The hazards, treatment measures and sustainable development of electronic waste

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Abstract——The faster upgrading and the rising consumer’s demand for electrical and electronic equipment (EEE) results in an ever-increasing number of waste electrical and electronic items (WEEE), which became a severe pollution problem at both local and global scales. This paper presents the current six categories of EEE that are widely used for electronic waste (E-waste) management worldwide and the major component of E-waste: non-hazardous materials, heavy metal, and persistent organic pollutants (POPs). To learn about E-waste’s negative impacts on both environment and the human body, this paper will show the specific polluting route in air, water, and soil. Those pollutants would affect the environment through burning and directly released into the air, penetrating and leaking into water and soil. The polluted environment and the poor sanitary conditions will further destroy people’s health. This paper shows and summarizes the development of current E-waste management, from direct landfill to chemical disposal, to today’s eco-friendly way--bioleaching. Future E-waste disposal technology needs to become more environmentally friendly and more efficient for reusable material recovery. Therefore, we hope that E-waste management can closely connect with Sustainable Development Goals (SDGs). We need to apply SDGs into every aspect of E-waste management, which can significantly reduce the adverse effects of E-waste and be beneficial for the electronic industry.

1. Introduction
Electrical and electronic equipment (EEE) is widely applied to every general situation. These products support and sustain our daily life, such as household appliances, toys, music creation and entertainment tools, mobile phones, laptops, etc. Besides, EEE is becoming more popular and will be applied on a more extensive scale of every aspect of our lives, like transportation, health care system, security systems [1]. Moreover, more and more enterprises will use the new EEE to expand the Internet of Things (IoT) sector and to build the concept of the “smart home” or “smart cities [1].” However, due to economic expansion and increasing usage demand, the faster upgrading of EEE results in an ever-increasing number of waste electrical and electronic items (WEEE). Electronic waste (E-waste) contains different kinds of materials. Some of them can cause irreversible damage to both ecosystem and human health. Nowadays, E-waste has become a severe pollution problem worldwide due to its vast annual generation and lacking of efficient and harmless management.

Since people realized the increasing volume of E-waste and its hazard, more and more scholars have studied different aspects of E-waste at different scales and areas. Daniel Mmereki et al. [2] and Jim
Pucket et al. [3] analyzed different area's E-waste generation. They indicated that the categories and management of E-waste in both European and Asian countries are pretty different. These differences closely depend on the countries' GDP and economic development level. Some researchers revealed E-waste's harmful effects on both environment and human health [3-6]. They analyzed some pollutants' polluting mechanisms and polluting routes on the environment. They assessed some specific toxic substances severe damage to human health and gave some feasible solutions. Peeranart Kiddee et al. [7] analyzed the disadvantage of current E-waste management. They introduced four strategies aimed at the whole electronic industry chain to mitigate the problems of E-waste pollution at both the national and international levels. Some researchers discussed the economic benefit of recycling materials from E-waste [8]. They indicated that recycling some metals from E-waste would be more effective than mining from the specific mineral. Chancerel et al. [9] stated the economic potential of some precious metals through analyzing their preprocessing. Norom and Osibanjo [10] reviewed some poor E-waste management practices and relevant legislation in developing countries and discussed future solutions. Baniasadi et al. [11] introduced a sustainable method for metal recovery from E-waste. They think bioleaching will become a popular method in the future. Mary and Meenambal [12] discussed the impacts of E-waste from a consumer perspective. Some regional reports [13] showed and discussed the annual generation of E-waste and posed some different strategies to reduce the E-waste.

This paper will summarize the categories and components of E-waste and its major pollutants. Then, this paper will discuss E-waste's hazards both on the environment and humans by analyzing pollutants' polluting route in the air, water, and soil. Finally, this paper will introduce the development of current E-waste management and look forward to more efficient and environment-friendly E-waste management that can be beneficial to reach Sustainable Development Goals (SDGs).

