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"Control-Alt-Delete": Rebooting Solutions for the E-Waste Problem

Jinhui Li,*,† Xianlai Zeng,*,† Mengjun Chen,‡ Oladele A. Ogunseitan,§ and Ab Stevels‖

†State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, China

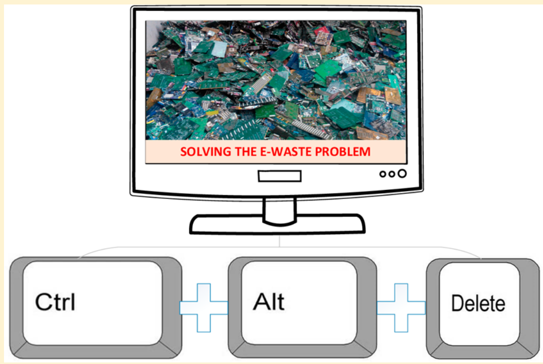
‡Key Laboratory of Solid Waste Treatment and Resource Recycle, Ministry of Education, Southwest University of Science and Technology, Mianyang 621010, China

§Program in Public Health and School of Social Ecology, University of California, Irvine, California 92697, United States

‖Design for Sustainability Lab, Delft University of Technology, 3-5655 JL Eindhoven, The Netherlands

Supporting Information

ABSTRACT: A number of efforts have been launched to solve the global electronic waste (e-waste) problem. The efficiency of e-waste recycling is subject to variable national legislation, technical capacity, consumer participation, and even detoxification. E-waste management activities result in procedural irregularities and risk disparities across national boundaries. We review these variables to reveal opportunities for research and policy to reduce the risks from accumulating e-waste and ineffective recycling. Full regulation and consumer participation should be controlled and reinforced to improve local e-waste system. Aiming at standardizing best practice, we alter and identify modular recycling process and infrastructure in eco-industrial parks that will be expectantly effective in countries and regions to handle the similar e-waste stream. Toxicity can be deleted through material substitution and detoxification during the life cycle of electronics. Based on the idea of "Control-Alt-Delete", four patterns of the way forward for global e-waste recycling are proposed to meet a variety of local situations.



INTRODUCTION

The rapid expansion of electronic inventions, manufacturing innovations, and consumer demand have revolutionized societal investments in infrastructure for networking and the rapid expansion of international commerce. However, the short useful life expectancy of electronic products, driven by rapid innovation, miniaturization, and affordability have led to a major increase in the accumulation of toxic electronic waste (e-waste).[1,2] Incongruous national and regional policies and practices have resulted in the disproportionate partitioning of risks associated with e-waste generation, stockpiling, and processing, although e-waste differs in the catalogue and generation time for various countries and regions (Figure 1).[3,4] The latest research indicates that global e-waste production is estimated to be 35 million tonnes per year.[5] China and the United States (U.S.), the largest producers of e-waste each generate more than 3 million tonnes per year, twice the level of production attributable to other individually industrialized countries.[6] The amount of e-waste generation in some populous developing countries such as India and Brazil will surpass most developed counties,[7] which will also impose upon them the need to find suitable solutions.

The rapid emergence of the e-waste problem has motivated some developing nations to leapfrog the technical hurdles through a rapid transfer of cleaner production and circular economy from end-of-pipe treatment.[8,9] Massive accumulation of a wide variety of electronic equipment at the end of their useful lives has bred at least two serious global problems.[10,11] First, the supply of some raw materials is increasingly difficult to meet the growing demand from electronics manufacturing, and concerns have been expressed about the future limitations on manufacturing based on the supply of valuable metals, precious metals, and rare metals.[12−17] For instance, a rapid exhaustion of already scarce natural elements is occurring, such as gallium (annual production of ∼215 tonnes) and indium (annual production of ∼1100 tonnes including recycling) both of which have an estimated availability of about 20 years until they will run out completely (SI Table S2).[18,19] Second, artisanal mining of e-waste to recover small amounts of precious metals has also expanded in developing countries, driving illicit international trade in hazardous e-waste. The artisanal mining practices have also contributed to environmental pollution from nonferrous metals and persistent organic pollutants (POPs) in e-waste with demonstrated adverse impacts on human health.[20,21]

Increasing recycling rates is a central strategy for dealing with the e-waste problem, in part because it can close the loop of

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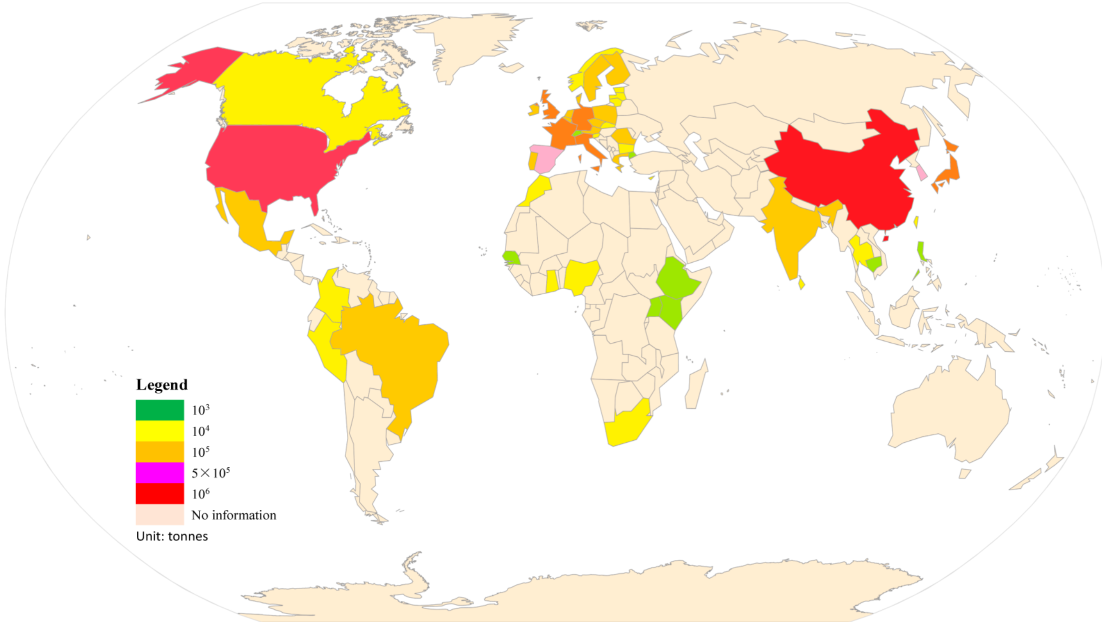

Figure 1. Sources of e-waste generation. Data source seen at Table S1 of Supporting Information (SI).

resource depletion, while also minimizing the multiscale risk of the environment and public health in formal manners.[22−24] However, due to the ubiquitous distribution of electronics, additional solutions are required at the manufacturing level, including reduction in the use of toxic materials, and designing for easier disassembly and resource recovery.[25,26] These solutions must be implemented in an internationally harmonious regulatory environment to provide incentives for manufacturers, retailers and consumers. A paradigm shift of the way we control both the resource exploitation and e-waste recycling is required in order to minimize the negative impact of our present and future generations on the environment and to create a sustainable future.

