Environment Protection Engineering

Vol. 51 2025 No. 4

DOI: 10.37190/epe/208488

HE ZHANG (ORCID: 0009-0008-9706-0240)[1]
ALEKSANDRA E. JACHIMOWICZ (ORCID: 0009-0004-1678-234X)[2]

MULTIDISCIPLINARY STRATEGIES FOR SUSTAINABLE -WASTE MANAGEMENT FROM END-OF-LIFE COMPUTERS. ADDRESSING CHALLENGES OF TECHNOLOGICAL INNOVATION AND RAPID OBSOLESCENCE IN THE DIGITAL ERA

This review comprehensively analyzes the current situation, problems, and solution strategies of e-waste management. With the rapid development of computer technology, the quantity of e-waste has increased dramatically, and the current recycling system is not perfect, resulting in a large amount of e-waste not being properly handled. E-waste contains a large number of hazardous substances, if not properly handled, will seriously pollute the soil, water, and air, posing a threat to human health, but also cause a waste of resources. In order to solve these problems, the article proposes a variety of strategies, such as multidisciplinary cooperation, improvement of the recycling system, technological innovation, policies and regulations, economic incentives, and public participation and education. Among them, improving public environmental awareness and participation is the key to the success of e-waste management, and community activities play an important role in e-waste management by providing a platform for public participation. Through multifaceted measures, the sustainable development of e-waste management can be effectively promoted.

1. INTRODUCTION

With the progress of the times, computer technology has experienced unprecedented rapid development and wide application. From the initial simple computing tool to today's intelligent system integrating data processing, network communication, artificial intelligence and other diversified functions, computer technology has not only revolutionized the way we work, but also profoundly affected daily life, education, medical care, entertainment and many other fields (Fig. 1). The rapid progress in this field has

[1]Department of Computer Science, City University of Hong Kong, Kowloon City, Hong Kong SAR, corresponding author, email address: hzhang832-c@my.cityu.edu.hk

[2]Department of Biochemistry and Cell Biology, Stony Brook University, New York, United States.

not only greatly improved productivity and quality of life, but also provided strong technological support for the sustained growth of the global economy and social progress.

Fig. 1. Computerized e-waste in the context of the modernization process

With the advancement of science and technology and the widespread use of electronic products in all walks of life, the demand for electronic equipment such as computers has risen sharply. The constant emergence of new technologies and the rapid iteration of new products have greatly accelerated the consumption of electronic equipment, resulting in a large amount of e-waste. Due to limitations in technology, materials, and processes, many computers and other electronic products have a relatively short service life. Frequent product updates result in a large number of devices still within the usable range being eliminated prematurely, increasing the amount of e-waste [1]. In terms of equipment maintenance, due to the high cost, lack of talent, and other issues, many people choose to directly discard rather than repair the equipment after failure. In terms of recycling and treatment, there is a lack of a perfect recycling system and effective means of treatment, resulting in a large amount of e-waste not being properly treated.

Electronic equipment, such as computers, contain a large number of hazardous substances such as heavy metals (lead, mercury, cadmium, etc.) and organic pollutants [2]. If not handled properly, these hazardous substances may leach into soil and water sources, causing long-term harm to the environment and human health. E-waste contains a large amount of valuable metals and other materials, which, if not effectively recycled and reused, will lead to a serious waste of resources. Through recycling, these materials can be reintroduced into the production cycle, reducing the need for new raw materials. The recycling and treatment of computer e-waste helps to promote the development of a circular economy and the sustainable use of resources. This not only helps to reduce production costs but also reduces the exploitation and destruction of natural resources.

2. COMPUTER E-WASTE DEFINITION AND COMPOSITION

Waste from computers is a complex and important environmental issue. Through rational classification, dismantling, and recycling treatment, the hazards of e-waste to the environment and human health can be effectively reduced, while the reuse of resources and sustainable development can be realized [3, 4].

Electronic waste, commonly known as e-waste, refers to electrical or electronic equipment that is no longer in use [5]. These devices usually use electric current or electromagnetic fields to operate, including household appliances, communication electronics, computers, and their parts. There is a wide variety of e-waste, ranging from simple household appliances to complex communications and computing equipment [6]

Computer e-waste is an important part of e-waste, mainly including the following categories:

- *Waste computer mainframes*. Computer mainframes are the core part of a computer system and contain key components such as processors, memory, and hard disks. Used computer mainframes usually contain a variety of metals and plastic materials, as well as potentially hazardous substances such as heavy metals and brominated flame retardants [7].
- *Monitors*. Monitors are computer output devices used to display images and text. Common types of monitors include cathode ray tube (CRT) monitors and liquid crystal displays [8]. CRT monitors contain hazardous substances such as lead and cadmium, while LCD monitors contain hazardous substances such as mercury.
- *Keyboards and mice*. Keyboards and mice are computer input devices used to enter commands and data. These devices usually contain materials such as plastics, metals, and circuit boards, some of which may contain hazardous substances [9].
- *Other computer components*. In addition to the major components listed above, computer e-waste also includes peripheral devices and parts such as printers, scanners, routers, switches, etc. These devices contain a variety of materials and may contain hazardous substances. These devices also contain a wide range of materials and potentially hazardous substances. These and additional ones can be read in Table 1.