2. E-waste category and component

2.1 E-waste category

During the development and productive process of EEE, laboratories, industries, and manufactures would generate vast amounts of discarded materials. At the same time, once those EEE products have been discarded, these discarded devices and materials will be disposed of or recycled in different ways. Generally, these E-waste consist of varying material content, and some of them are destructive to the environment and human health if not handled well.

Since the market has many different kinds of EEE, classifying these products may help describe E-waste and determine the process to be used to dispose of the product. Therefore, to manage the E-waste well and for statistical purposes, many areas or countries have established E-waste classification guidelines. Classifications have not defined special details, for example, when they do not threaten the environment. On the other hand, classifications should not be too aggregated because of countries' differences in interpretation. For example, the E-waste Statistics Guidelines on Classification Reporting and Indicators are widely used and recognized in many countries [1]. This Guideline puts EEE into 54 different product-centric categories. Furthermore, the 54 EEE product categories are grouped into six categories. Globally, European member states widely use this categorization for the WEEE directive. And this categorization is also recognized as an international framework for E-waste management. Table 1 shows the six categories and the global quantity of E-waste in 2019.
Table 1 The Six Category of E-waste and the global quantity in 2019 [1].

| No. | Category                                | Global quantity of E-waste in 2019 |
|-----|-----------------------------------------|-----------------------------------|
| 1   | Temperature exchange equipment          | 10.8 Mt                           |
| 2   | Screens and monitors                    | 6.7 Mt                            |
| 3   | Lamps                                   | 0.9 Mt                            |
| 4   | Large equipment                         | 13.1 Mt                           |
| 5   | Small equipment                         | 17.4 Mt                           |
| 6   | Small and telecommunication equipment   | 4.7 Mt                            |

2.2 E-waste component

As mentioned above, E-waste normally contains a huge variety of materials. Some of them would be harmful to the environment and human health. Some of them are valuable materials that have great economic potential to reuse. The composition of E-waste relies on different factors such as the usage of electronic device, the category of electronic device or electronic materials, manufacturer and the date of manufacturing.

2.2.1 non-hazardous or precious materials

Aluminum could be found in nearly all electronic products, such as heatsinks, ICs, electrolytic capacitors. Copper is widely used in many electronic elements such as component leads printed circuit board tracks, ICs, component leads, and some wire is made of copper [3]. Lithium and Nickel could be found in lithium-ion batteries and nickel-cadmium batteries. Gold is usually used in computer equipment and connector plating. Silicon is usually found in glass, transistors, ICs and printed circuit boards. Tin is used in solder, coatings on component leads. For example, those discarded IT and telecommunication devices would contain more precious metals than discarded household appliances. Some research has showed that recycle some metals from E-waste would be more effective compared to mining from the specific mineral [9]. For instance, a smart phone or electronic entertainment device contains dozens of metallic elements and persistent organic elements, base metals like copper (Cu) and tin (Sn); special metals like lithium (Li) and indium (In); and precious metals such as silver (Ag), gold (Au), and palladium (Pd).