Only three articles reviewed e-waste management in terms of legislation or recycling technology in global or large regional level, which were published in 2005,[10] 2006,[11] and 2013.[27] However, both regulation updating and technology innovating, and some emerging negative problems such as new types of e-waste management oblige that to find a new solution for global e-waste problem is extremely necessary. The feasible solution should be strongly relevant to resource recycling and environmental improvement. Both the aspects are considered by e-waste legislation system, but resource recycling and environmental improvement are concerned mainly by recycling technology and eco-design (or design for environment). Therefore, this work, based on international insight, intends to review all the past notable adventures involving regulation, processing technology, and eco-design consideration, and examine their effectiveness and role in e-waste management. Meanwhile, we will outline a rebooting solution integrating the key relevant approaches within the life cycle of electronics, and tentatively raise the future pertinent road of e-waste management for various countries or regions.

■ REGULATORY CONTROL

International Initiatives and Regulations. The United Nation's Basel Convention was designed to control transboundary movements of hazardous wastes and their disposal.[28,29] E-waste is classified as hazardous waste because it contains chemicals at concentrations that are potentially toxic to humans, animals, and the environment.[30,31] International organizations to control e-waste include the Mobile Phone Partnership Initiative (MPPI), Solving the E-Waste Problem (StEP) Initiative, and the Partnership for Action on Computing Equipment (PACE).[27] MPPI was launched in 2002 to address the refurbishment, collection, materials recovery and recycling of used mobile phones. StEP, founded in 2004, attempts to offer an impartial platform for developing sustainable solutions for e-waste management in order to reduce environmental and health risks and increase resource recovery. Focusing on end-of-life (EoL) computing equipment, PACE, under Basel Convention, was launched in 2008 to increase the environmentally sustainable management of e-waste.

In the European Union (EU), the scarcity of landfill sites for solid waste drove technological innovation toward alternative waste treatment techniques and encouraged recycling and source reduction approaches. Although e-waste may account for only ∼1% of landfilled waste, its content of hazardous materials necessitated the development of new regulatory approaches to deal with this category of solid waste.[32] Therefore, in 1998, the European Commission published the *Directive on Waste Electrical and Electronic Equipment* (WEEE Directive) (The detailed legislation system and framework can be seen in SI Table S3(A)).[33] Similarly in Japan, the scarcity of land for solid waste disposal also motivated the development of special e-waste regulation, the *Home Appliance Recycling Law* (HARL) and *Small Appliance Recycling Law* were implemented to increase recycling rates by imposing responsibilities and costs on manufacturers, retailers and consumers (SI Table S3(B)).[34,35]

The United States (U.S.) has not ratified the Basel Convention, and only a small fraction of e-waste generated within the country is recycled whereas there is evidence of exportation to developing countries such as China and India.[36] Transboundary movement of e-waste seems to have declined with enforcement of environmental and custom officials by developing countries and the joint effort of international society under Basel Convention. But in some cases, becoming a party

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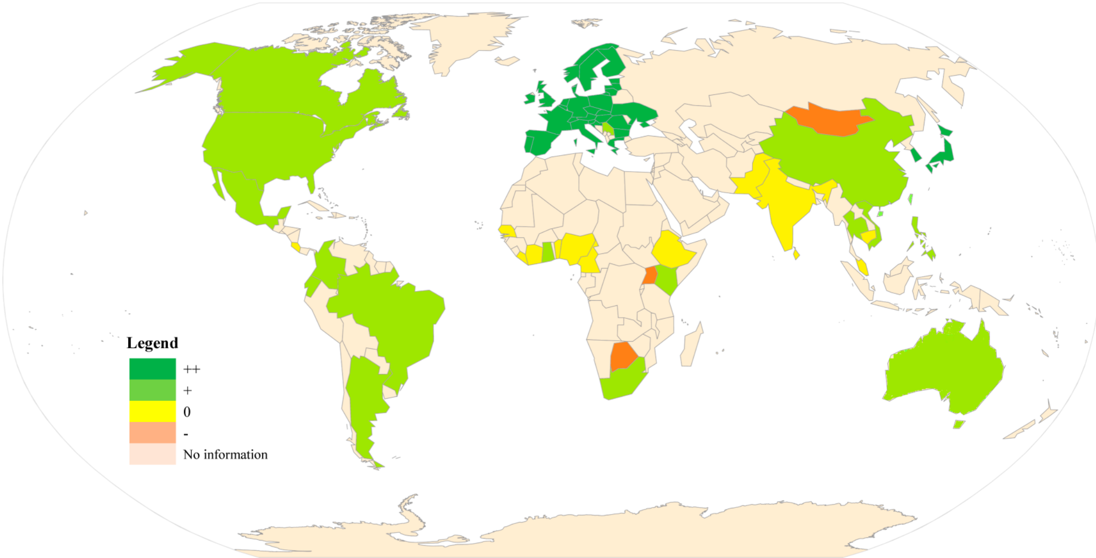

Figure 2. Status for global e-waste management in terms of legislation. ++: implemented controls, +: new command and control regulations, 0: control regulations under development, and -: no regulations.

of the Basel Convention and bilateral agreements were reached to continue the practice.[37] The lack of federal regulation of e-waste has obliged many states within the U.S. to develop specific policies requiring higher volumes of e-waste to be collected and processed separately from the domestic waste stream. Until now, 25 states have similar e-waste regulations, although most do not provide sufficient infrastructure or dedicated revenue streams to enforce compliance and to promote public participation (The detailed legislation framework can been seen in SI Table S3(C)).[38]

Gaps in Regulatory Controls. China generates a large amount of e-waste, and the country used to be a major destination for e-waste generated in other countries and imported illegally. Regions of Southeast China are noted for artisanal operations through which e-waste are recycled in ill-equipped workshops.[39,40] The artisanal processes include open strong acid leaching of e-waste to extract precious metals, grilling of waste printed circuit boards (PCBs) to salvage reusable components, and uncontrolled open burning of plastics and copper wires to recover copper.[41] As these processes often lack pollution control measures, excessive levels of toxicants have been released into the environment.[42,43] To discourage informal e-waste recycling, the Chinese government issued a variety of environmental laws, regulations, standards, and technical guidance (The detailed legislation system and framework can be seen in SI Table S3(D)).[44]

Although the ISO/TR 14062 (2002), ISO 14001 (2004), and the Basel Convention were implemented through international agreement, national regulation concerning e-waste remains different in all countries or regions. Some developed countries have advanced e-waste treatment facilities, and most countries are at the early stages of developing environmentally sustainable solutions, but a few countries remain underdeveloped in terms of e-waste regulation and management (Figure 2).

