A Review on the Management of E-waste and the Role of Urban Mining: A Global Assessment

By

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EXECUTIVE SUMMARY

The rapid advancement of technology over the past few decades has undoubtedly benefitted society in countless ways. Consumers benefit from more advanced, faster, and more reliable technology, which has created new opportunities in health, education, government, entertainment, and business. However, the rapid development of these new technologies entices consumers to purchase newer and more advanced products, and thus, electronics quickly become obsolete in a "new is better" society. Unfortunately, the rapid growth in electronics has not been met with proportionate growth in the collection, reuse, or recycling of those products as they reach end-of-life (EOL), thus resulting in an exponential increase in e-waste generation world-wide. It is now the fastest growing form of waste worldwide, increasing at a rate of 3 to 5% every year. Globally, it is expected that 52 million tons of e-waste will be discarded in 2021. Asia generates the largest amount of e-waste, producing over 40% of the globe's total volume, but it only collects and recycles 15% of that waste (Balde et al., 2017). Solving this problem requires an integrated approach involving multiple key players including government, business, consumers, and formal recycling companies. This paper focusses on one aspect of the solution to e-waste: urban mining.

Despite the fact that e-waste only makes up two percent of the world's waste in landfills, it comprises 70 percent of all heavy metals and causes enormous damage to both the environment and human health, especially in developing countries where most of it is disposed of improperly (Jiang et al., 2012). Approximately 80% of all e-waste that is collected in developed countries is exported to developing countries such as China, India, Nigeria, and Ghana (Solving the E-waste Problem, 2009). These countries lack the regulation and infrastructure to dispose of e-waste safely, and hence, primitive recycling methods cause significant harm to the environment polluting the soil, air, and aquatic ecosystems. E-waste recycling sites also adversely affect human health as over 1,000 toxic substances found in e-waste harm the human body, causing lead and other heavy metal poisoning, cancers, kidney disease, neurotoxicity, liver damage, fetal toxicity, and skin and eye irritations, among others.

Although e-waste is categorized as hazardous waste, it also contains precious metals such as gold, silver, platinum, and palladium and other valuable materials, 90% of which can be recycled and reused in new electronic devices (Prasad et al., 2020). The term urban mining describes the process of recovering precious metals and energy from e-waste streams through sustainable recycling methods. It consists of three main phases: collection, pre-processing, and end-processing. Collection is crucial because it determines the amount of material available for recovery. During pre-processing, products are dismantled, materials are separated from each other, and hazardous substances are removed. End-processing options may include pyrometallurgical, hydrometallurgical, and biometallurgical methods to recover and purify copper, gold, silver, and palladium and other valuable materials. Three major global smelters are the Boliden Rönnskär Smelter in Sweden, the Umicore Precious Metals Refining plant in Belgium, and the Horne Smelter in Canada.

Urban mining plays a key role in the effort to reduce and valorize the world's rapidly increasing e-waste. Proper urban mining programs can have positive environmental, health, and economic impacts, which include:

1. releasing fewer harmful elements and generating less CO_2 emissions than primary mining;
2. reducing the need for new resources and preserving rare earth elements that are effectively non-renewable;
3. reducing the amount of e-waste directly deposited into landfills and the amount of toxins released into the environment through primitive recycling methods, and in turn, reducing human exposure to these toxins;
4. generating massive financial potential as The United Nations University estimates the current amount of global e-waste is worth 55 billion euros of raw materials (Balde et al., 2017);
5. using significantly less energy than primary mining since e-waste streams hold a much higher concentration of valuable minerals, and "The proportion of valuable metals that can be recovered from e-waste is up to ten times greater than the amount extracted from primary mineral deposits" (Xavier, 2019);
6. reducing countries' dependency on China for rare earth elements (REE) which holds about 90% of the world's supply of REE (Xavier, 2019);
7. helping to create circular economies to recover the precious and special metals required to produce electronic equipment. One advantage to recycling metals is that they can be recycled repeatedly without any loss in quality.

Despite its numerous benefits, urban mining faces financial, legal, and logistical challenges. First, the initial cost of constructing state-of-the-art recycling centers is extremely high. Thus, only a handful of smelters exist globally, which means e-waste must be transported far distances from around the world. Second, inconsistent legislation exists not only within the United States, but also around the globe. Because laws differ from region to region, enforcement becomes nearly impossible across borders. Third, for urban mining to be efficient, large quantities of e-waste are required. Low collection rates around the world mean many valuable materials are lost as a vast majority of e-waste is either thrown away with municipal waste by consumers or sent to developing countries for informal recycling. Fourth, companies lack the incentive to design products with end-of-life (EOL) in mind. Products are not designed to facilitate dismantling, to promote resource recovery, or to prevent eco-toxicity at their disposal. In fact, recent studies reveal an increasing trend of toxic metals in smartphones between 2007 and 2015 (Singh et al., 2019).

To overcome these challenges coordination and cooperation must occur between the key players including individual governments, non-government organizations, informal and formal recyclers, manufacturers, and the public, who should take the following steps: enact and enforce federal legislation in the U.S., which includes ratifying *The Basel Convention*; coordinate laws and methods of compliance internationally, increase collection rates by offering more convenient and less expensive recycling options to consumers, incentivize companies to design less toxic products with EOL in mind, invest in research to improve all phases of e-waste recycling, and explore newer technologies such as non-toxic hydrometallurgical processes.

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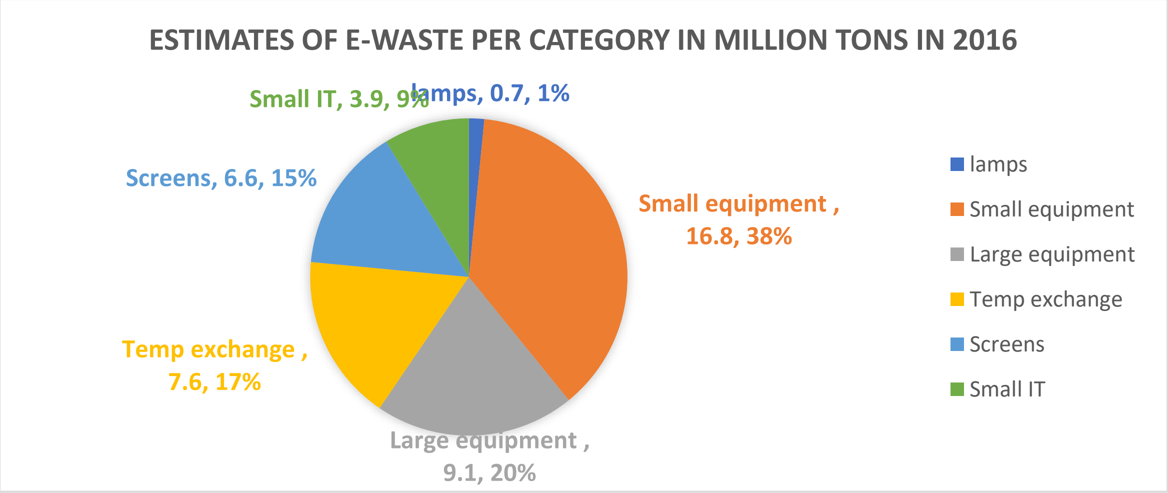
1.0 INTRODUCTION

1.1 What is E-waste?

E-waste, derived from electrical and electronic equipment (EEE) or Waste Electrical and Electronic Equipment (WEEE) refers to a wide range of household and business equipment that has been discarded without the intent of re-use (Balde, et al., 2017). E-waste is separated into six categories: (1) temperature and heat exchange equipment, which includes refrigerators, freezers and air conditioners; (2) screens and monitors, which include televisions, monitors, laptops and tablets; (3) lamps, which includes fluorescent lamps, tungsten bulbs, discharge bulbs and LED lamps; (4) large equipment, which includes washing machines, dryers, dishwashers, electric stoves copy machines, and large printing machines; (5) small equipment, which includes vacuum cleaners, microwaves, toasters, scales, calculators, electric tools, medical devices and electronic toys; (6) and small IT and communications equipment, which includes mobile phones, global positioning systems, personal computers, printers and routers (Balde et al., 2017). Small equipment accounted for 16.8 million tons of e-waste in 2016, constituting the largest percentage of overall e-waste at 38%. (Table 1.1.1).