2.2.2 Heavy metal

The normal circuit boards in most of the electronic equipment and devices would contain heavy metal like lead (Pb), cadmium (Cd), mercury (Hg), and Hexavalent Chromium (Chromium VI) [2]. Lead is widely used in EEE. The negative effects of lead are well established and recognized [3]. The main applications of lead in electronic devices are: glass panels and gasket in computer monitors, solder in printed circuit boards, lead-acid batteries, some formulations of PVC. Some data showed that a typical 15-inch cathode ray tube may contain 1.5 pounds of lead, and other CRTs may have up to 8 pounds of lead. Cadmium usually in the form of Cadmiumoccurss. Cadmiumccriss usually found in certain components such as SMD chip resistors, infra-red detectors, semiconductor chips, light-sensitive resistors, corrosion-resistant alloys for marine and aviation environments, and nickel-cadmium batteries. Cadmium is also used in plastics stabilizer and some older cathode ray tubes contain cadmium. Mercury is also another heavy metal used in EEE. Mercury is a common material used in electronic equipment such as medical equipment, lamps, mobile phones, screens. Mercury is also used in electronic elements like thermostats, sensors, relays, switches, and batteries. As mercury would replace cathode ray tubes in flat panel displays, the usage of mercury would increase in the future. It’s estimated that more than one-fifth of mercury usage worldwide is used in electronic equipment manufacturing. Hexavalent Chromium (Chromium VI) Chromium VI is also a common material used in electronic equipment manufacturing, such as corrosion protection of untreated and galvanized steel plates, as a decorative or hardener for steel housings.
2.2.3 Persistent organic pollutants (POPs)
Brominated Flame Retardants (BFRs) [3]. BFRs used as flame retardants in plastics in most electronic products. Includes PBBs, PBDE. In electronics industry, nearly 50% usage of BFR consists of TBBPA, 10% is PBDEs and less than 1% is PBB. Polychlorinated biphenyls (PCBs). PCBs used as condensers, transformers and heat transfer fluids. Plastics including PVC (Polyvinyl chloride). Plastics would make up the major part of most electronic entertainment devices. The most usage of plastics is PVC [2]. Cabling and computer housings usually use lots of PVC. This is because, in these devices’ fire-retardant properties, PVC is the primary material. Dioxin can be generated when PVC is burned within a specific temperature, similar to other chlorine-containing compounds.

3. Hazards of E-waste

3.1 Hazards to the environment
E-waste has caused great harm and impact on the environment, which is mainly reflected in three aspects: air, water and soil.

3.1.1 air
When E-waste heats up, toxic chemicals will be released into the air and destroy the atmosphere. The damage to the atmosphere is one of the biggest effects of E-waste on the environment. E-waste pollution has a larger impact on some animal species than on others, putting the biodiversity of these species and some long-term contaminated regions in jeopardy. Particulate pollution is a significant environmental issue, owing to the presence of hazardous chemicals and trace metals in the air. Informal E-waste recycling, industrial point sources (such as mines, foundries, and smelters), and diffusion sources (such as vehicle emissions and fossil fuel burning) are the primary anthropogenic sources of heavy metals. Heavy metals become hazardous when their content surpasses the permissible limit. The presence of hazardous chemicals and trace metals in the atmosphere contributes to fine dust pollution, which is a major environmental issue. Informal trash recycling, industrial point sources (such as mines, foundries, and smelters), and diffusion sources such as vehicle emissions and fossil fuel burning are the primary anthropogenic sources of heavy metals [14]. Heavy metals can become hazardous if their concentration surpasses the permissible limit. Over time, air pollution will damage water quality, soil and plant species and cause irreversible damage to ecosystems. For example, Guiyu town in China is the largest E-waste disposal site in China and even the world, receiving toxic E-waste from all over the world. In the past, the vast electronic disassembly industry in Guiyu Town polluted the surrounding air, water, and land, resulting in a scarcity of birds in the sky and fish in the water. Entering Guiyu land by smelling “Guiyu flavor” was once the most straightforward and successful means of identification [15].

3.1.2 water
Heavy metals included in e-waste, such as mercury, lithium, lead, and barium, penetrate further into groundwater following soil contamination. These heavy metals eventually reach groundwater and end up in ponds, streams, rivers, and lakes. Water may get acidified and poisoned as a result of these routes, which is dangerous to animals, plants, and communities, even if they are kilometers away from a recycling bin. Finding clean drinking water gets more challenging. Acidification causes the death of marine and freshwater species, in addition to biodiversity disruption and ecological degradation. If there is acidification in the water supply, it may damage the ecosystem so that restoration is problematic, if not impossible.

3.1.3 soil
The soil will also be seriously affected. Heavy metals and flame retardants can directly penetrate into the soil from E-waste when it is not adequately treated in a normal landfill or illegal dumping site, polluting the subsurface groundwater or polluting the crops that could be cultivated. In the immediate vicinity or in the future, it will also affect the land and marine animals. When heavy metals contaminate
the soil, crops may easily absorb these poisons, resulting in a slew of illnesses and a reduction in farming productivity.