In countries that have implemented rigorous regulations, rapid increase in e-waste generation has exceeded the current collection target or recycling capacity.[45] Therefore, existing regulatory policies need to be updated. In the EU, the new mandatory collection target of WEEE directive was set at 65% of the average weight of electrical and electronic equipment placed on the market over the previous two years.[46] However, in countries that are just beginning to contemplate e-waste regulation, mass balance data are lacking. For instance, China has implemented the regulation of e-waste, only covering discarded television, microcomputer, washing machine, refrigerator, and air conditioner. And in 2015, the additional nine types, including range hood, electric-water-heater, gas water-heater, printer, copier, fax machine, monitor, mobile phone, and single-machine telephone, are added in the new catalogue.[47] But current fund standards of levying and granting are still lack of scientific basis, and China's single state fund model can restrict the e-waste management owing to their significant difference in size and weight. Therefore, China's e-waste regulation should be also improved, in particular on defining the fund standard of e-waste and updating single fund model. But for the other countries or regions, they can issue their e-waste regulation based on local situations and lessons from experienced countries.

Consumer Participation. Based on "polluter pays" principle, extended producer responsibility (EPR) is emerged in Sweden and German in the early of 1990s.[46] It emphasizes the responsibility of take back, recycling and final disposal, and is very eminent for e-waste recycling in some developed countries.[48] Among all the stakeholders of e-waste recycling, consumers are vitally key actors in the e-waste recycling chain because they choose the disposal channels and destinations for their household e-waste.[49,50] Consumers finance the majority of the recycling system in Switzerland, California (U.S.), and Alberta (Canada). Consumers in Japan will have to pay an EoL fee that covers the recycling and transportation expenses.[37] Nevertheless in some developing countries such as China, consumers tend to sell their e-waste to the collectors who offer the best collection price, regardless of their actual technical and environmental performance.[51] A large amount of EoL electronics are still stored in the home and do not enter into collection channel.

Major stakeholders include government, producer, consumer, and recycler, which play different roles in e-waste recycling. For instance in the EU WEEE directive, government needs to

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Table 1. Advanced Collection Experience of E-Waste in Some Industrial Nations[46a]

countries	registration of appliances	PROs	financing of collection	financing of recycling	municipal recycling activities	control of results
Germany	EAR on behalf of the Federal Environment Agency	Only lightcycle for CG4	municipalities	producer/ importers	complete CGs can be recycled/sold	Federal Environment Agency
Switzerland	none	SWICO, SENS, SLRS and INOBAT	producers/ importers	producers/ importers	none	Experts reporting to the Swiss Environment Agency
Denmark	DPA on behalf of the Danish Environment Authority	PROs: Elretur, RENE, ERP with the exception of CG4	municipalities (partial refunding)	producers/ importers	none	Miljostyrelsen (Umweltbehörde)
Sweden	Naturvårdsverket (Env. Agency)	PROs: El-Kretsen, EAR	producers/ importers	producers/ importers	none	Naturvårdsverket

[a]Note: CG: collection group; DPA: Dansk Producentansvarssystem; EAR: "Stiftung ear"; PRO: producer responsibility organization.

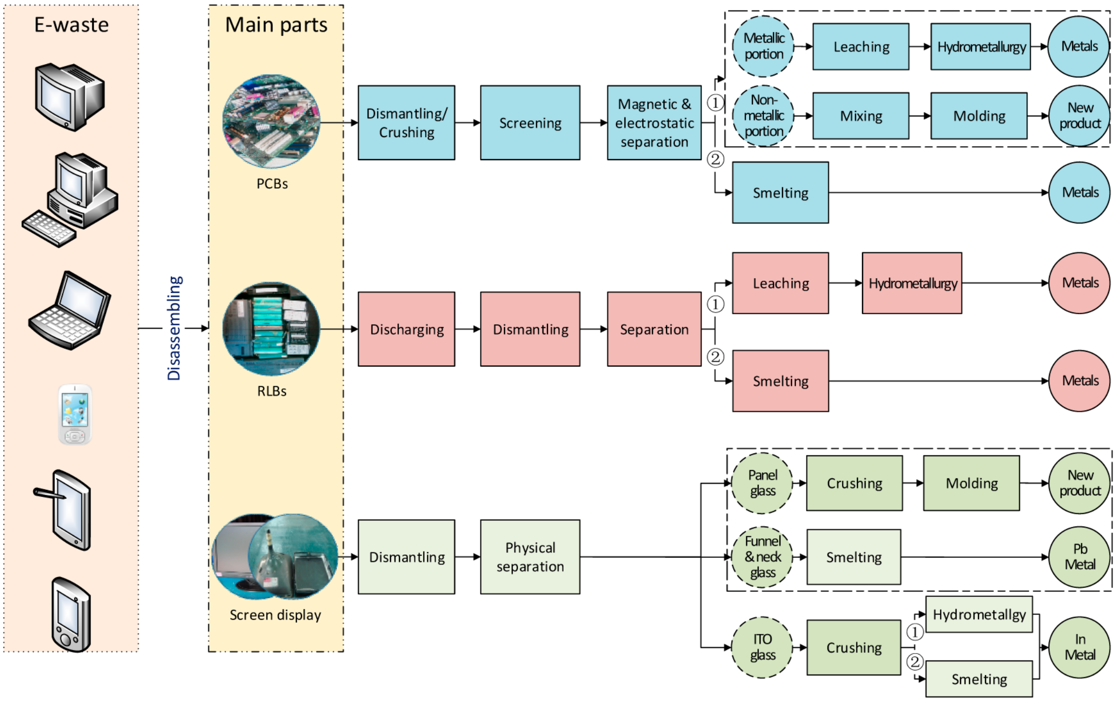

Figure 3. Major schematic recycling processes of typical e-waste. ① popular in developing countries, ② predominate in industrial nations. Information source from the references.[18,59,60,75,86,89−100]

create the necessary collection and recycling infrastructure, producer should establish the EPR system, directly charge collection and recycling, levy the fee, and launch publicity and education, and consumer should pay for the recycling fee. Additionally, the responsibility of stakeholders also varies in different countries or regions. But EPR has not been well implemented in most developing nations.[27] And there is still some debate over the definition of EPR. For example, some jurisdictions have interpreted EPR as manufacturers taking responsibility for used packaging and products (e.g., Japan, Australia), and other jurisdictions (e.g., Sweden) interpret EPR to mean that producers should assume responsibility for manufactured or imported goods throughout their life cycle, including the waste phase.