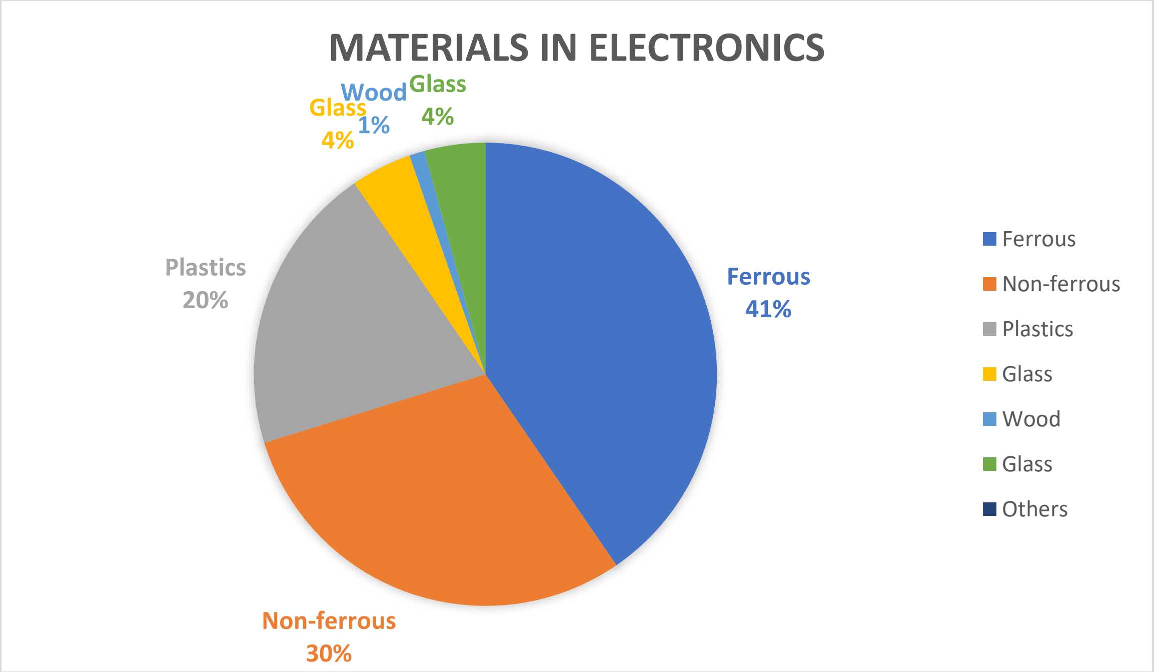
Figure 1.1.1 Estimates of E-waste per Category in Million Tons in 2016



Source: Balde, C.P., V. Forti, R. Kuehr, and P. Stegmann. 2017. Rep. *The Global E-Waste Monitor 2017*.

E-waste is problematic not only in terms of quantity but also because of its toxicity. It is comprised of a complex set of materials including plastics, ceramics, ferrous metals, and non-ferrous metals. It contains up to 1000 toxic substances such as “arsenic, cadmium, lead, chromium, mercury, indium, brominated flame retardants, polyaromatic hydrocarbons, polybrominated diphenyl ethers, and polychlorinated biphenyls” which cause significant harm to the environment and to human health (Prasad et al., 2019). On the other hand, e-waste also contains a combination of rare earth metals and precious metals, including gold, silver, platinum, and palladium, which make it a valuable resource and appealing for recycling. Table 1.1.2 outlines the average material composition of e-waste, and Table 1.1.3 classifies the various elements found in e-waste.

Figure 1.1.2 Average Material Composition of all Categories E-Waste Combined



Source: Tesfaye, Fiseha, Daniel Lindberg, Joseph Hamuyuni, Pekka Taskinen, and Leena Hupa. 2017.

Table 1.1 Classification of Elements found in all Categories of E-waste Combined

Scare Elements	Precious Metals	Base Metals	Platinum group metals	Metals of Concern
Tellurium	Gold	Copper	Platinum	Mercury
Gallium	Silver	Aluminum	Palladium	Lead
Selenium		Nickel	Ruthenium	Cadmium
Germanium		Tin	Iridium	Arsenic
Tantalum		Zinc	Rhodium	Indium
		Iron		Antimony
				Beryllium

Source: Tesfaye, Fiseha, et. al., 2017.

1.2 E-Waste's Alarming Growth Rate

E-waste is the fastest growing form of waste in the industrialized world and is increasing at an alarming rate of 3 to 5 percent each year, which is about three times faster than any other form of waste (Kumar et al., 2017). For instance, in 2016 the world generated "44.7 million metric tons (Mt) of e-waste, the equivalent of nearly 4,500 Eiffel Towers, and that amount is projected to grow to 52.2 Mt in 2021" (Balde et al., 2017). Without intervention, this trend will continue because of multiple factors: rapid product innovation, high consumer demand, decreasing prices of electronic equipment, and an increasing middle class in developed countries with more disposable income (Balde et al., 2017). These factors increase the amount of obsolete equipment, and in turn, the amount of e-waste. Consumers and businesses often replace their laptops, computers, PCs, routers, and TV sets even if they are not broken to benefit from the latest upgrades, higher speeds, and latest technologies. For instance, the average smartphone lifecycle in the USA, China, and the major EU economies does not usually exceed 18 months to 2 years (Table 1.2).

Table 1.2 Smartphone Lifecycles in Months by Country

	USA	China	France	Germany	Great Britain	Italy	Spain
2015	21.6	19.5	21.6	18.8	23.5	17.7	20
2014	20.9	21.8	19.4	18.2	22.0	18.7	18.2

Source: "Double Digit Smartphone Market Growth Is Over." 2016. *Double Digit Smartphone Market Growth Is over - Global Site - Kantar Worldpanel*.

1.3 Where is E-waste Generated?

According to Balde et al. (2017), Asia generated the most e-waste in 2016 at 18.2 Mt, which constituted over 40% of the total global e-waste. Despite its high generation rate, Asia only collected 15% of its total e-waste, lower than both the Americas and Europe. Europe produced the next highest amount of e-waste at 12.3 Mt, but it had the highest collection rate of 35%. Interestingly, Oceania, which only generated 0.7 million tons of e-waste, had the highest rate per inhabitant at 17.3 kg and had the lowest collection rate of only 6% (Balde et al., 2017). (Table 1.3). Population is not the key factor determining how much e-waste a country produces, contrary to what one might think. Kumar et al. (2017) explains, "A country with a higher GDP is most likely to have a higher e-waste generation, on the other hand, a country with a larger population doesn't necessarily produce significantly larger amount of e-waste if the purchasing power and GDP is lower." Basically, richer countries produce much more e-waste than poorer, developing countries irrespective of population.