When large particles are released when E-waste is burned, crushed or dismantled, due to their size and weight, they will soon re-establish on the ground and contaminate the soil. Temperature, soil type, pH, and soil composition all play a role on the quantity of pollutants in the soil [16]. These contaminants can remain in the soil for an extended length of time, posing a threat to soil microbes and plant microbes. Animals and wildlife that rely on nature will eat the damaged plants in the end, causing internal health concerns.

3.2 Hazards to human body
In recent decades, electronic products have proliferated because they help us work more efficiently and live more conveniently. This should not be a problem in itself. In reality, living in an industrialized culture provides daily efficiency and convenience. The problem lies in how fast we abandon these products, whether they are broken or we simply want something more efficient and handy. Our human health is being harmed by throwing them away without thinking what will happen to their hazardous components.

Mercury, lead, cadmium, polybrominated flame retardants, barium, and lithium are among the hazardous components found in e-waste. The consequences of these poisons on humans include harm to the brain, heart, liver, kidneys, and bone system. It can also have a significant influence on human brain and reproductive systems, resulting in diseases and birth defects.

Only 10% of mobile phones in the United States are recycled, and most Americans replace their phones every 12 to 18 months. As a result, there is an increasing amount of E-waste [17]. E-environmental waste's concerns are growing as a result of a lack of proper recycling. The more electronic products we discard, the greater the harm to everyone's environment and health. Guiyu town in China is an excellent place to deal with E-waste today, but before, because to inadequate hygienic conditions, poverty, and informal working circumstances, residents showed serious digestive, neurological, respiratory and bone problems. For example, 80% of children in Guiyu suffer from respiratory diseases, especially the risk of lead poisoning [18]. The harm of E-waste to human body cannot be ignored.

4. Disposal measures

4.1 past regular process
In the last century, the main actions of disposal have been landfilling or incineration, but the environmental impact of these two methods is incalculable. Noted that most E-waste is disposed of informally at landfill sites. Most abandoned electronic items wind up in landfills with other municipal garbage or are burned in the open, releasing harmful and carcinogenic chemicals into the environment. In developing and transition nations, E-waste disposal in the informal sector is extremely primitive in terms of safe procedures and practices, resulting in poor material recovery. E-waste generation is estimated to be over 40 million metric tonnes per year worldwide, accounting for around 5% of total solid wastes [19].

The handling of E-waste differs in industrialized, developing, and transitional nations. Guidelines and education campaigns on the destiny of E-waste do not exist in developing and transition nations. Table 2 summarizes the treatment of e-waste in developed and developing countries. Obviously, developed countries will adopt less polluting electronic processing methods. Less complex disposal techniques, such as open burning and dump to uncontrolled landfill sites, are commonly utilised, resulting in considerable contamination and occupational exposure to E-waste-derived toxins [20].
Table 2 Comparison the different type of E-waste disposal system between developed and developing countries [21].

| Developed countries | Developing countries |
|---------------------|----------------------|
| Incineration with MAW | Opening burning |
| Landfill disposal | Open dumping |

4.2 Extraction and separation of heavy metals in industrial processes

As a result, recycling E-waste is vital and beneficial for environmental protection. E-waste comprises a variety of harmful elements such as metals, polymers, and refractory oxides, all hazardous to human health and environment condition, making E-waste treatment a must. The pyrometallurgical process might be a viable choice for improving recycling efficiency and reducing reactant usage. Experiment by Ojeda et al, they found that pyrometallurgical techniques, particularly selective chlorination processes, have shown to be more efficient and less expensive for the extraction and refinement of metals, creating increased interest in their use. Besides, by using an alternative technique like chlorination to recover gold from alluvial materials, environmental contamination concerns caused by gold extraction and concentration by other traditional methods may be avoided [22]. It is impossible to have a high efficiency in extraction, recyclability, and low-cost extraction procedure using any of the methods. The extraction and separation of platinum and palladium become important in the PCBs pollutants treatment. In recent technical studies, high metal extraction and separation rates (up to 90% or more) have been demonstrated, but the problems associated with such high separation rates are also visible. Table 3 illustrates and compares the different treatments of the same material (PCBs) based on the results of some previous studies. (e.g. problem from stripping, time consuming process, separation efficiency of other metals)