Different types of e-waste have different characteristics and treatment difficulties. For example, cell phones and tablet computers, these devices usually contain high-value metal and plastic materials, as well as potentially hazardous substances. Specialized techniques and equipment are required when handling these wastes to ensure safe and effective recycling. Computer-related waste usually contains a wide range of metal and plastic materials, as well as complex components such as circuit boards.

Table 1

PC e-waste, features, and processing difficulties

Classification of e-waste	Features	Processing difficulties
Used computer mainframe	the main board, the central processing unit (CPU), hard disk and other core components, with high recyclable value	medium, professional disassembly required to avoid damage to internal components
Display	a display screen and a circuit board, with various types of display screen processors	medium, the display processor needs to be specially processed
Keyboard	the structure relatively simple, containing plastic and metal	lower, easy to disassemble and sort for recycling
Mouse	circuit boards and small motors, and the working principle of optoelectronics or lasers	low, plastic, metal, and circuit boards can be recycled separately after disassembly
Printer	cartridges, toner cartridges, and circuit boards, with high recycling value for ink cartridges	medium, need to separate the ink cartridge and other components
Copier	the structure complex, containing multiple circuit boards and mechanical components	complex, requires professional disassembly and separation of each component
Others (connecting wires, power supplies, etc.)	plastics as the main components and metals, with low recycling value	lower, easy to disassemble and sort for recycling

Disposal requires disassembly into different components for recycling and reuse. Since computer e-waste may contain hazardous substances, such as heavy metals and brominated flame retardants, special care needs to be taken when disposing of it to avoid harming the environment and human health [10].

The difficulty in handling computer e-waste depends largely on its type and complexity. Some simple electronic equipment may be easier to dismantle and recycle, while some complex electronic equipment may require more advanced technology and equipment for treatment. In addition, hazardous substances in e-waste may also add to the difficulty and cost of treatment (Fig. 2). Therefore, when handling e-waste, it is necessary to use specialized techniques and equipment and follow relevant environmental regulations and standards to ensure safe and effective recycling and reuse [11].

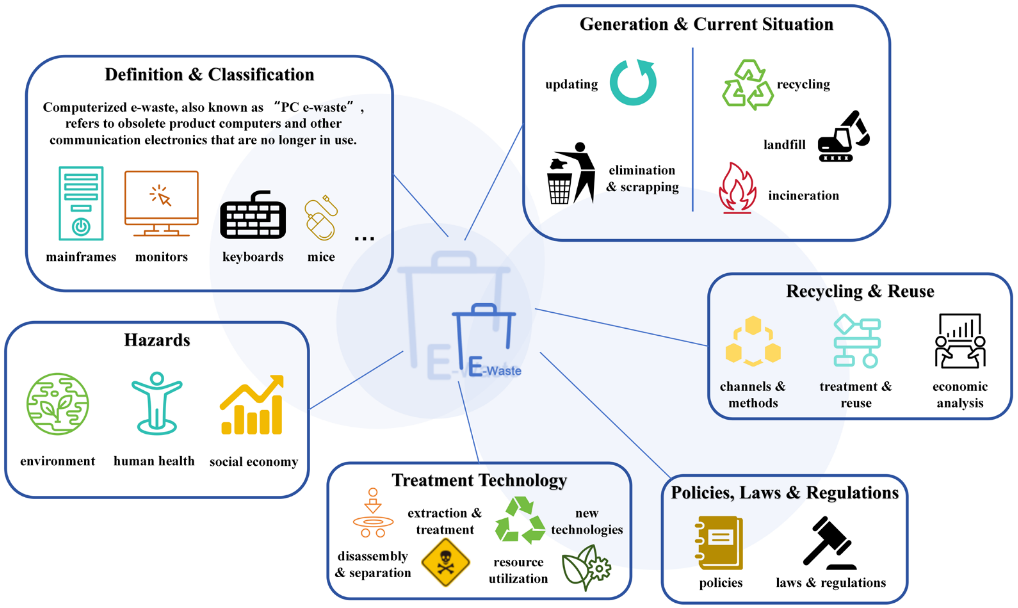

Fig. 2. E-waste from decommissioning computers in the rapidly evolving information age

3. GENERATION AND STATUS OF COMPUTER E-WASTE

With the rapid development of information technology and the continuous growth of the global economy, the generation of computer e-waste has shown a phenomenal growth trend. Globally, the amount of e-waste generated annually has reached tens of millions of tons, of which computer e-waste occupies a considerable proportion. According to the United Nations Environment Program (UNEP) and the International Telecommunication Union (ITU), and other organizations, the annual growth rate of global e-waste is as high as 5–10%, and the growth rate of computer e-waste is even higher than the average [12, 13].