Table 1.3 Amount of E-waste Generated by Continent

Continents	**Amount (in million tons)**	**Amount (kg per inhabitant)**	**% of global e-waste**	**Collection Rate**
Africa	2.2	1.9	5%	0%
Americas	11.3	11.6	25.3%	17%
Asia	18.2	4.2	40.7%	15%
Europe	12.3	16.6	27.5%	35%
Oceania	.7	17.3	1.6%	6%

Source: Balde, C.P., V. Forti, R. Kuehr, and P. Stegmann. 2017. Rep. *The Global E-Waste Monitor 2017*.

1.4 Where Does E-Waste Go?

E-waste is commonly exported from developed countries to developing countries, often illegally. It is estimated that only 20% of all the annual e-waste is collected and recycled, and 80% or approximately 34.1 million tons of e-waste generated worldwide is untraced and unreported, “likely dumped, traded, or recycled under inferior conditions” (Balde et al., 2017). Even in countries with formal recycling programs such as the United States, e-waste is often not properly recycled. In fact, Basel Action Network, a non-profit that was formed to create international awareness of the dangers of improper processing of electronic waste, designed a project called the E-trash Transparency Project in which it placed 205 GPS tracking devices into electronic devices and delivered them to Goodwill and other recyclers to find out where the equipment was sent. BAN tracked three types of e-waste: liquid crystal display (LCD) monitors with mercury backlights, cathode ray tube (CRT) monitors, and printers. The study found that 34% of the 205 trackers were moved offshore, almost all to developing countries. 93% of the trackers exported went to developing countries, primarily to Asia, and 7% moved to Mexico and Canada (Puckett, 2016). In addition, of the 152 trackers that were delivered directly to formal recyclers, 40% of those were exported and 96% of those exports were illegal (Puckett, 2016).

1.4.1 China

In December of 2017, China passed a law termed the “National Sword” banning the import of 24 kinds of waste, including e-waste (Greenpeace East Asia, 2017). Until then, China had imported 70 percent of the world’s e-waste, most of which was treated and disposed of unsafely through primitive methods (Prasad et al., 2020). Until this law was passed, Guiyu, China had been considered the e-waste dumping ground of the world. Guiyu has a population of about 150,000 people and, until the ban, it had about 6000 family owned businesses, most of which dismantled electronic waste to extract lead, gold, and other valuable materials. This industry employed thousands of people of all ages who dismantled "over 1.6 million pounds of electronics such as cell phones, computers, and electronic home appliances yearly" and earned only $1.50 per day working 16-hour shifts (Misachi, 2017).

Figure 1.4.1.1 Women picking through wires torn out of computers in Guiyu, China

Source: Basel Action Network. 2013.

Despite the efforts to stop the export of e-waste to China, Basel Action Network's tracking system discovered that more than half of the exported trackers in 2016 ended up in Hong Kong's New Territories, sparking concern that this area might become the new Guiyu. BAN's 205 trackers found 48 different electronics junkyards in the New Territories and estimated "there are likely between 100 and 200 such sites now involved there smashing and crudely separating commodity and toxic fractions from printers, LCD screens, and other equipment" (Puckett, 2016).

Figure 1.4.1.2 Computer parts scattered at a New Territories electronics junkyard in Hong Kong

Figure 1.4.1.3 Piles of American printer waste at a typical New Territories electronics junkyard

Source Images 1 and 2: Puckett, Jim, and Eric Hopson. 2016. "Scam Recycling: e-Dumping on Asia by US Recyclers. The e-Trash Transparency Project." *Basel Action Network*.

1.4.2 Other Developing Countries: India, Nigeria, Ghana

While most of the world's e-waste has historically been exported to China, "the remaining portions mostly find their way to India and other East Asian and African countries such as Nigeria" (Prasad et al., 2020). For example, between 50-60% of all e-waste in India was imported from OECD (Organization for Economic Co-operation and Development) countries (Prasad et al., 2020). In 2015, Nigeria imported 66,000 tons of computers, televisions, and monitors, out of which 16,000 tons were not working (Prasad et al., 2020). Even though the Nigerian Government specifically banned the import of CRT-devices, around 260 tons are still imported annually, and the majority of these came from China (23%), the USA (15%), and the UK and Spain (14%) (Balde et al., 2017). Other studies show that despite Europe's strict laws regarding e-waste trades, 70% of the total e-waste in Nigeria is coming from Europe (Prasad et al., 2020). Furthermore, Ghana has also attracted a lot of attention for its illegal importation of electronic waste and primitive recycling practices. Ghana imports about 150,000 tons of secondhand electronics a year according to a study done by the Basel Convention in 2011 (Yeung, 2019). The recycling activities in Ghana are mostly done informally and often involve open burning in dumpsites or landfills. About 80,000 men, women, and children work in the Agbogbloshie e-waste dump, living either on the site or in the nearby slums (Yeung, 2019).

Figure 1.4.2.1 **Young men and boys burning electronics at the Agbogbloshie dump in Accra, Ghana.**

1.4.2.2 Agbogbloshie dump on the Odow River in Accra, Ghana

Source Images 1 and 2: Puckett, Jim. 2015. "Exporting Deception: The Disturbing Trend of Waste Trade Denial." *Basel Action Network*. Basel Action Network.

1.5 Negative Impacts of E-Waste on the Environment

E-waste contains up to 1,000 toxic substances including heavy metals (lead, mercury, and cadmium), persistent organic pollutants (POPs), and other hazardous substances, which if not properly treated cause significant harm to both the environment and human health (Prasad et al. 2020). The lack of legislation, weak environment protection measures, and poor recycling infrastructures in many developing countries allow for unsafe and uncontrolled recycling practices. After e-waste products can no longer be reused, they are informally collected and often recycled through "backyard recycling" or primitive methods, which can cause severe damage to the environment and the people residing in nearby areas. Some of the primitive treatment techniques include the following: open burning of cable to extract metals, toner sweeping, acid leaching for precious metals, unprotected chipping and melting of plastics without proper ventilation, stripping of metals in open-pit acid baths, and direct dumping of unsalvageable matters into the sites (Balde, et al., 2017, Prasad et al., 2020). Cyanide leaching is another commonly used technique for processing e-waste. These recycling sites act as the pollution source to ecological systems and contaminate the soil, water, and air.

The hazardous substances emitted from e-waste are categorized by Solving the E-waste Problem (StEP) (2009) into three distinct groups as either primary, secondary, or tertiary. (Table 1.5). Primary emissions, like lead and arsenic are substances found in the e-waste, which leach directly into the environment. Secondary emissions, like dioxins or furans, are released into the environment through incineration or smelting. Tertiary emissions, like cyanide, are hazardous substances used during the recycling process that are released because of improper handling.