Table 3 The extraction and separation of Pd in PCBs from different exactment.

| Material | Leaching conditions | Advantages | Disadvantages | Reference |
|----------|---------------------|------------|---------------|-----------|
| PCBs     | H2SO4 and H2O2, H2O2 1%, NaClO 10%, HCl 2 mol/L | Pd 97.87% | Poor separation efficiency of Au and Ag | [23] |
| PCBs     | Aqua regia, Temperature = 25 °C, time = 3 h | Au 97%, Ag 98%, Pd 93% | Crucial Stripping problem | [24] |
| PCBs     | CuSO4+NaCl (Cu/Cu2+ ≥1.4), Temperature = 60 °C, time = 0.5 h | Pd 96.9% | Separation of Pd from stripping step. | [25] |
| PCBs     | Aqua regia, Organic solvent, Aliquat336, NaBH4, Temperature = 60 °C, time = 2 h, pH about 6.0 | Pd 100% | Time consuming process | [26] |

These are commonly used to make circuit board metals, their treatment measures are also very common. Using a comparable electrolytic cell, silver is routinely electro-refined. Typically, different lixiviants were used in an acid leaching method for the treatment of E-waste, followed by the separation of Ag and Cu, Sn. Among metal separation processes, the cementation method was shown high efficient for silver recovery. Xing et al [26] have suggested a combined pyro- and hydrometallurgy-based anode slime for effective metal recovery. Sulfuric acid was shown to be more efficient than HCl acid at recovering nickel from printed circuit boards. During nickel recovery, however, nickel-related causes human health risks and environmental issues are prerequisite. Gas purification systems for dioxin, furans, waste gas disposal, and slag disposal all require special attention. For metal recovery from trash, a biological method may minimise energy usage and negative environmental impact.
4.3 Metal recovery through a biological method

Bioleaching refers to a natural process with a variety of microorganisms, including chemo lithotrophic, heterotrophic, and fungi, dissolve metals from E-waste. Biosorption, a metabolically independent process that includes precipitation, complexation, adsorption, and ion exchange. Separation of materials is accomplished by autotrophic, heterotrophic, or chemical leaching. Taking advantages from those benefits of heterotrophic, autotrophic, or chemical leaching, metals from E-waste might be recovered. The two primary steps in the biological process are the growth of microorganisms without the inclusion of E-waste and the put E-waste powder into the reactor. The first stage involves the interaction of organic sugar and acid with E-waste powder, and the second stage involves the development of microorganisms. Heavy metals may be recovered selectively from electronic trash using these methods. The experiment reported by Gu et al [27], their research employed a unique simplified material (nitrogen-doped carbon nanotubes (NCNTs) modified electrode) to increase the copper bioleaching efficiency of Acidithiobacillus ferrooxidans (A. ferrooxidans) from waste printed circuit board (WPCB). Inorganic acid and enzymes might be used to convert Fe^{2+} to Fe^{3+} during the bioleaching process. The generation of H^{+} during the oxidation of metallic sulphide to sulphate by Fe^{3+} speeds up the bioleaching reaction process. It should be mentioned that the bioleaching process is accelerated by the generation of Fe^{3+} by A. ferrooxidans and A. thiooxidans.