Domestically, with the increasing popularity of computers and the accelerating speed of replacement, the amount of computer e-waste generated is also increasing rapidly. According to the statistics of relevant organizations, computer e-waste occupies a considerable share of the e-waste generated in Asia every year, and shows a year-on-year growth trend. This growth trend not only reflects the rapid development of the computer industry in Asia but also reveals the serious challenges faced by e-waste disposal [14].

Computer e-waste comes from a variety of sources, including the following: first, with the continuous progress of computer technology and the emergence of new products, many users will regularly replace computer equipment in order to pursue higher performance and better experience [15]. These replaced old devices often become part of e-waste. Secondly, some computer equipment is phased out and scrapped because it can no longer meet the needs of users due to prolonged use, declining performance, or damage. These devices also become a source of e-waste.

With the restructuring of business and upgrading of technology, some enterprises will eliminate old computer equipment in order to replace it with more advanced and efficient equipment. This obsolete equipment likewise needs to be disposed of properly [16].

In the face of growing computer e-waste, countries are actively exploring effective treatment methods and approaches. At present, recycling is one of the most important ways to deal with computer e-waste. Through recycling, the useful substances in the waste can be reused, and the waste of resources can be reduced [17]. At the same time, recycling can also help avoid harmful substances from causing harm to the environment and human health. However, since computer e-waste contains a variety of complex materials and hazardous substances, the recycling process requires the use of specialized techniques and equipment to ensure safe and effective recycling.

While landfilling is a traditional waste disposal method, landfilling is not an ideal choice for computer e-waste [18]. Because computer e-waste contains many hazardous substances, landfills may leach into soil and groundwater, causing long-term harm to the environment and human health [19]. Therefore, landfilling of computer e-waste is restricted or prohibited in many countries and regions. Incineration is a treatment method that burns waste at high temperatures [20]. Although incineration can reduce the volume and weight of waste, the incineration process produces a large amount of harmful gases and soot, which is harmful to the environment and human health [21]. Therefore, incineration is also not a recommended treatment method for computer e-waste.

4. HAZARDS OF COMPUTER E-WASTE

The hazards of computer e-waste are multifaceted and far-reaching. It not only poses a serious threat to the natural environment but also has far-reaching impacts on human health and socio-economics. In order to mitigate these hazards, we need to strengthen the recycling and treatment of e-waste, improve resource utilization, and raise environmental protection awareness. At the same time, the government and enterprises also need to strengthen cooperation and supervision to promote the standardization and professional treatment of e-waste.

The harm of computer e-waste to the environment is mainly reflected in soil pollution, water pollution, and air pollution [22]. When e-waste is casually discarded or landfilled, the heavy metals (e.g., lead, mercury, cadmium, etc.) and other hazardous substances in it will penetrate into the soil, change the structure and fertility of the soil, and lead to soil pollution. This pollution not only affects plant growth but may also enter the human body through the food chain, posing a threat to human health.

Hazardous substances in e-waste can enter underground and surface water bodies under the action of rainwater flushing and waste leachate, resulting in water pollution. These hazardous substances are difficult to degrade in water and will persist for a long time, causing harm to aquatic organisms and human drinking water sources. During the incineration of e-waste, a large amount of harmful gases and particulate matter, such as sulfur dioxide, nitrogen oxides, and dioxins, will be released [23]. These pollutants not only pollute the atmospheric environment, but also may enter the human body through respiration and harm human health.

The harm of computer electronic waste to human health is mainly reflected in the release of toxic substances and heavy metal pollution. E-waste contains a variety of toxic substances, such as brominated flame retardants and polyvinyl chloride [24]. These substances are released into the environment during incineration or improper disposal, which is hazardous to human health. Long-term exposure to these toxic substances may lead to respiratory diseases, neurological diseases, and cancer, etc. Heavy metals in e-waste are extremely hazardous to human health. Heavy metals are difficult to metabolize and excrete in the human body and can accumulate and cause damage to human organs and systems over time [25]. For example, lead poisoning may lead to mental retardation, anemia, and neurological damage in children; mercury poisoning may lead to kidney damage, neurological symptoms, and reproductive system diseases [26].