As indicated in Table 1, the German system (clearing house for registration and organization of collection from take-back points, no producer responsibility organizations with the exception of gas discharge lamps representing a very small part of the e-waste market) is partially owing to objections of the Commission in the case of the packaging ordinance against large collective producer systems in the German market. Despite these objections by the Commission, only one (Germany) or few (Denmark, Sweden, Switzerland) PROs (third party organization) have been established in the other countries studied here. Without collective organization of the producers, the promotion of e-waste collection systems is more or less left to the cities. This impedes nation-wide campaigns across TV and web.[6,46]

These situations have influenced the financial model of the formal collection system, which strongly declines the e-waste recycling. Past adventures demonstrated that consumer participation should be cultivated to facilitate e-waste collection, especially in developing countries. E-waste collection can be stimulated by economic compensation and promoting moral norms, educating the public about the benefits of collecting e-waste, and making e-waste collection more convenient but other measures will likely be necessary to tackle the e-waste problem.[25,51] Meanwhile, the formal sector or government can offer consumers convenient services such as home pick-up and cash pay-back when collecting e-waste in order to stay competitive toward the informal counterpart for collecting sufficient volumes.

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■ ALTERNATIVE TECHNOLOGIES AND PARADIGMS FOR RECYCLING

Review for E-Waste Recycling Technology. Almost all types of electronics are mainly composed of physical-combined PCBs, RLBs, screen display, and plastics, which could be obtained with a substantial disassembling. Previous studies indicates waste PCBs, spent RLBs, and waste screen display (e.g., cathode ray tube (CRT) and liquid crystal display (LCD)) are the most difficult parts to be handled in e-waste.[52] Their recycling technological maturity can demonstrate the whole development of e-waste recycling process.

Waste PCBs. It, first, is dismantled and separated, generally using mechanical or metallurgical processing to upgrade the desirable material content. Shredding, electrostatic separation, supercritical extraction, and pyrolysis are the main technologies employed in this step.[53] The second step is the further separation or screening and processing of metal streams; this is probably the most important step from economic and environmental viewpoints.[36,54] Two major methods extracting metals from postprocessing PCBs include leaching for hydrometallurgy, and smelting for pyrometallurgy.[55−59] Nonmetallic portion can be mixed with additives and molded for new products such as phenolic molding compounds and wood plastic compounds.[60−62] In addition, smelting following a simple mechanical treatment is popularly employed for deep recovery, especially in industrial nations (Figure 3).

A nonignorable fact is that heavy metals and POPs dramatically linked with waste PCBs recycling in an informal approach.[63] Numerous studies have revealed that abundant toxicants, including, but not limited to, heavy metals, polychlororinated biphenyls, polybrominated diphenyl ethers (PBDEs), polybrominated dibenzo-*p*-dioxin and dibenzofurans (PBDD/Fs), and polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs), could be leached into the ambient environment during e-waste processing with informal incineration, posing serious risks to environmental and human health.[64−67] Therefore, POPs released from informal e-waste recycling should be controlled through alterative technology and approach.[64,68]

Spent RLBs. To prevent short-circuiting and self-ignition, spent RLBs often are first discharged commonly by salt solution. Similar to other e-waste, spent RLBs should be dismantled and separated by manual or by mechanical for further treatment. Mechanical operations were required because metals in batteries are covered with or encapsulated by plastic or iron shell.[69−72] Manual dismantling was commonly employed to easily and completely the plastic and metallic shells.[73,74]

Although some cathode material or anode material can be stripped from Al foil or Cu foil during the pretreatment process, the majority is still attached to the foil. To properly separate cathode material from Al foil, many alternatives have been tested, including solvent extraction, *N*-methylpyrrolidone dissolving, application of ionic liquid, bioleaching, and acid leaching.[70,75,76] Then based on the principles of green chemistry,[77,78] the hydrometallurgical process combined with solvent extraction, precipitation, electrowinning, crystallization, and calcining has been developed for high purity metals.[79] Alternatively, the pretreating outputs can be directly smelted for metals product (Figure 3). An asynchronous progress in terms of academic research and industrial practice exists because more attention has been paid for waste PCBs in the past decades. Spent RLBs recycling in a commercial-oriented application should be also altered to promote e-waste system.

Waste Screen Display. Conventional CRT monitor can be dismantled to remove the CRT from the plastic casing. Physical separating methods including thermal shock, melting, heating wire, and laser treatment are ways to heat the low melting point weld glass jointing funnel glass and panel glass, and then the CRT will split and be separated by cooling or pressure treatment.[80−82] The funnel glass can be delivered to a glass production facility as a feedstock to manufacture new product such as foam glass and glass matrix composites. CRT funnel glass is delivered to a lead (Pb) smelter to be incinerated as a fluxing agent or as a substitute for lead-bearing ores.[83,84] Regarding LCD monitor, indium−tin oxide (ITO) glass can be achieved while LCD monitor is simply dismantled and separated physically. Afterward, the rare metal (e.g., In) can be crushed and recovered by hydrometallurgy or smelting route.[85−88]

National Adventures on E-waste Recycling Technology. *European Union.* E-waste recycling technology was developed in the EU, covering three major stages of sorting, metals recovery and refining. Sorting is typically involves physical size fractionation of various electronic products or material fractionation of various component parts. The recovery of metallic parts is achieved through magnetic separation, shredding and sieving. The mixed metals constituents are then subjected to refining in a beneficiation process.[101] Advances in technological enhancement of e-waste recycling were stimulated by the implementation of EU WEEE directive. Automatic dismantling and sorting systems were invented to process common e-waste components and for hydrometallurgical or pyrometallurgical processes to recover precious and valuable metals. The state-of-the-art e-waste recycling process that minimizes, but does not eliminate potential environmental impacts is illustrated in Figure 3.

There are some variations among Europe countries in technical capacity to implement state-of-the-art technology for e-waste treatment. Switzerland has four separate WEEE recycling systems such as the SWICO Recycling Guarantee and the SENS system (Table 1).[102] These processes are responsible for recycling approximately 75 000 tonnes of e-waste annually, exceeding the goal of European WEEE directive.[102−105] The German e-waste recycling system is more fragmentary and is supervised by Federal Environment Agency, and operated by authorized Elektro Altgeräte Register. An estimated 300−600 e-waste treatment companies in Germany are approved by the government to process e-waste.[106] Most of these are small enterprises and divisions of larger waste management parent companies. There are approximately 120 social enterprises owned or partly owned by municipalities that repair, refurbish, or resell e-waste deposited at municipal collection sites.