The typical fungus used to extract gold and silver from E-waste is Aspergillus niger. The leaching agents generated by the Aspergillus niger are gluconic acid and citric acid, respectively. Bacterium produced ligands through the chelation process, which started the adsorption of metal ions in the biosorption process [28]. Using A. niger as an adsorbent, extraction of mental from E-waste. Metals are leached by bacteria in both aerobic and anaerobic environments. The solid-liquid ratio, temperature, and pH of the solution might all influence the process. Many microorganisms employed in the metals extraction from E-waste. In comparison to traditional approaches, microorganisms have evolved to more environmentally friendly living circumstances. On the other hand, speed of metal dissolving with bacteria is much slower. Because of its low environmental effect, biotechnology has been highlighted as a potential technique in noble metal extraction from E-waste.

5. Regulation E-waste contribute to SDGs

5.1 The link between technology and development

In the developed world, value recovery is done in centralized facilities using advanced technologies in a highly regulated industrial environment; from the developing world, value recovery is done in a largely unregulated artisanal industry using simplistic, labor-intensive, and environmentally hazardous methods. As a result, value is created securely in the developed world's hi-tech environment, whereas environmental liabilities connected with exporting trash and residual pollution from simple processing are primarily borne by underdeveloped countries. To enhance waste management methods in developing nations, strict regulatory frameworks are necessary that do not clash with waste management aims, such as E-waste collection from households. These rules, in combination with customized EPR schemes based on the local economy, might result in waste management systems that are simple to implement and offer optimum value to all stakeholders.

5.2 Synergy between environment and economy

The recycling trend is significant in terms of maximizing precious metal recovery while minimizing environmental effect. The separation of noble metals can be used as a source of revenue for long-term growth. The greatest option will be for industry participants to take a "proactive route" toward more sustainable production and consumption. Manufacturers may take the lead by developing novel business models that prioritize electronic device lifespan extension and reuse. Despite the inevitable rise in the usage of electronics, this transition to more circular business practices will decrease the negative effects of E-waste and assist to avoid E-waste creation. Many SDGs, including SDG 8 on decent employment and economic growth, SDG 3 on excellent health and well-being, SDG 6 on clean waste and sanitation,
and SDG 14 on life below water, are intimately linked to E-waste management. E-waste is also strongly related to the SDG indicators on the material footprint and the SDGs on domestic material consumption, given the high raw material requirement in manufacturing of EEE. Rapid urbanization, with more than half of the world's population living in cities, necessitates innovative solutions to manage growing environmental and human life hazards, particularly in high density population area. Because cities can create most of the E-waste, it is critical to effectively manage E-waste in urban areas, increase collection and recycling rates, and reduce the quantity of e-waste dumped in landfills. In 2030, the global goal is to ensure that chemicals and their waste are managed in an environmentally sound manner throughout their life cycles, in full compliance with internationally agreement frameworks, and to significantly reduce their discharge into air, water, and soil to mitigate their negative effects on human health and the environment.

6. Conclusion
E-waste has become a serious and concerning pollution problem worldwide due to its fast generating and colossal volume. Meanwhile, E-waste contains different kinds of pollutants that can cause irreparable damage to the environment and human health. This paper first showed that E-waste could be classified into six major categories and listed its primary component: non-hazardous materials, heavy metals, and persistent organic pollutants (POPs). Because E-waste classification could help better manage them and determine their disposal. Then, to study E-waste’s hazard to the environment and human health better, this paper analyzed E-waste polluting route in air, water, and soil. Generally, those harmful substances can pollute the environment through burning and directly released into the air, untreated drainage directly penetrating and leaking into water and soil. Ultimately, those polluted environments with poor management would endanger human health. The current E-waste management goes through few stages, from direct landfill to chemical disposal, and now, we can have a more environment-friendly choice- bioleaching. This paper also reviewed these management’s disadvantages. Most of them are low-efficient, high-cost, and can cause adverse effects on the environment. Therefore, we seek more feasible, eco-friendly, and cost-effective management to treat our E-waste. Furthermore, it is essential to link E-waste management with Sustainable Development Goals (SDGs), which can reduce E-waste’s harm and make the electronic industry more practical and in line with future development.

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