The harm of computer e-waste to the social economy is mainly reflected in the waste of resources and economic losses. E-waste contains a large amount of useful substances, such as metal, plastic, and glass [27]. If these wastes are not effectively recycled and utilized, it will cause a great waste of resources. At the same time, with the speed of renewal of electronic products, the amount of waste generated is also increasing, and the problem of resource waste is becoming more and more serious. The treatment of electronic waste requires the investment of large amounts of human, material, and financial resources. If it is not handled properly, it will not only cause environmental pollution and human health hazards, but also bring economic losses to the state and enterprises.

5. COMPUTER E-WASTE TREATMENT TECHNOLOGY

Treatment technologies for computer e-waste are advancing with the development of technology and environmental awareness. With the continuous progress of science and technology and the enhancement of environmental protection awareness, the research and development of new treatment technology will become an important driving force to promote the development of the e-waste treatment industry.

The disassembly and separation technology of waste computers is the first and most critical step in the treatment of e-waste. Scrap computers are disassembled into different components, such as motherboards, monitors, hard disks, power supplies, etc., by hand or using specialized tools [28]. This step requires delicate handling to avoid damage to the components, thus facilitating subsequent separation and recycling. The disassembled components are further separated into different materials such as metal, plastic, glass, etc. This step usually requires the use of specific separation equipment and techniques, such as magnetic separation, air separation, flotation, etc., to improve separation efficiency and purity [29]. During disassembly and separation, hazardous components such as batteries, capacitors, fluorescent tubes, etc. need to be identified and properly disposed of. These components contain hazardous substances, such as heavy metals, mercury, cadmium, etc., and require specialized treatment technologies for harmless treatment.

Waste computers contain a variety of hazardous substances, such as heavy metals, brominated flame retardants, polyvinyl chloride, and so on. The extraction and treatment of these substances is an important link to ensure the harmlessness of e-waste. Heavy metals, such as lead, mercury, cadmium, etc., are extracted from used computers by chemical or physical methods. The extracted heavy metals can be utilized for resource utilization or safe disposal [30]. For hazardous substances that cannot be extracted or resourcefully utilized, harmless treatment technologies such as incineration, solidification, and landfill are required. These technologies need to ensure that there is no secondary pollution to the environment during treatment. During the treatment process, real-time monitoring and evaluation of the discharged pollutants are needed to ensure that the treatment effect meets the environmental standards.

Resource utilization technology is one of the core technologies of e-waste treatment, aiming to recover and reuse the useful substances in the waste computer. Waste computers contain a large number of metal elements, such as copper, aluminum, iron and so on. Through metal recycling technology, these metal elements can be separated from the waste and utilized for resource utilization. Plastic parts in waste computers can be recycled through crushing, cleaning, melting and other steps to obtain new plastic raw materials [31]. These raw materials can be used in the production of new plastic products to realize the recycling of resources. In addition to metals and plastics, scrap computers contain other materials such as glass and rubber. These materials can also be resourcefully utilized through the corresponding recycling technology.

With the continuous progress of science and technology and the continuous improvement of environmental protection requirements, the research and development of new treatment technology has become an important direction in the field of electronic waste treatment. The use of microorganisms or plants and other organisms degrade or transform the harmful substances in e-waste, in order to achieve harmless and resourceful use. Supercritical fluids (e.g., carbon dioxide) are used to extract and separate useful substances in e-waste to improve the recovery efficiency and purity [32, 33]. Combining robotics, artificial intelligence and other technologies to realize intelligent disassembly and separation of waste computers improve processing efficiency and accuracy. Construct a closed-loop system for e-waste that connects recycling, treatment, and resource reuse to establish a complete industrial chain.

6. RECYCLING AND REUSE OF COMPUTER E-WASTE

Recycling and reuse of computer e-waste is an important part of resource recycling and environmental protection, and has important economic and environmental significance. The healthy development of e-waste recycling and reuse industry can be promoted by constructing diversified recycling channels, perfecting the treatment process, improving the efficiency of resource utilization and strengthening policy support.

Computer e-waste recycling channels and methods are diverse, mainly including government recycling, enterprise recycling and community recycling. The government usually establishes specialized e-waste recycling centers or commissions third-party organizations to carry out recycling [34]. These recycling points are usually located in the main areas of cities or communities for the convenience of the public to drop off. The government also raises public awareness and participation in e-waste recycling through publicity and education campaigns. Many electronic product manufacturers and retailers provide recycling services. They usually offer recycling options for old products when selling new products to encourage consumers to participate in recycling activities [35].