Japan. The e-waste recycling industry of Japan emerged in three stages: (1) e-waste was initially recycled for metals recovery, and the nonmetallic components were disposed as solid waste; (2) After the implementation of the implement of *Promotion Law on Effective Utilization of Resources* in 1990, more e-waste flowed into conventional treatment facilities; and (3) after the implementation of HARL in 2001, e-waste recycling was expanded and about 55% of e-waste was being recycled. Currently, two channels consisting of seller and professional recycling sites are employed to collect e-waste. About 379 designated collection sites and 49 recycling facilities

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exist in Japan (Table 1).[107] Most of the e-waste recycling facilities in Japan are financially supported by the governmental ministries and municipalities or by manufacturers of electronic products. Retailers collect household e-waste when consumers buy new products. The collected e-waste is transferred to one of 380 designated collection points where they enter the waste management system. A key feature of the Japanese system is the use of primary disassembly process to remove major components that may still be functional. Automation and mechanization have been introduced to ensure safe handling of large and heavy e-waste (Figure 3).[108,109] Before the implementation of HARL, more than 70% of e-waste entered into solid waste treatment. HARL encouraged increases in the manufacturer take-back rate (to 60%) and average material recycling rate (to 72%).[110]

U.S. E-waste in U.S. is collected through various processes, including residential curbside collection, special drop-off event, permanent drop-off at hazardous waste collection sites, manufacturer take-back, and point-of-purchase collection. Developments that encourage e-waste recycling are the bans on both the disposal of CRTs in landfills and their incineration, which began in Massachusetts in 2000 and in California in 2001. Maine and Minnesota have also recently banned CRTs disposal. According to these bans, all CRTs must be recycled in these states.[111] The State of California passed the 'California Electronics Waste Recycling Act' in 2010 stipulating that each manufacturer that sells electronic devices must either collect an equivalent to 90% of the number of devices they sell or they must pay the alternative fee for recycling the devices they sell. The U.S. Environmental Protection Agency (EPA) provides conditional exclusions from the federal hazardous waste management if CRTs glass destined for recycling. These safe, yet simplified standards aim to increase the collection and recycling of CRTs, and to reduce the amount of lead in landfills by allowing the lead to be reused to make new CRTs glass or sent to lead smelters (Figure 3).

E-waste recycling industry development in U.S. emerged in two stages: before 2003, valuable electronic components were mostly recovered but unserviceable parts were exported and the rest landfilled. After 2003, the sprouting of state-level legislation increased the rates of e-waste recycling. Approximately 2000 U.S. companies are involved in e-waste recycling and disposal, of which about 275 are certified electronics refurbishers and recyclers. Many of these companies, focus on dismantling and exportation. The State of California has only four companies dedicated to recycling various e-waste, 11 companies focusing on TV, monitors and computers, and 35 dealing with appliances. Five companies engage precious metals refining as part of the e-waste recycling process.[112]

China. Before 2000, the majority of e-waste in China was processed in backyards or small workshops using manual disassembly and open burning.[113] The techniques used in recycling of e-waste are often primitive, without the appropriate facilities to safeguard environmental and human health. These include stripping of metals in open-pit acid baths to recover gold and other metals, removing electronic components from PCBs by heating over a grill using honeycombed coal blocks as fuel, chipping and melting plastics without proper ventilation, burning cables for recovering metals, and also burning unwanted materials in open air, disposing unsalvageable materials in the fields and riverbanks, toner sweeping, dismantling electronic equipment, and selling computer monitor yokes to copper recovery operations.[114] After the implementation of specific e-waste legislation, advanced processes for waste TV, waste computer, and waste PCBs were developed to improve the efficiency of manual dismantling and mechanical treatment (Figure 3).[94,115,116]

China developed three levels of e-waste recycling processes. Informal e-waste recycling with manual dismantling and materials recovery homemade equipment. The majority of e-waste disposal remains at this level. Formal, small-scale companies recycle a small proportion of e-waste volume, but they use processes that generate environmental pollutants, thus are not supported by the government. The third level is large-scale or national pilot corporations that are permitted and supported by the government. At present, approximately 106 licensed enterprises in China engage in the e-waste recycling, and most operate in four phases. Four phases can be prospected for e-waste management: informal manual dismantling phase (1980s to 2000), coexisting phase of informal recycling and national pilot (2001 to 2008), development phase (2009 to 2020), and mature phase (beyond 2020).[44]

The Performance of E-Waste Recycling in Different Countries. Current e-waste recycling processes vary greatly among developing and developed countries (Figure 3).[117,118] Extensive manual disassembly is typically not economically feasible in industrialized countries but may be advantageous in emerging economies in Africa, Asia, and Latin America, where labor costs remain relatively low.[119,120] In the developed nations, the options available for e-waste management are recycling and recovery of materials and components from defunct products for use in making new similar (closed-loop recycling) or different (open-loop recycling) products; or incineration and landfilling, which are increasingly rare because of legislation.[121] In developing countries, the collection of e-waste from consumers remains a major impediment against the development of coherent and sustainable management practices that minimize adverse environmental impacts. The differences in the national development of e-waste recycling industry can be attributed to a lag in technology transfer, high cost of necessary equipment and maintenance, capacity of facilities, and paucity of skilled labor.

Many recycling processes have been applied into global e-waste management. A number of approved facilities have also been built and operated in many countries (Table 2), which ensures that over 80% of collected e-waste was treated properly in dismantling or recycling approach in the EU, China, U.S., and Japan. However, collection and formal recycling of e-waste still stay low level (13%) worldwide. In this context, only 15% of the gold in e-waste has been recovered properly.[13] Meanwhile, pollution control during e-waste recycling should be substantially evaluated owing to much concern of public health. With sound legal and technology, the EU, Japan, and South Korea are prominent in pollution control. Other industrial nations such as U.S., Canada, and Australia are excellent owing to new legislation and few informal manner. In contrast, China is not so excellent in light of still existed informal recycling. And most developing countries remain poor in pollution control because they lack ineffective legislation, the waste removal infrastructure and technical capacities necessary to ensure the safe disposal (Figure 4).

Toward Standardization of Best Practices. Environmental protection policies based on "Best Available Technology" (BAT) have become prominent and aim to minimize environmental impacts using existing technology and minimizing costs with recognition that risks may remain.[125] "Best

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Table 2. Collection and Recycling of E-Waste in Formal System[a]

country	collection rate (%)	formal recycling rate (%)	recycling rate (%)	number of approved facility
U.S. (2009)[122]	25	20	80	275
EU-27 (2009)[123]	33	33	∼100	NA
China (2013)[b]	28.78	28.78	∼100	106
Japan (2011)	NA	NA	80	49
Switzerland (2006)[112]	NA	NA	90	4[c]
Worldwide (2009)[124]	NA	13	NA	NA

[a]Note: NA, no data. [b]Data source from SI Table S4; Collection rate = collection amount/generation amount; Formal recycling rate =formal recycling amount/generation amount; Recycling rate = (reused part + recycling part)/collection amount. [c]4 PROs (SWICO, SENS, SLRS, and INOBAT) systems.