Table 1.5 Categories of E-waste Emissions

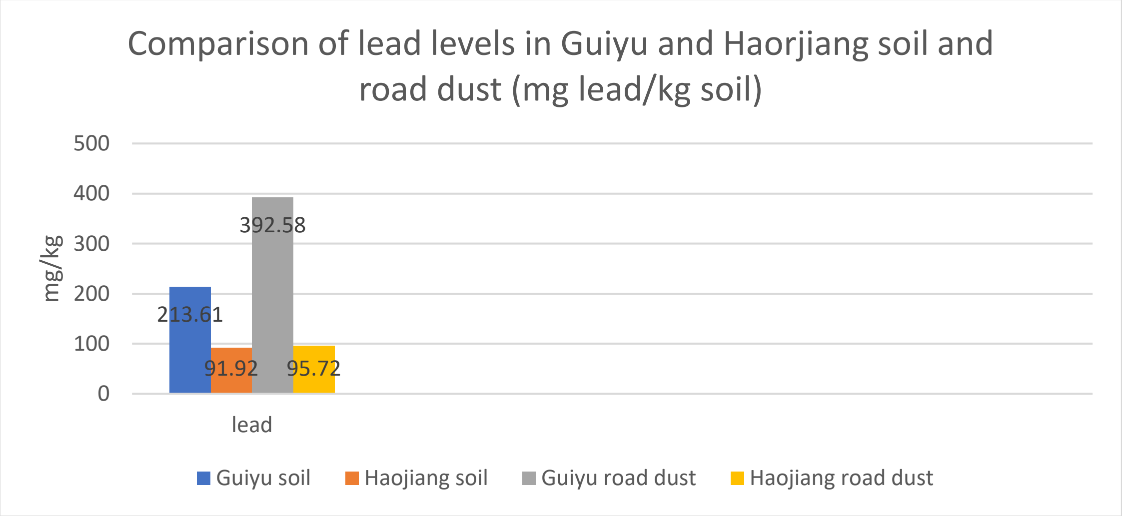
Type	Definition	Examples
Primary Emissions	Hazardous substances in e-waste	Lead, mercury, arsenic PCBs, fluorinated cooling fluids.
Secondary Emissions	Hazardous reaction products of e-waste because of improper treatment	Dioxins or furans formed by incineration or inappropriate smelting of plastics with halogenated flame retardants
Tertiary Emissions	Hazardous substances used during recycling that are released because of improper handling and treatment	Cyanide for leaching, mercury for gold amalgamation

Source: Solving the E-Waste Problem (StEP). 2009. "Sustainable Innovation and Technology Transfer Industrial Sector Studies: Recycling from E-Waste to Resources*." United Nations Environment Program.*

1.5.1 Soil

Contaminates from e-waste such as lead, mercury and cadmium are leached into the soil of landfills and primitive recycling cites. "The toxic substances in e-waste are decomposed and transferred by water to percolate through the soil as landfill leachate" (Prasad et al., 2020). The leachate contains "high levels of dissolved and suspended organic substances, inorganic compounds, and heavy metals" (Prasad et al., 2020). Scientists have studied the leaching of toxins from e-waste and determined that the concentration of lead and other heavy metals was significantly higher in the leachate from landfill that contained broken e-waste material than the leachate without e-waste. (Prasad et al, 2020). For instance, the National Institute of Environmental Health (NIEH) studied the levels of lead in the soil and road dust of two different cities in China: Guiyu, which is highly contaminated by large quantities of e-waste, and Haojiang, the control city, which has little to no electronic waste. The samples were collected in four seasons between 2012 and 2013 and concluded that lead levels were more than double in the soil sample and four times higher in the road dust samples in Guiyu than in Haorjiang (Chen and Kim, 2018). Xinatras from the Center for Disease and Control Prevention (2016) states, "To protect pica children, a lead soil standard should be below 100mg/kg."

Figure 1.5.1 Lead Levels in Soil and Road Dust in Guiyu and Haorjiang



Source: Chen, Aimin, and Stephani Kim. 2018. *NIEHS PEPH WEBINAR: E-WASTE AND ENVIRONMENTAL HEALTH*. National Institute of Environmental Health.

1.5.2 Aquatic Ecosystems

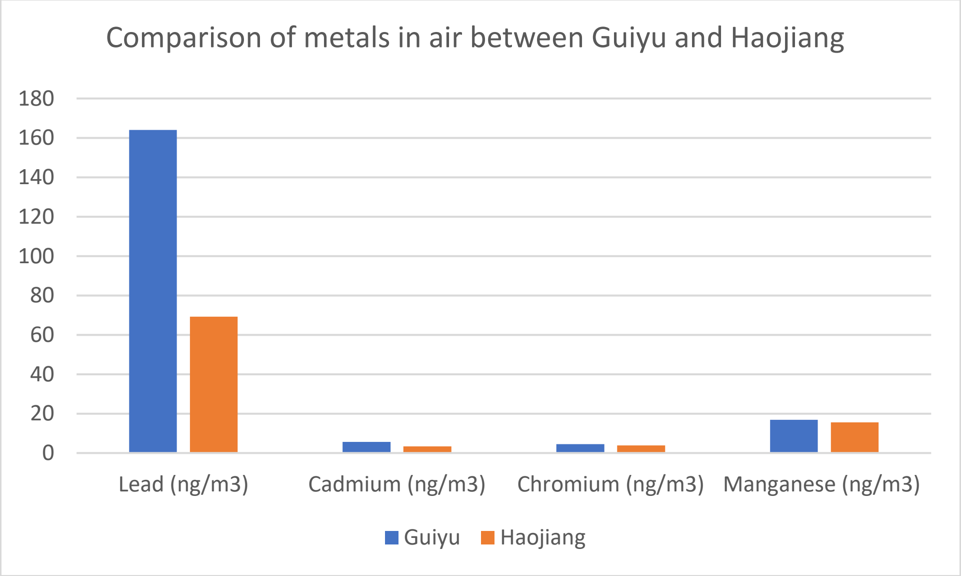
The improper treatment and disposal of e-waste also contaminates the aquatic ecosystems near treatment sites. Many of the e-waste treatment processes take place near water sources "due to the requirement of continuous and easy supply of water for metal extraction processes" (Prasad et al., 2020). For instance, before the reforms in China, workers in Guiyu used primitive methods such as highly corrosive acid baths to extract valuable materials from electronics and to wash out the printer toner from the cartridge in the river. The water in the area is now highly polluted and locals must bring in drinking water from nearby towns. "The nearby Lianjiang River is highly contaminated by heavy metal three times above the desired levels" (Misachi, 2017). Toxic substances from the improper treatments of e-waste such as lead, tin, barium, hydrocarbon, and brominated substances are leached into the groundwater and get released directly into river and banks, destroying the fish and flora (Prasad et al., 2020). Primitive recycling techniques like the chemical stripping of chips and other gold-plated compounds using nitric and hydrochloric acid along riverbanks release toxins into the water supply (Prasad et al., 2020).

Furthermore, hazardous substances from e-waste also leach into groundwater from older landfills that were not designed to receive e-waste because they had no liners or barriers to prevent leakage of leachates. Studies have shown that E-waste leachate contains "several genotoxic and mutagenic substances" and that the underground water table has more mutagenic characters than raw leachate "as the underground water table is the place where accumulation takes place" (Prasad et al., 2020). Additionally, e-waste discarded directly into bodies of water causes significant harm. Kumar et al. (2017) states, "The amount of cadmium present in a cell phone battery has a potential to contaminate 600 cubic meters of water."

1.5.3 Air

Informal and crude e-waste recycling methods also leads to the release of toxins into the air, particularly through the shredding and open burning of wires and other plastics. Contaminated air is one of the major contributors for contamination of the human body "through inhalation, ingestion, and dermal contact" (Prasad et al., 2020). The contaminates released into the air depend on the type of e-waste being treated. For example, circuit boards release large amounts of lead and copper into the atmosphere. One site in New Delhi, India reported lead levels at 375,000 mg/kg and copper at 2670mg/kg. Similarly, in the aforementioned study by the NIEH between Guiyu and Haojiang researchers compared the air quality of the two cities over a period of 14 months and confirmed the elevated presence of heavy metals in the air near e-waste sites. The study found higher levels of lead, cadmium, chromium, and manganese in the air samples, with lead levels almost twice as high in Guiyu as in Haojiang (Chen and Kim, 2018).