Moreover, some companies cooperate with professional recycling organizations to establish long-term and stable recycling partnerships. Community recycling is an important complement to e-waste recycling. Communities usually organize regular recycling activities, such as "e-waste recycling day", inviting residents to bring their e-waste to designated places for recycling. In addition, some communities also set up fixed recycling bins or recycling stations for residents to drop off their e-waste at any time.

After recycling, computer e-waste goes through a series of treatment processes to achieve its reuse. Recycled e-waste will first be initially categorized and classified according to different types of waste. Then, professionals will test the waste to assess its reuse value. For e-waste with reuse value, it will be disassembled and separated. This step aims to separate useful substances (e.g., metals, plastics, etc.) from the waste for subsequent reuse. The separated useful substances are then utilized for resource utilization. For example, metals can be smelted and remade into new metal products; plastics can be processed into recycled plastic pellets for the production of new plastic products [36].

In addition, some components of e-waste (e.g., circuit boards, chips, etc.) can be repaired and reused. For e-waste that cannot be reused, it is treated in an environmentally sound manner. This usually includes incineration, landfill, and other treatment methods to ensure that the waste does not pose a hazard to the environment and human health. However, as environmental awareness increases, harmless treatment technologies are being developed and improved to minimize negative impacts on the environment.

Recycling and reuse of computer e-waste has significant economic. By recycling and reusing e-waste, the need for new resources can be reduced, thus saving production costs. In addition, the recycling process reduces waste disposal costs and lowers the operating costs of businesses. The recycling and treatment of e-waste is a huge industrial chain, involving dismantling, separation, resource utilization and other links [37]. This creates a large number of employment opportunities for society and promotes economic development. Recycling and reuse of e-waste is an important part of the circular economy. By realizing the recycling of resources, it can reduce the dependence on natural resources, reduce environmental pollution, and promote the sustainable development of the economy.

In order to encourage the recycling and reuse of e-waste, many countries and regions have introduced relevant policies. These policies usually include measures such as tax incentives and subsidies and rewards to reduce the operating costs of recycling enterprises and improve their market competitiveness.

7. POLICIES AND REGULATIONS ON COMPUTER E-WASTE

Globally, the treatment of computer e-waste has become a topic of great concern. Governments and international organizations have introduced a series of policies and regulations aimed at regulating the process of e-waste disposal, reducing environmental pollution and promoting the recycling of resources.

The European Union (EU) is a pioneer in e-waste legislation. As early as 2003, the EU promulgated the *Directive on Waste Electrical and Electronic Equipment* (WEEE Directive) and the *Directive on Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment* (RoHS Directive) [38].The WEEE Directive requires member states to establish a system of collection, recycling, treatment, and reuse of e-waste, while the RoHS Directive restricts the use of lead, mercury, cadmium, and other hazardous substances in electrical and electronic equipment. The implementation of these directives has significantly improved the recycling rate and treatment efficiency of e-waste in the EU.

In the United States, although there is no uniform e-waste legislation at the federal level, state governments have taken a series of measures to address the e-waste problem. For example, California has implemented an e-waste recycling law that requires manufacturers to take responsibility for recycling and establish a system for recycling and reuse of e-waste [39, 40]. In addition, the U.S. Environmental Protection Agency (EPA) has issued a series of guidelines and standards to guide the treatment and management of e-waste.

Japan has also put in place stringent regulations on the treatment of e-waste. The Japanese government has enacted the Household Appliance Recycling Law and the

Small Household Appliance Recycling Law, which require manufacturers and importers to take responsibility for recycling and establish a recycling and reuse system [41]. At the same time, the Japanese government also encourages enterprises and individuals to actively participate in the recycling and treatment of e-waste through economic incentives, such as the provision of recycling subsidies and tax incentives.

Although governments and international organizations have introduced a series of policies and regulations to deal with the e-waste problem, there are still some problems and challenges in the actual implementation process. On the one hand, the e-waste recycling and treatment systems in some countries and regions are not yet perfect. In some regions, there is a lack of adequate recycling facilities and specialized personnel, which prevents e-waste from being handled in a timely and effective manner. In addition, the high cost of recycling and treatment in some regions also limits the recycling rate and treatment efficiency of e-waste. On the other hand, the problem of illegal treatment and dumping of e-waste still exists. Some unscrupulous enterprises and individuals discard or illegally dump e-waste in order to reduce costs, which poses a serious threat to the environment and human health [42]. In addition, insufficient supervision in some areas has also exacerbated the problem of illegal handling and dumping of e-waste.

In order to further improve the e-waste treatment policies and regulations, and to increase the recycling rate and treatment efficiency of e-waste, the following are some policy recommendations and directions for improvement: governments should strengthen international cooperation and communication to jointly address the e-waste problem [43]. Promote the development and innovation of global e-waste treatment technology by sharing experience and technology. Then, governments should further improve the e-waste recycling and treatment system, increase recycling facilities and professionals, and improve the efficiency of recycling and treatment. At the same time, they should strengthen the supervision of recycling and treatment enterprises to ensure that they comply with environmental protection requirements and safe operation norms.