Environmental Practice" (BEP) extends BAT through the integration of pollution control technology and strategies that may differ from one country to another depending on local conditions and resources.[126,127] A thorough understanding of applicable BAT and BEP that can support international policies to minimize illegal transboundary trafficking of e-waste. Therefore, the ideas of BAT and BEP are fundamental guideline to improve the e-waste management. Additionally, BAT and BEP on e-waste recycling should be developed with the three aspects: making full use of the abundant human resources in the developing countries, taking full account of the level of equipment manufacturing in the developing countries, and considering the requirements of human health and environmental protection.

At the macro level, although the formal recycling rate and pollution control of e-waste recycling in most industrial nations are better than those in developing countries, yet the formal recycling rate are still low and negative.[128] Moreover, both rapid increase in the amount of traditional e-waste and brisk growing of emerging e-waste are main problems and barriers that most industrial nations are facing. In view of the sophisticated experience of BAT and BEP, industrial nations need to extend recycling capacity for experienced e-waste, and develop new technology for intractable and emerging e-waste.

Actually, developing countries face more serious e-waste problem subjected to notorious informal recycling.[129] Few related solution or approach can be discussed here. First, a solution of "best-of-2-Worlds" was proposed to seek technical and logistic integration of "best" preprocessing in developing countries and "best" end-processing in international state-of-the-art end-processing facilities.[130] But current challenges and barriers exist dominantly for the solution: many products generated from e-waste dismantling will be difficult to legally enter into international market because of their hazardous characteristics; and this philosophy will extend the material flow of e-waste from domestic to international, and thus it prominently raise the total cost of e-waste management and disturb the fund system. Second, the previous adventures indicate that formalization of the informal e-waste recycling sector in most developing countries may be quite effective approach. Successful formalization strategies tend to incorporate simple approaches and implementation efforts, and foster positive economic conditions for workers and local communities.[93]

But at the micro level, eco-industrial parks (EIPs) in industrial ecology[131,132] are increasingly seen as a standardized means to strengthen circular economy for green growth and reduced resource consumption.[133,134] It can be expectantly employed to improve the e-waste system not only for industrial nations, but for developing counties. Nowadays, EIPs are not widely adopt for e-waste recycling industry, in particular at most developing countries. Two typical EIPs called Qingdao New World and Tianjin TEDA in China have been proved to successfully deal with many types of solid waste.[135,136] Since almost all the e-waste contain PCBs, screen display, and RLBs, and they can be appropriately handled by their respective processes, modular plants can be hopefully equipped for e-waste recycling in EIPs. Despite the type of e-waste, modules from I to VIII will enable EIP to effectively implement

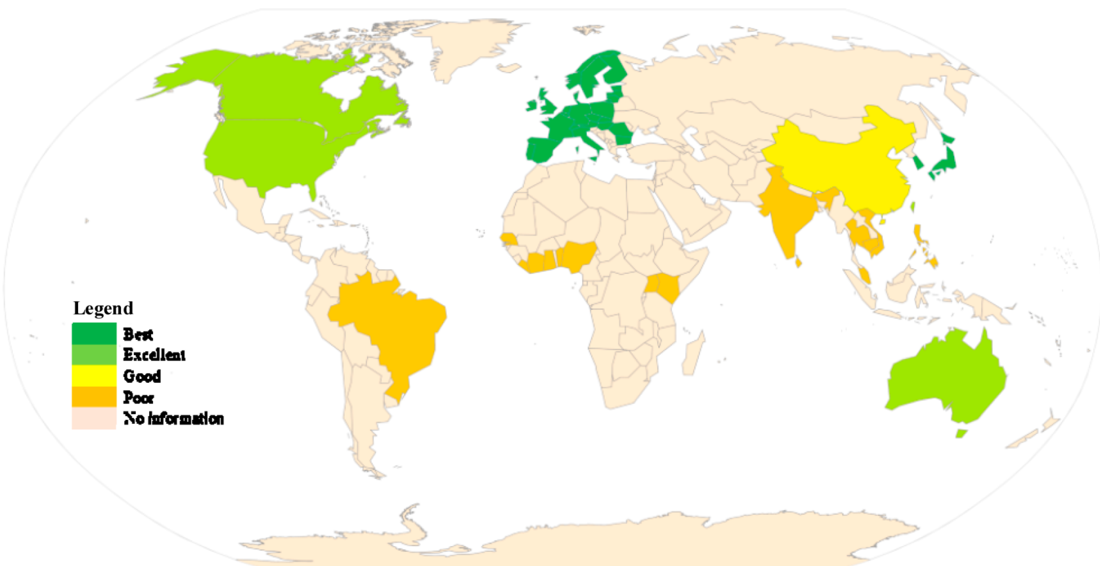

Figure 4. Global distribution of e-waste recycling in terms of pollution control.