Figure 1.5.2 Comparison of Metal Concentration in Air in Guiyu and Haojiang, China



Source: Zheng, X.B., et al. 2016. "Ambient Air Heavy Metals in PM2.5 and Potential Human Health Risk Assessment in an Informal Electronic-Waste Recycling Site of China."

1.6 Negative Impacts of E-Waste on Human Health

E-waste recycling sites also adversely affect human health as over 1,000 toxic substances found in e-waste cause significant harm to the human body. Crude recycling methods pose health risks to those working in informal recycling because workers do not wear protective gear and are unaware of the risks involved in handling e-waste. Moreover, the practice of informal recycling often involves the use of illegal labor of children and pregnant women. “The traditional recycling methods in Guiyu are dangerous and harmful to the workers’ health with about 80% of the children population in the area suffering from lead poisoning. Workers do not put on protective clothing and use their unprotected hands to rip and strip away the electronic parts” (Misachi, 2017). Lead is one of the most common toxins found in e-waste and it has a wide range of harmful effects on people depending on their exposure. Short-term exposure may result in, “loss of appetite, headache, hypertension, abdominal pain, renal dysfunction, fatigue, sleeplessness, arthritis, hallucinations and vertigo,” but long-term exposure can result in more severe side effects such as, “mental retardation, birth defects, psychosis, autism, allergies, dyslexia, weight loss, hyperactivity, paralysis, brain damage, kidney damage, and even death” (Prasad et al., 2020). Other common ailments brought on by the dangerous working conditions and toxic air pollution at e-waste recycling sites are burns, back problems, infected wounds, respiratory problems, nausea, and headaches (Yeung, 2019).

Table 1.6 Toxic Substances in E-waste and their Associated Health Effects

Substances	Precious metal	Component of electrical equipment	Human health effect
Aluminum (Al)		Printed wiring board, cathode ray tubes, computer chips, hard drives, mobile phones, and connectors	Skeletal development and metabolism, neurotoxicity, and fetal toxicity
Arsenic (As)		Printed wiring board and mobile phones	Skin alterations, increased risk of diabetes and cancer; decreased nerve conduction
Cadmium (Cd)		Switches, springs, connectors, batteries, circuit boards, semiconductor chips, cathode ray tubes, mobile phones, toner	Long-term cumulative poison, bone disease, affects kidneys, reproductive damage, and lung emphysema, carcinogen
Chromium (Cr)		Anticorrosion coatings, data tapes, floppy disks, mobile phones	DNA damage, lung cancer, impacts on neonates, reproductive, and endocrine functions
Copper (Cu)		Printed wiring board, cathode ray tubes, computer chips, central processing unit, cables, mobile phones	Liver damage

Gold (Au)	Yes	Printed wiring board, computer chips, central processing unit, mobile phones, connectors	Nausea, headache, and paresthesia
Iron (Fe)		Printed wiring board, cathode ray tubes, mobile phones, housing	Liver damage
Lead (Pb)		Printed circuit boards, glass in cathode ray tubes, light bulbs, tv's, mobile phones, batteries	Kidney failure, central and peripheral nervous systems, damage to blood and reproductive systems, anemia, chronic neurotoxicity
Lithium (Li)		Batteries	Causes nausea, diarrhea, dizziness, muscle weakness, fatigue, and dazed feeling
Mercury (Hg)		Thermostats, sensors, monitors, cells, printed circuit boards, batteries, cathode fluorescent lamps	Chronic damage to brain, damage to liver, central and peripheral nervous system, fetus, neurobehavioral development of children, anemia, kidney damage and neurotoxicity
Nickel (Ni)		Batteries, printed wiring board, mobile phones, cathode ray tubes, housing	Lung cancer, cardiovascular disease, neurological and developmental deficits in children
Palladium (Pd)	Yes	Hard drives, circuit board components, mobile phones, printed wiring board	Skin and eye irritations
Platinum (Pt)	Yes	Hard drives and circuit board components	Respiratory effect
Silver (Ag)	Yes	Printed wiring board, computer chips, keyboard membranes, mobile phones, capacitor	Induction of genes associated with cell cycle progression and DNA damage
Zinc (Zn)		Cathode ray tubes, printed wiring board, mobile phones, batteries, metal coatings	Increased risk of copper deficiency, anemia, and neurological abnormalities
Brominated flame retardants (BFR's)		Fire retardants for electronic equipment, plastic casing of computers, cables, mobile phones, connectors	Neurotoxicity, impaired learning, and memory functions, interferes with thyroid and estrogen hormone systems
Polyaromatic hydrocarbons (PAH)		Released as combustion byproduct	Carcinogenicity, mutagenicity, and teratogenicity
Polybrominated diphenyl ethers		Fire retardants for electronic equipment	Reproductive development, neurobehavioral development, thyroid function, and hormonal effects in animal

Polychlorinated biphenyls		Dielectric fluids, lubricants and coolants, fluorescent lighting. Ceiling fans, dishwashers	Carcinogenicity, liver, thyroid, immune function, reproductive, neurobehavioral development
Polyvinyl chloride (PVC)		Insulation on wires and cables	Incineration of PVC produces chlorinated dioxins and furans, which are highly persistent in the environment and toxic even in low concentrations.

Source: Prasad, M. N. V., Meththika Vithanage, and Anwesha Borthakur. 2020. *Handbook of Electronic Waste Management: International Best Practices and Case Studies*.

The contaminants in e-waste also harm human health by entering the food chain in nearby areas. Prasad et al. (2020) states, "The main route for heavy metal exposure to humans is ingestion (90%), with the chain of soil-crop-food." For instance, a recent study done by BAN and International Pollutants Elimination Network (IPEN) found the "highest levels of brominated and chlorinated dioxins – some of the most hazardous chemicals on Earth – ever measured in free-range chicken eggs in Agbogbloshie, Ghana" (BAN, 2019). The process of smashing and burning the plastic casing and wires to extract the metals releases dangerous chemicals and creates by-product chemicals like brominated and chlorinated dioxins and furans. These chemicals were ingested by the chickens in the area, and the sampling of the eggs showed "alarmingly high levels of some of the most hazardous and banned chemicals in the world (BAN, 2019). Studies like this reveal that the improper treatment of e-waste can lead to dangerous food chain contamination.

2.0 PHASES AND PROCESSES OF URBAN MINING

2.1 What is Urban Mining?

Modern electronics contains a heterogenous mix of up to 60 different elements, many of which are valuable, some are hazardous, and some are both (Balde et al, 2017). Although e-waste is categorized as hazardous waste, it also contains precious metals such as gold, silver, platinum, and palladium and other valuable materials such as iron, copper, aluminum, glass, ceramics, and plastics. The term urban mining describes the process of recovering precious metals and energy from e-waste streams through sustainable recycling methods (Tesfaye et al., 2017). E-waste should be viewed as a valuable resource because more than 90% of WEEE can be recycled and reused in new electronic devices (Prasad et al., 2020). The most precious part in e-waste streams are the printed circuit boards (PCBs), which are found in TV's, computers, mobile phones, smart phones, and LCD notebooks because they contain the highest concentrations of precious metals (Tesfaye et al., 2017). The most valuable metals recovered from urban mining are gold, silver, palladium, and copper. According to Zeng et al. (2018), "The total economic share of copper and gold account for over 50% among all resources in e-waste." The potential for recovery of precious metals through urban mining is significant. For example, according to the Basel Action Network (2020) the responsible recycling of one million cell phones can recover 20,000 pounds of copper, 550 pounds of silver, 50 pounds of gold and 20 pounds of palladium. Additionally, the plastics derived from e-waste can be melted down for use as raw materials for new products or for fuel. Even glass from e-waste that often contains lead can be recycled, recovering silica and other valuable components at facilities like Noranda's smelter in Quebec (Bleiwas, 2001).

