannot be effectively solved only by relying on the management decree. Therefore, as a global issue, e-waste requires cross-sector cooperation to form a system of holistic control and recycling measures.

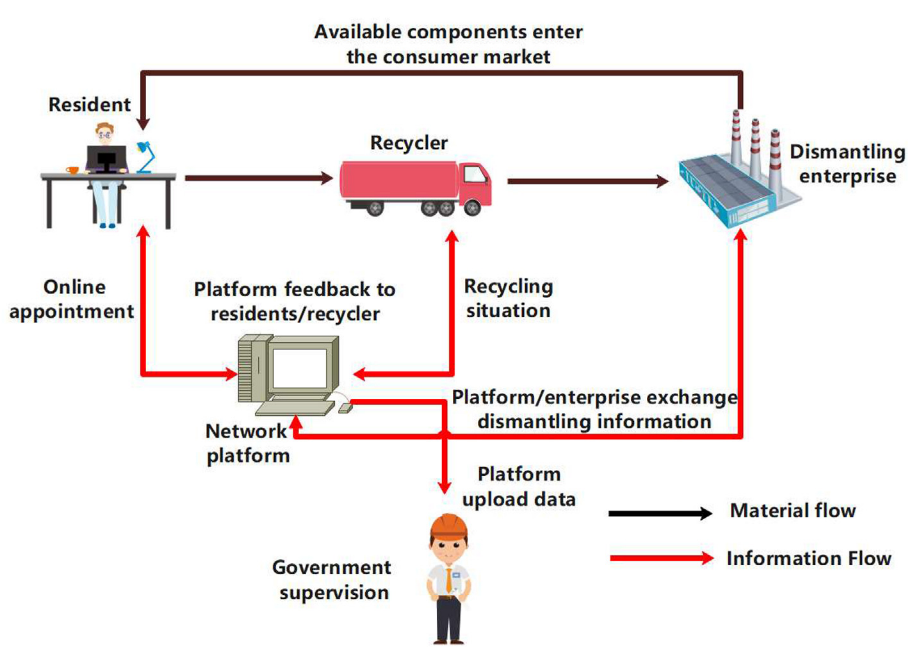

Fig. 5. Integrated online and offline e-waste collection models.

What we need is a series of substantial interventions, international cooperation, and strong goal-oriented actions for e-waste management.

First, as an effective tool to stop transboundary transfer of hazardous wastes, the *Basel Convention* needs to add e-waste and second-hand electronic products to its management framework, with the constraint for joining of developed countries such as the USA. We are supposed to establish management and regulatory associations for electronic products globally, put forward strict classification standards for the durability, availability, and safety of electronic products to ensure the controlled circulation and use of electronic products. Countries should strengthen law enforcement and cooperate closely to encourage the safe repatriation of illegally smuggled goods, while promoting the development of international agreements to achieve controlled circulation of e-waste.

Extended producer responsibility system can help effectively curb the disastrous outflow of e-waste. As the profit maker of electronic products, producers need to take environmental responsibility and involve deeply in green design, product coding, registration circulation, and end-of-life disposal. At present, due to differences in national legislation, the implementation of the extended producer responsibility system is difficult to be carried out effectively. In the future, countries must further implement and strengthen this system by improving enforcement under the supervision of international organizations.

The recycling of e-waste becomes a global challenge that must be addressed. The dismantling, sorting, and recycling of e-waste must take place in workplaces with safety and high specification. Useful components should be recycled rather than crudely broken down. Thorough decomposition of e-waste is supposed to be carried out by trained labor. Moreover, heavy metals and persistent organic pollutants in water, air, soil, and solids need to be strictly monitored. It is expected that green recycling of e-waste can be achieved by continuous development of fine separation technology.

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.

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