Governments should strengthen legislation and law enforcement and formulate stricter regulations and standards for e-waste treatment. At the same time, penalties for violations should be increased to curb the illegal treatment and dumping of e-waste. Governments should actively promote advanced e-waste treatment technologies, such as resource utilization and harmless treatment. Through technological innovation and industrial upgrading, improve the treatment efficiency and environmental protection level of e-waste [44]. Finally, governments should actively carry out environmental education activities to improve public awareness and participation in environmental protection.

Through publicity and education, the public should be guided to actively participate in the recycling and treatment of e-waste, so as to jointly promote the development of a green economy and the realization of sustainable development goals.

8. SOCIAL EQUITY AND JUSTICE IN ELECTRONIC WASTE MANAGEMENT

The impacts of e-waste management on developing countries and vulnerable groups are manifold. First, environmental pollution is a notable problem. E-waste contains a large number of hazardous substances, such as lead, mercury, cadmium and other heavy metals, and organic pollutants such as polychlorinated biphenyls (PCBs) and brominated flame retardants, which can use receptor model (i.e. Positive Matrix Factorization aka PMF) for future ingredient source testing [45]. In developing countries, these wastes are often not properly disposed of due to a lack of treatment technology and infrastructure, leading to the leaching of hazardous substances into the soil, water and air and causing long-term pollution of the ecosystem. For example, in some African and Asian countries, e-waste is dumped or incinerated at will, releasing toxic gases and particulate matter, seriously polluting the local environment and affecting the quality of life of residents [46].

Secondly, health risks cannot be ignored. Vulnerable groups, such as women and children, face higher health risks in e-waste management [47]. They often work in the informal recycling industry, lack the necessary safety measures and come into direct contact with toxic substances. The World Health Organization warns that hazardous substances in e-waste can lead to increased risk of respiratory problems, nerve damage, kidney disease and cancer. Children, whose bodies are not fully developed, are more sensitive to these toxic substances and may face cognitive impairment, developmental delays and long-term health complications [48].

In addition, the economic burden is an important challenge faced by developing countries in the management of e-waste. The treatment of e-waste requires high costs, including in terms of technological inputs, infrastructure development and personnel training. Developing countries often find it difficult to bear these costs due to their limited economic conditions, leading to inefficiencies in e-waste treatment [49]. This not only exacerbates environmental pollution and health risks, but also hinders a country's economic development. Developing countries also face other challenges in e-waste management, such as outdated technology and inadequate regulations. Lagging technology prevents developing countries from effectively extracting valuable resources from e-waste and safely disposing of hazardous substances. Inadequate regulations have led to illegal dumping and improper disposal, further aggravating environmental pollution and health risks [49].

International cooperation plays an important role in addressing these issues. Through international cooperation, developing countries can obtain assistance in technology transfer, financial support and regulation development to improve the capacity and efficiency of e-waste treatment. For example, some international organizations and non-governmental organizations have helped developing countries to establish better e-waste treatment systems by providing training and technical support. At the same time, international cooperation has also promoted the standardization and normalization of e-waste management on a global scale, which has helped to reduce illegal dumping and improper disposal [50].

In conclusion, e-waste management has far-reaching implications for developing countries and vulnerable groups. Developing countries face multifaceted challenges in e-waste management, and there is a need for enhanced international cooperation to jointly address these challenges. Through technology transfer, financial support and the development of regulations, the e-waste treatment capacity of developing countries can be improved, vulnerable groups can be protected from e-waste hazards and sustainable development of the global environment can be promoted.

9. ECONOMIC INCENTIVE MECHANISMS FOR SUSTAINABLE DEVELOPMENT OF ELECTRONIC WASTE

The French WEEE system is centered on Extended Producer Responsibility (EPR), which requires producers of electronic products to take responsibility for the environmental impacts of their products throughout their life cycle, including recycling and disposal [51]. The system requires producers to register and join producer responsibility organizations (PROs), pay recycling fees based on product category and weight, and set recycling targets that increase year by year [52]. Our study has compiled data from various countries over the past 20 years into charts for intuitive judgment (Table 2).