2.2 Collection

Urban mining consists of three main phases: collection, pre-processing, and end-processing. The first stage, collection, is defined as "the act of gathering, sorting and packaging e-waste for transportation and proper disposal" (Hieronymi, 2013). This step is crucial because it determines the amount of material available for recovery, and in turn, the efficiency of the urban mining process overall. There are six different types of collection methods, including (1) curbside pickup by collection companies, (2) donation to charitable organizations, (3) collection events hosted by recyclers, governments, or private companies, (4) drop off locations at companies or local city recycling facilities, (5) mail-in services, or (6) disposal in the waste stream (Hieronymi, 2013).

2.3 Pre-processing

2.3.1 Sorting and Dismantling

During the second phase of urban mining, pre-processing, products are dismantled, materials are separated from each other, and hazardous substances are removed. The mechanical disassembly of electronic equipment occurs either selectively, in which specific components are removed individually, or simultaneously, in which “de-soldering is done by heating the whole unit in a tin furnace” (Prasad et al., 2019). During this phase, batteries are removed, which can be taken to facilities for recovery of cobalt, nickel, and copper (StEP, 2009). Refrigerants must also be removed from air conditioners and refrigerators to avoid harmful emissions. Items containing cathode ray tubes (CRT) such as TVs and monitors must be removed from the panel glass. Finally, backlights containing mercury must be carefully removed from liquid crystal display (LCD) monitors before the next phase (StEP, 2009). Circuit boards, which contain most of the precious metals and special metals should be removed from equipment before shredding to prevent losses of those metals. However, preprocessing is not necessary for all forms of e-waste. For instance, mobile phones and MP3 players only need the battery to be removed before being treated directly by an end-processor (StEP, 2009).

2.3.2 Crushing, shredding, and milling

After the e-waste materials have been physically dismantled, they are then crushed, shredded, and ground into a powder form to decrease the particle size for further processing. Various types of equipment such as double shaft metal shredders, hammer mills, and knife mills are used for crushing and shredding (Kumar et al., 2017). An efficient dust collection system must be used because crushing can generate hazardous dust and result in a 40% loss of materials (Kumar et al., 2017). After the crushing process, the remaining fragments are pulverized using "ball and disc milling" (Prasad et al., 2019).

2.3.3 Separation

The final step of pre-processing phase is to separate non-metals from metals before sending the concentrate for end-processing. Gravity separation is considered the best option for separating nonmetals from metals. "Density separators such as air tables, air cyclones, and centrifugal separators are used to recover base metals such as copper, gold, and silver from nonmetal fractions" (Kumar et al., 2017). Magnetic separation, a second method, uses low-intensity drum separators to recover ferro-magnetic metals from nonferrous metals and other nonmagnetic waste (Prasad et al., 2019). Copper alloys are separated from the waste stream in this method. Finally, electrostatic separation is used to separate nonconductive material from conductive material and is advantageous because it is less hazardous and uses less energy. Following either of these processes, eddy current separators are used to separate diamagnetic form paramagnetic materials. As an example, eddy current separators are used to recover aluminum (Kumar et al., 2017).

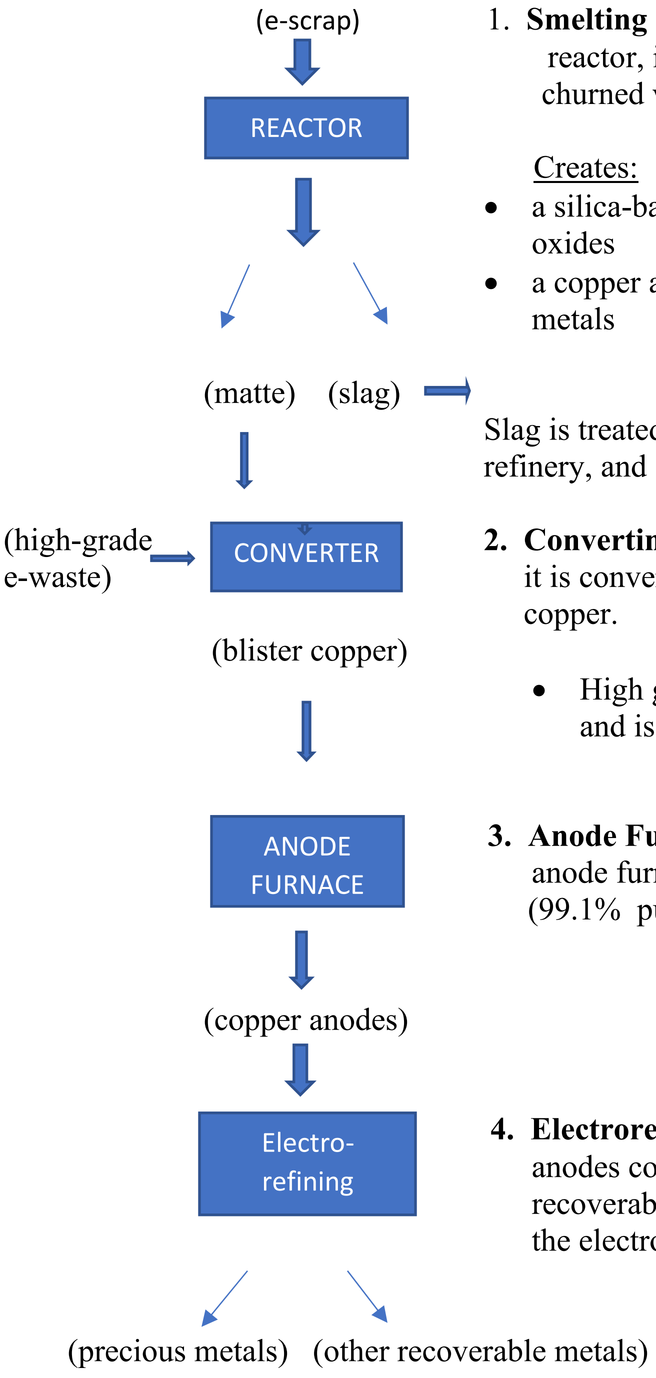
2.4 End-processing

End-processing is the final stage in the e-waste recycling process and involves various methods to recover valuable metals from the concentrate obtained from the pre-processing phase. The three main processes, pyrometallurgical, hydrometallurgical, and biometallurgical are used mostly to recover and purify copper, gold, silver, and palladium.