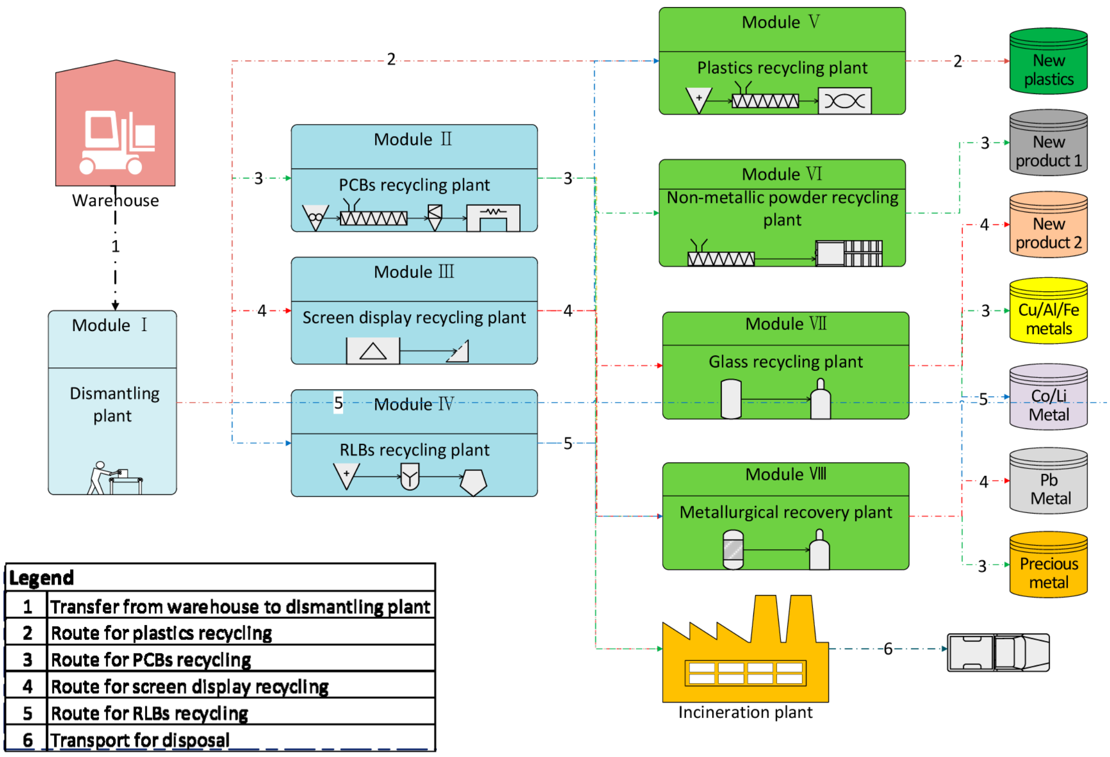

Figure 5. Vision for EIP of e-waste recycling in modular fashion.

dismantling, parts recycling, and deep recovery and yield new products and metals. The residues generated from Module II, III, and IV can enter into incineration plant and then transport for safely disposal (Figure 5). With EIP's scaling-up, normalization, and intensification,[137] the philosophy of standardized EIP can be applied and popularized for most countries or regions to rapidly strengthen the local management of e-waste.

But there is approximately 30 small countries or regions with less than 20 thousand km^2 of land area. The standardized EIP cannot function in these areas owing to limit land area and mandatory prohibit of hazardous waste transboundary movement. They are obliged to establish their own facilities or plants to solve the e-waste problem. Only a few attempts were carried out to design many integrated mobile recycling plants, which were equipped with dismantling tables, crusher, separator, and even hydrometallurgical devices in large containers. After running test, they successfully played roles in e-waste collection, recycling, and deep recovery.[138,139] Consequently, integrated mobile recycling plants can offer an effective solution to solve the e-waste problem for small countries or regions.

■ DELETING TOXICITY TOWARD ECO-DESIGN

Environmental improvement of the e-waste problem is dominantly related to eco-design along the electronics' life cycle. But comparing to other ph ases (e.g., manufacturing, use), the two phases of production and EoL treatment can be much easier to deal with to reduce the negative environmental impacts.[23,140] Material substitution of electronics and detoxification of e-waste in green design and green disposal could be regarded as the most decisive and effective approaches in these two phases.[141]

Material Substitution. Significant shifts of electronics have been occurring: CRT utilized in TV and computer is substituted by LCD,[142] and fluorescent lamp is replaced with light-emitting diode.[15] From the perspective of life cycle consideration, these shifts can effectively delete toxicity and decline the negative environmental impact.[143,144] In a wider perspective, electronics producers can initially delete the utilization of toxic materials subjected to *Directive on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment* (RoHS Directive), and should enhance eco-design and promote design for recycling,[145] through altering new materials, developing longer life and more durable equipment, and taking responsibility for safe recycling pathways.[146,147]

Material substitution of solder in electronics packaging is always evolving in recent 30 years. Traditional tin−lead solder was so widely used that the heavy metals in circuit boards are extremely prone to being released into the environment when EoL electronics is informally handled. To deal with the potential risks for both the environment and human health, two alternatives in 2000s were developed: lead-free alloys and electrically conductive adhesives (ECAs), which soon predominated in electronics manufacturing world.[148,149] Currently, replacing the metal particles with carbon nanotubes in conductive adhesive compositions has the potential benefits of providing a material that is lead-free, corrosion resistant, electrically/thermally conductive, and lightweight, with a low process temperature and high mechanical strength.[150] The new materials such as carbon nanotube and phase-change materials will also propel the transistors to the forefront of future microchip technologies.[151] The transfer of new material reveals a distinctive potential of the considerable eliminating of the toxicity and the splendid enhancing of eco-design for electronics.[152]

In a boarder perspective, organic electronics (or green electronics) is aiming at identifying compounds of natural origin and establishing economically efficient routes for the production of synthetic materials that have applicability in

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environmentally safe (biodegradable) and/or biocompatible devices.[153] Organic electronics may help to fulfill not only the original promise of organic electronics that is to deliver low-cost and energy efficient materials and devices but also achieve unimaginable functionalities for electronics, for example benign integration into life and environment.[154] Pyrene-based materials has been utilized or modified as substitute in organic electronics such as organic light-emitting diode and organic field-effect transistor.[155] Novel two-dimensional graphene is considered a realistic candidate to replace ITO electrode due to its unique properties, such as favorable work function, low resistance, high optical transmittance, good chemical and thermal stability, high mechanical strength, and flexibility.[156] Many organic materials are biodegradable, safe, and nontoxic, including compounds of natural origin. The unique features of such organic materials suggest they will be useful in biofunctional electronics; demonstrating functions that would be inaccessible for traditional inorganic compounds. Such materials may lead to fully biodegradable and even biocompatible/biometabolizable electronics for many low-cost applications.[157] Paper-based electronics have been also considered as one of the most exciting technologies in the near future due to sustainability, low cost, and mechanical flexibility.[158−160] Using the carbon material such as nanocarbon,[161,162] electronics of the future will be stretchable, twistable, and deformable into curvilinear shapes, thereby enabling applications that would be impossible to achieve by using the hard, rigid electronics of today.[163]

Almost all the previous studies indicate biodegradable-material electronics (organic bioelectronics) is current trend of the ongoing electronics revolution, proving to be the suitable host for welcoming natural and nature-inspired organic materials and a perfect trampoline for achieving the ambitious goal of "'green'" and sustainable electronics future. Despite intense effort of the scientific community during the past three decades, the performance and stability of organic semiconductors remain at current times major hurdles in their development as solid competitors of the inorganic counterparts.[154]

Detoxification of E-Waste. Green disposal (or environmental-benign disposal) is the final approach to delete toxicity of electronics. This is reflected in a sound depollution of e-waste with appropriate disposal of hazardous components and substances and high worker health and safety standards. A huge number of toxic substances have entered into electronics industry. Taking computer for instance, about 1300×10^6 kg of Pb, 2.16×10^6 kg of Cd, 0.43×10^6 kg of Hg, and 1.2×10^6 kg Cr VI were consumed for global computer production in 2011,[25] which reveals that a copious amount of toxic heavy metals have been transferred and stocked in electronics. Although detoxification is a sound method in the recycling process of e-waste in China, recyclers do not face economic incentives for sound depollution and appropriate disposal of the toxics. In contrary, strong economic disincentives to do so exist.[116]

Recently, waste CRT was focus of detoxification in e-waste. Microbial biopolymers of xanthan gum and guar gum was utilized to encapsulate lead from hazardous CRT glass waste with biopolymer cross-linked concrete systems.[164] Various types of CRT glass powders were blended with suitable amount of ferric oxide and magnesium, and the mixtures could generate self-propagating reaction once locally ignited by a thermal source. Leaching tests demonstrated that heavy metals in the final products fulfilled the environmental regulations of USEPA. It is supposed that the detoxified products have the potential of being used as construction materials.[165] Lead was also successfully removed from CRT glass by $PbCl_2$ volatilization making use of polyvinyl chloride (PVC) as chloride source and $Ca(OH)_2$ as HCl absorber.[166] But other toxic substances including heavy metals (e.g., Cd, Hg, Cr) and brominated flame retardants[167,168] gain little attention, and need more concern to delete their toxicity in e-waste recycling in the near future.