Table 1

e-waste recycling subsidies. Trends (2003–2023)

Country /Region	Early 2000s	2010s	2020s	Key policies
EU	€10–30 M/year (WEEE Directive 2003)	€50–100 M/year	€100–200 M/year	WEEE Directive updates, Circular Economy Action Plan
United States	state programs only (e.g., CA: < $50M)	CA: ~100 M/year, NY/TX: 100 M/year, NY/TX: 10–20 M/year	CA: $180M (2020), federal grants (IRA)	state-led Extended Procedure Responsibility (EPR) laws, Inflation Reduction Act (IRA) funding
Japan	~$5 M/year (2001 Recycling Law)	~$20 M/year	~$30–50 M/year	Home Appliance Recycling Law (consumer fees)
China	minimal (informal recycling)	$50–100 M/year (2011 E-Waste Fund)	$300–500 M/year	2012 E-Waste Regulations, subsidies per ton
South Korea	~$5 M/year (2008 EPR system)	~$20 M/year	~$30–40 M/year	Extended Producer Responsibility (EPR)
India	negligible	~$5 M/year (2016 e-waste rules)	~$10–20 M/year	E-Waste Management Rules, pilot projects
Australia	none (pre-2011)	~$10 M/year (2012 NTCRS)	~$20 M/year	National Television and Computer Recycling Scheme

Economic incentives play a significant role in this system, with the government guiding the orderly development of the recycling industry by levying a fund on producers and granting fixed subsidies to recycling and disposal companies. This mechanism not only incentivizes producers to improve product design to promote recycling, but also increases the motivation of consumers to participate in recycling.

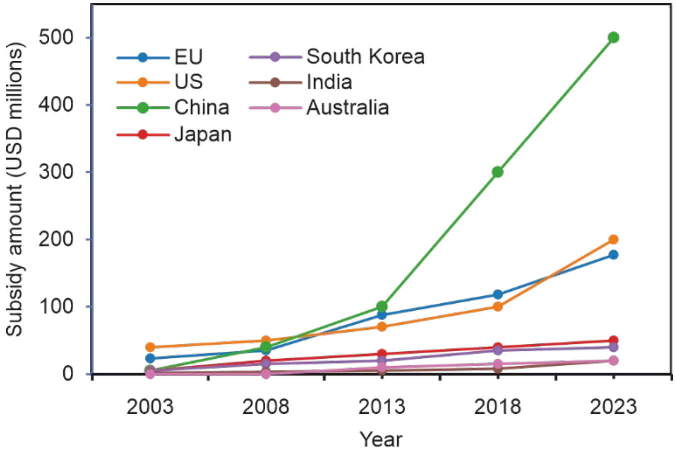

Fig. 3. E-waste recycling subsidies by country (2003–2023)

The trends in global e-waste recycling subsidies over the past two decades highlight a dynamic interplay of policy ambition, technological demand, and geopolitical priorities (Fig. 3). China s subsidies have grown exponentially, from 5 million in 2003 to 100 million in 2013, and then to 500 million in 2023, driven by its 2012 Electronic Waste Management Regulations and circular economy goals, aimed at formalizing recycling in rapid urbanization and technological consumption. The EU, leveraging the WEEE Directive and Circular Economy Action Plan, achieved steady growth through cross--border collaboration and producer responsibility frameworks.

In contrast, the U.S. exhibited state-led variability, with California dominating funding via consumer fees, later supplemented by federal grants under the Inflation Reduction Act. Japan and South Korea maintained moderate growth through consumer-funded systems and R&D investments in critical material recovery, while India's delayed progress reflected challenges in transitioning from informal recycling dominance to formalized systems. Regional disparities persisted, with Africa and Latin America lagging due to weak regulations and fiscal constraints.

Key challenges included data transparency gaps (e.g., underreported subsidies in India), inflation distortions, and COVID-19 disruptions, as seen in Australia's plateaued funding. Looking ahead, China is poised to maintain dominance with aggressive recycling targets, while the EU will focus on tech-driven solutions for AI and IoT waste.

Developing nations may see growth if international aid and policy reforms address informal sector reliance and funding gaps. Ultimately, bridging these disparities demands global coordination, standardized reporting, and robust public-private partnerships to align economic and environmental goals in the e-waste sector.

Government subsidies directly affect the efficiency and effectiveness of the e-waste recycling system[53]. On the one hand, subsidies directly reduce the operating costs of recycling and processing enterprises, increase their willingness and ability to recycle, and thus boost the overall recycling volume. Subsidies promote technological innovation and industrial upgrading, prompting enterprises to adopt more efficient recycling technologies and equipment, and improving the utilization rate of resource recycling [54]. However, subsidy policy also has certain disadvantages, such as increasing the government's financial burden, and long-term subsidies may weaken the market's own regulatory function, leading to enterprises' dependence on subsidies.