2.4.1 Pyrometallurgical

Pyrometallurgical processes are the most conventional method for recovering non-ferrous and precious metals from the e-waste stream because they are more economical and eco-efficient, and they maximize the recovery of precious metals (Tesfaye et al., 2017). Cui and Zhang (2008) state that pyrometallurgical processing involves "incineration, smelting in plasma arc or blast furnaces, drossing, sintering, melting and reactions in a gas phase at high temperatures." In the first step of the process, materials are placed into a reactor where they are immersed in a molten bath at a temperature of 1250 degree Celsius and then "churned by a mixture of supercharged air (up to 39% oxygen)" (Cui and Zhang, 2008). The smelting process creates a silica-based slag which contains iron, lead, and zinc oxides and is cooled and milled to recover more metals before it is disposed. Next, the copper matte is removed and transferred to a converter. Finally, the "liquid blister copper is refined in anode furnaces and cast into anodes with purity of 99.1%. The remaining 0.9% contains the precious metals, including gold, silver, platinum, and palladium" along with other metals such as selenium, tellurium, and nickel (Cui and Zhang, 2008). In the final step of the process, electrorefining of the anodes recovers purified metals. **See figure 2.4.1 below.**

Figure 2.4.1 Steps of Pyrometallurgical Processing



1. **Smelting Step:** shredded e-scrap is entered into a reactor, immersed in molten bath at 1250 Celsius, and churned with 39% oxygenated air.

<u>Creates:</u>

- a silica-based “slag” – contains iron, zinc, and lead oxides
- a copper and iron-based “matte” – contains precious metals

Slag is treated separately through lead blast furnace, lead refinery, and special metals plant.

2. **Converting Step:** “matte” is sent to a converter where it is converted into an impure copper called “blister” copper.
   - High grade e-waste does not go through smelting and is placed directly into converter.

3. **Anode Furnace:** liquid blister copper is sent to anode furnace to be refined and cast into anodes (99.1% purity).

4. **Electrorefining Step:** The remaining 0.9% of the anodes contain the precious metals and other recoverable metals, which are recovered through the electrorefining processes.

The benefits of the pyrometallurgical method are that the high temperatures make it a fast process and the combustion of the plastics can be used to fuel the process. Some of the drawbacks to the pyrometallurgical method are that (1) it cannot recover iron or aluminum, which oxidize and dissolve into the slag, (2) it requires high levels of energy, (3) it generates dioxin and furans from the combustion of halogenated flame retardants, (4) ceramics and glass increase the amount of slag, which in turn, increases the loss of precious and base metals, (5) it requires subsequent hydrometallurgical or electrochemical techniques because only partial separation of the metals can be achieved (Cui and Zhang, 2008).

2.4.2 Hydrometallurgical

Hydrometallurgical processing can be more environmentally friendly than pyrometallurgy and involves three basic steps: leaching, solution concentration and purification, and metal recovery. Leaching, the first step in the hydrometallurgical process, is defined as ‘the process of extracting a soluble constituent from a solid by means of a solvent” (Kumar et al., 2017).The four most common leaching agents used to recover precious metals are cyanide, halide, thiourea, and thiosulfate (Cui and Zhang, 2008). While cyanide has been used to leach gold by the mining industry for over 100 years, concern has arisen over its use because of environmental accidents at mines around the world. Cui and Zhang (2008) conclude that based on a comparison of the different leaching methods from an economic and environmental perspective “the leaching of gold by thiourea may be the most realistic substitute.” In the second step, the leachate solutions are separated to concentrate the valuable metals and separate out the impurities. The final step of the hydrometallurgical process involves recovering the precious metals from the leaching solutions. This process includes a variety of separation and purification techniques including "cementation, chemical precipitation, solvent extraction, activated carbon adsorption, ion exchange by resin, and electrodeposition" (Li, 2018).

In general, hydrometallurgy is considered a better option than pyrometallurgy because it is more selective, more predictable, more easily controlled, less energy intensive, and more environmentally friendly (Cui and Zhang, 2008). However, some of the drawbacks of this method are (1) it is a slower and less profitable process, (2) mechanical processing of e-waste for efficient dissolution is more time-consuming and causes a 20% loss of precious metals, (3) cyanide is hazardous and requires high safety standards for operators, (4) halide leaching requires stainless steel and rubber-lined equipment due to strongly corrosive acidic and oxidizing conditions, (5) thiourea-based gold leaching is expensive and the process needs further development (Tesfaye et al., 2017). It should be noted that often pyrometallurgical and hydrometallurgical steps are combined for treatment of complex materials. For example, Umicore uses hydrometallurgy for further upgrading and purification of the value stream after the initial pyrometallurgical processing (Hageluken, 2007).

2.4.3 Biometallurgical

Biometallurgy is a promising alternative technology because of its reduced initial investment costs, easier control of waste, lower energy consumption, and low environmental impact (Xavier, 2019). Biometallurgy relies on the interaction between microbes and metals to remove metals, using, "microorganisms that convert metals into soluble salts in aqueous media from ores/concentrates/wastes" (Prasad et al., 2019). Biometallurgy incorporates two main methods: bioleaching and biosorption. The first method, bioleaching, uses diverse microorganisms such as bacteria, fungi, and actinomycetes to recover metal from particles in e-waste. The microorganisms can leach the metal particle in two ways, either direct action, in which the organisms directly oxidize minerals and solubilize metals, or indirect action, in which the microorganisms generate the oxidizing agent (Prasad et al., 2019). Because certain bacteria can withstand extreme conditions of pH, they are able to extract metals by oxidizing e-waste with ferric ions. "With this process, in about 5 days, copper can be totally bio-solubilized from waste PCBs" (Xavier, 2019). Even though it is possible to extract metals such as Co, Mo, Ni, Pb, and Zn through bioleaching, "today only copper and gold are industrially produced in significant proportions by this method" (Cui and Zhang, 2008). Since this is a slower process than others it may require a greater footprint. The benefits of bioleaching are that it has low operational costs, is highly efficient, is environmentally friendly, and can be carried out at room temperature (Prasad et al., 2019). As can be seen in the chart below, a high percentage of metals is recovered through the bioleaching process.

Table 2.4 Recovery Percentage of Metals from Various Types of E-waste Using Bioleaching

E-waste	Organisms	Recovered metals	Percent Recovered
PCBs of computers	*Acidithiobacillus ferrooxidans*	Cu Zn Pb Ni	94 92 64 81
LCDs	*Acidithiobaeilllus thiooxidans*	In Sr	100 10
Printed Circuit Boards	*A.thiooxidans*	Zn Cu Al	83.8 96.8 75.4
Dust from WEEE shredding	*A.thiooxidans*	Ce Eu Nd La Y	>99 >99 >99 80 80

Source: Prasad, M. N. V., Meththika Vithanage, and Anwesha Borthakur. 2020. Handbook of Electronic Waste Management: International Best Practices and Case Studies.

Biosorption, the second method, is a process in which living and nonliving organisms can be used for releasing metals from substrates. Cui and Zhang (2008) define biosorption as, "a passive physico-chemical interaction between the charged surface groups of micro-organisms and ions in solution, in which living as well as dead organisms can be used." Bacteria, fungi, algae, yeasts, and protein can be used for biosorption. Biosorption-based recovery offers many benefits including, "low operating costs, minimization of the volume of chemical and/or biological sludge to be handled, and high efficiency in detoxifying effluents" (Cui and Zhang, 2008). However, it is a slow process and that has not been fully developed for waste with complex metals.