■ CONCLUSIONS AND THE WAY FORWARD

Although many endeavors from industrial nations to developing countries have been attempted to solve the e-waste problem, yet until now there are still a huge room to achieve the sustainability of e-waste management. At least in the perspective of academic research, some tasks and questions related to fundamental knowledge, recycling technology, and eco-design have been completed and answered. However, there are still many key questions not to be well concerned. Accordingly, next works illustrated in Table 3 should be strengthened toward the smooth sustainability of e-waste management.

Strict environmental regulation of some counties is changing the landscape of e-waste trafficking. The struggle against illegal imports of e-waste has become one of the major challenges for most developing countries. Some established regulations are often limited since they exclude many hazardous substances that are used in electronics. And many regulations simply fail to address the management of e-waste. More serious is that many countries and regions are issuing new regulation or still remain no regulation. Practical e-waste management in Africa is unregulated so that rudimentary techniques are widely used. Although tightening of regulations alone will not solve these problems, regulation should be issued and updated to control local e-waste system, and it should be designed in conjunction with the establishment of formal recycling infrastructure. Meanwhile, consumer participation should be also controlled and reinforced to improve the collecting channel.

Lack of environmental-sound technology and facilities lead to a still weak performance of e-waste recycling in terms of resource recycling and environmental improvement. For international standardization and policy harmonization to succeed for e-waste management, BAT and BEP on e-waste recycling should be put as fundamental criteria. Technology and paradigm of e-waste recycling should be also altered toward international standardization. Basically, to extend recycling capacity and develop new technology, and to formalize informal recycling sector are urgent to improve e-waste system for industrial nations and developing countries, respectively. Since almost all electronics contain similar physical components, modular recycling process and infrastructure will be expectantly effective to handle various types of e-waste. We can use the idea of EIPs and design modular recycling process and infrastructure, which could be applicable not only for most industrial nations, but for emerging economies. But for small countries and regions, integrated mobile recycling plant is much promising candidate to solve local e-waste problems.

In order to improve eco-design of electronics, toxicity should be appropriately deleted during the life cycle of electronics. In particular, the evolution of electronics packaging indicates that material substitution can be initially ignited to eliminate toxicity and splendidly enhance eco-design based on RoHS directive and environment-oriented standard. On the basis, organic

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Table 3. Endeavors and Next Works of Research Community in E-Waste Management

aspect	completed	answered	missing	next work
fundamental knowledge	(1) physical components and chemical composition of e-waste (2) identification for environmental pollution and public health from e-waste	basic e-waste's attribution in terms of resource and environmental performance	how the physical components and chemical composition affect e-waste recycling?	to recognize relationship between choice of recycling technology and physical-chemical composition
recycling technology	(1) dismantling by manual approach and mechanical modes for whole e-waste, waste PCBs, and spent batteries, etc. (2) mechanical treatment for waste PWBs and CRT monitor (3) the systematic technologies (e.g., hydrometallurgy and pyro-metallurgy)	(1) basic dismantling technology for recycling (2) mechanical treatment of waste PWBs and CRT monitor (3) the hydrometallurgy technology from leaching to precipitation (4) the pyro-metallurgy using smelter	(1) the regular technologies in disassembling for remanufacturing and dismantling for recycling (2) effective automatic dismantling technologies and machines (3) recovery for low-valuable materials (e.g., nonmetallic powder from waste PWBs, and lead-containing glass)	(1) to outline the selections for disassembling and dismantling toward remanufacturing and recycling of components (2) to build the robust dismantling technology and machine (3) to develop and popularize the recovery technology for low-valuable materials
eco-design[25]	(1) the utilization of environmentally friendly materials (e.g., lead-free solder) (2) technological innovations of electronic packaging (3) technological innovations from CRT to LCD (4) e-waste treatment and disposal	life cycle thinking for eco-design from material choosing to EoL disposal	(1) the linkage between producer and recycler is somewhat broken. (2) some hazardous materials and substances in e-waste have been neglected.	(1) to intensify design for disassembling, dismantling, recycling, and recovery between producer and recycler (2) to delete more hazardous materials and substances

electronics is a promising prospective and direction while it is constructed with nontoxic, biodegradable, and biocompatible materials such as carbon, pyrene, and paper. Regarding EoL electronics, in view of hazardous waste disposal standard, rational detoxification is vital option of solution so that e-waste can be exempted as common waste. Recent advances indicate that toxicity of waste CRT could be successfully mitigated, and later it can be easily disposed in general landfill plant. Delete toxicity toward eco-design of electronics can be regarded as the groundbreaking solution to alleviate the e-waste's environmental problem.

The solution of "Control-Alt-Delete" should be combined together to improve e-waste management system. Four patterns of the way forward can be prospected for global e-waste recycling. Regarding most developed nations, EPR has been adopting to ensure the adequate collection of e-waste. Technologies innovation and facilities expansion of e-waste recycling should be reinforced to solve the e-waste problem in these areas. With respect to most developing countries, legislation improving and collection channel strengthening will significantly contribute to e-waste recycling. Recycling developed processes can be characterized as much labor to improve material recycling rate and pollution controlling. Regarding small countries or regions ratifying the Basel Convention, mobile plant with much equipment can be a promising candidate for e-waste recycling. And for some countries with little e-waste production such as Africa, a feasible solution for e-waste recycling is that related counties can unite to establish some field facilities for a synergic management of their e-waste.

ASSOCIATED CONTENT

Supporting Information

Tables S1–S4. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b00449.

AUTHOR INFORMATION

Corresponding Authors

*(X.Z.) Phone: +86 10 6279-4143; Fax: +86 10 6277-2048; E-mail: xlzeng@tsinghua.edu.cn.
*(J.L.) E-mail: jinhui@tsinghua.edu.cn

Author Contributions

J. H. L. and O. A. O. designed the research and contributed equally, X.L.Z conducted literature review and wrote most of the manuscript, M.J.C. contributed research findings, and A.S. contributed insights that improved the structure of the manuscript.

Notes

The authors declare no competing financial interest.

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