Different subsidy strategies have their own advantages and disadvantages. The direct subsidy strategy can quickly mobilize enterprises, but it lacks specificity and may not be able to accurately solve the key problems in the recycling system [55]. The tax incentive strategy incentivizes recycling by lowering the tax burden on firms, but its effectiveness is highly affected by tax policy adjustments [56]. The loan preference strategy, on the other hand, provides financial support to enterprises, but may increase financial risks. Therefore, when formulating the subsidy strategy, it is necessary to comprehensively consider the policy objectives, financial situation and market response to form a diversified incentive mechanism in order to promote the sustainable development of the e-waste recycling system.

10. PUBLIC PARTICIPATION AND EDUCATION ON SUSTAINABLE E-WASTE RECYCLING AND UTILIZATION

Raising public awareness of and participation in e-waste issues is an indispensable part of e-waste management and is important in a number of ways. E-waste contains a large number of hazardous substances, such as heavy metals and organic pollutants, which, if not handled properly, can cause serious pollution of soil, water and air, thereby jeopardizing human health. By raising public awareness, the hazards of e-waste can be fully understood so that they can enhance their environmental awareness and sense of responsibility and take the initiative to participate in the proper handling and recycling of e-waste [57]. Such participation not only helps to reduce environmental pollution, but also promotes the recycling of resources and sustainable development.

Effective public participation strategies are crucial to increasing public awareness and participation. Publicity and education are indispensable tools for this. The government can make use of the media, the Internet and other channels to popularize the knowledge of e-waste treatment among the public, including its hazards and proper treatment methods [58]. By producing and broadcasting public service announcements, organizing environmental protection seminars and conducting online interactive quizzes, the public can be made to understand the e-waste problem more intuitively and be motivated to participate [59]. In addition, community activities are also one of the effective public engagement strategies. The government or community organizations can regularly organize activities such as e-waste recycling days and environmental theme carnivals to provide a platform for public participation [60]. In these activities, the public can experience the process of e-waste recycling and understand the importance of resource recycling, while also exchanging experiences with other participants to form a favorable environmental atmosphere.

Public education has an irreplaceable role in e-waste management. Through education, it can raise the public's awareness of environmental protection and make them realize that e-waste disposal is closely related to everyone. At the same time, education can also disseminate environmental protection knowledge, such as the correct classification method of e-waste, recycling channels, etc., to help the public better participate in e-waste management. In addition, education can cultivate environmental habits among the public, such as cleaning and recycling e-waste regularly and choosing environmentally friendly electronic products [61]. The formation of these habits will not only help reduce the generation of e-waste, but also promote the environmental protection process of the whole society.

In order to increase public awareness and participation in environmental protection through education, it is necessary to focus on the diversity of educational content and the interactivity of educational methods. The content of education can cover the hazards of e-waste, the correct treatment methods, the importance of resource recycling, etc., in order to comprehensively and systematically raise the public's awareness [62]. The education approach can take various forms, such as classroom teaching, outdoor practice and interactive games, to attract public interest and participation. For example, visits to e-waste treatment plants can be organized for the public to witness the treatment process of e-waste [63]; or environmentally themed handicraft activities can be carried out to allow the public to use discarded electronic parts to create works of art, which not only raises their awareness of environmental protection, but also fosters their hands-on ability and creativity.

11. SUMMARY AND OUTLOOK

The generation of e-waste stems mainly from the rapid iteration of technological development and the shortening of product lifespan. With the rapid development of computer technology, new products are emerging all the time, leading to the premature elimination of a large number of devices that are still within their usable range. At the same time, due to the lack of perfect recycling system and treatment means, a large amount of e-waste has not been properly handled, exacerbating the problems of environmental pollution and waste of resources. E-waste contains a large amount of heavy metals and organic pollutants, and improper treatment can cause long-term harm to the environment and human health.

To address this challenge, the research article describes the recycling and reuse process of e-waste, including classification, disassembly, separation and extraction, and resource utilization. By recycling and reusing valuable materials from e-waste, not only can production costs be reduced, but resource waste can also be significantly reduced. At the same time, the article emphasizes the importance of raising public awareness of environmental protection. The government has actively popularized knowledge of e-waste treatment and cultivated the public's environmental protection habits through a variety of means, such as publicity and education, community activities and education and guidance.

Looking to the future, the treatment of e-waste will be more efficient and environmentally friendly. With the advancement of science and technology, new recycling and treatment technologies will continue to emerge, further increasing the recycling rate and resource utilization of e-waste. At the same time, the government will further improve its policy and regulatory system, strengthen international cooperation and exchange, and jointly address the challenges posed by e-waste. Enhanced public awareness of environmental protection will also promote the continuous development of e-waste management. In the future, the public will be more actively involved in the recycling and reuse process of e-waste, forming a favorable atmosphere of common concern and participation of the whole society. Through the joint efforts of the government, enterprises and the public, the handling of e-waste will become more standardized and scientific, making greater contributions to sustainable development.

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