3.0 BENEFITS OF URBAN MINING

3.1 Environmental Benefits

3.1.1 Less harmful to environment than ore mining

Urban mining uses significantly less energy, releases fewer harmful elements, and generates less CO_2 emissions than primary mining. StEP (2009) states, "Primary production, i.e. mining, concentrating, smelting, and refining, especially of precious and special metals has a significant carbon dioxide (CO_2) impact due to the low concentration of these metals in the ores and often difficult mining conditions." Bleiwas (2001) further explains that U.S. mineral processing companies mine circuit boards because they contain much lower levels of harmful elements like arsenic, mercury, and sulfur, which can all potentially be emitted into the atmosphere during primary mining. Primary mining requires considerable amounts of land, creates wastewater and sulfur dioxide, consumes large amounts of energy, and produces high carbon dioxide emissions. For example, to produce 1 ton of gold, palladium, or platinum, generates about 10,000 tons of CO_2 emissions (StEP, 2009). "According to Boliden Ronnskar (Skelleftehamn, Sweden), extracting metals from e-waste requires only from 10 to 15% of the total energy required in metals extraction from ore concentrates" (Tesfaye et al., 2017). Therefore, recovering metals from state-of-the art recycling processes creates only a fraction of these CO_2 emissions and has significant benefits compared to mining in terms of land use and hazardous emissions.

Table 3.1.1.1 CO_2 Emissions of Primary Metal Production of Important EEE Metals (2006)

Metal needed for EEE	Annual demand for metal (tons)	Primary Production of CO2/ton of metal	CO2 emissions (Mt) per year
Copper	4,500,000	3.4	15.3
Cobalt	11,000	7.6	.08
Tin	90,000	16.1	1.45
Silver	6,000	144	.86
Gold	300	16,991	5.1
Palladium	32	9,380	0.3
Platinum	13	13954	.08

Source: Solving the E-Waste Problem (StEP). 2009. "Sustainable Innovation and Technology Transfer Industrial Sector Studies: Recycling from E-Waste to Resources."

Table 3.1.1.2 Recycled Material Energy Savings Over Virgin Materials

Materials	Energy Savings in percentage
Aluminum	95
Copper	85
Iron and Steel	74
Lead	60
Zinc	60

Source: Kumar et. al. 2017. "E-Waste: An Overview on Generation, Collection, Legislation and Recycling Practices."

3.1.2 Preserves finite supply of rare earth elements

Urban mining also reduces the need for new material and preserves rare earth elements that are becoming more difficult to recover including gold, silver, palladium, copper, lithium, platinum, iridium, copper, iron, manganese, nickel, palladium, tin, and zinc. For example, a mobile phone can contain over 40 elements from the periodic table including base metals like copper and tin, special metals such as cobalt, indium, and antimony, and precious metals such as silver, gold and palladium (StEP, 2009). In 2007, the sale of mobile phones and personal computers added up to

3% of the world mine supply of gold and silver, 13% of palladium and 15% of cobalt (StEP, 2009).

To keep metals available for the manufacture of new electronic products and to preserve energy resources for future generations, effective recycling is crucial. For instance, antimony is an important element that is used to make flame retardants in plastics, coatings, and electronics, but its reserves are estimated to be scarce by 2050. Xavier (2019) claims, “Antimony will be the first mineral to have its production totally dependent on secondary sources, mainly from e-waste.” Gallium and Indium, two other elements which only have an estimated life of 20 years before they completely run out, can also be recovered from e-waste, thus preserving the earth’s finite supply.

3.1.3 Reduces amount of toxic waste released into environment

One obvious benefit of urban mining is that it reduces the amount of e-waste directly deposited into landfills, and in turn, it reduces the amount of hazardous substances such as lead, mercury, cadmium, chromium, and flame retardants. Urban mining also reduces the amount of toxins released into the environment through unsafe and primitive recycling methods as discussed in section 1.5. It should be noted that certain processes of urban mining such as the smelting of e-waste materials at high temperatures can release hazardous gasses into the environment. These gasses contain dioxins, furans, and polybrominated diphenyl ethers, but this can be avoided through special emission controls (Tesfaye et al., 2017). On the other hand, the primitive approaches to extracting raw materials from printed wiring boards, wires, and other components release hazardous toxins into the soil, water, and air without any form of control or safety measures in place. “Essentially, the environmental footprint of a fridge, a computer and other electronic devices could be significantly reduced if treated in environmentally sound managed recycling operations, which prevent hazardous emissions and ensure that a large part of the contained metals are finally recovered for a new life in a new (electronic) device" (StEP, 2009).

3.2 Human Health Benefits

3.2.1 Reduces human exposure to e-waste toxins

Similarly, if electronic waste is disposed of properly and treated in state-of-the-art recycling facilities, human exposure to e-waste toxins can be significantly reduced. Currently, thousands of people in underdeveloped countries are still exposed to e-waste toxins through the contamination of the soil, water, and air from both landfill deposits and primitive recycling methods. Strict safety measures still need to be taken at end-processing facilities to protect workers from exposure to harmful toxins during the metal extraction processes.

3.3 Economic Benefits

3.3.1 Profitable Industry

The United Nations University estimates that the current amount of global e-waste is worth 55 billion euros of raw materials (Balde et al., 2017). A study done in 2014 found that that "the potential revenue that could be achieved from the efficient recycling of the generated WEEE from the selected 14 EEE in EU alone to be 2.5 billion euros, and in the future with increasing volumes of electronic devices, it estimated the revenue to rise to 3.67 billion euros" (Tesfaye et al., 2017). Balde et al. (2017) claims that in 2016 about 435 kilotons (kt.) of mobile phones waste was generated across the globe and that the value of raw materials in those phones was worth 9.4 billion euros. Overall, a massive financial potential exists for recovering raw materials from e-waste. Table 3.3.1 specifies the amount of raw materials in kilotons generated in the e-waste stream in 2017 and their corresponding economic value. The total potential revenue from the raw materials present the e-waste in 2017 was 54,827 million euros. Even though the precious metals and strategic minerals only account for 1% of the total equipment weight, they account for 80% of the intrinsic value (Xavier, 2019).

Table 3.3.1 Value of Materials Present in E-waste Stream in 2017

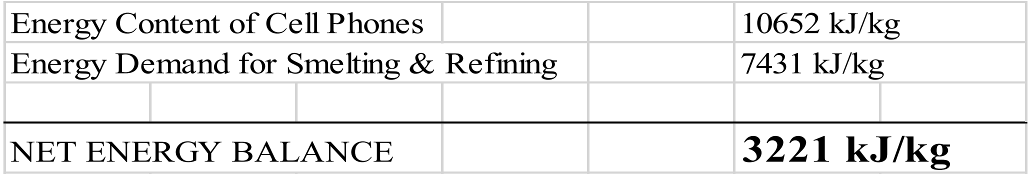
Material	**Amount (kt.)**	**Value (million Euros)**
Iron/steel	16,283	3,582
Copper	2,164	9,524
Aluminum	2,472	3,585
Gold	1.6	884
Silver	0.5	18,840
Palladium	0.2	3,369
Plastics	12,230	15,043
Total		**54,827**

Source: Balde, C.P., V. Forti, R. Kuehr, and P. Stegmann. 2017. Rep. *The Global E-Waste Monitor 2017*.

3.3.2 Urban mining uses less energy than primary mining

Urban mining is more cost effective than ore mining because it uses less energy. In fact, in some cases, rather than depleting energy resources, urban mining generates energy from the process, which results in a positive net balance of energy. For example, Hageluken (2007) claims that Umicore experiences a positive energy balance from the entire refining process because it uses plastics and other materials from the e-waste stream as energy sources for the process. (Table 3.3.2.2) The energy surplus can then be used to smelt other materials.

Table 3.3.2.1 Energy Balance of Umicore Process



Energy Content of Cell Phones	10652 kJ/kg
Energy Demand for Smelting & Refining	7431 kJ/kg
NET ENERGY BALANCE	**3221 kJ/kg**

Source: Hageluken, Christian. 2007. "Metals recovery form e-scarp in a global environment; Technical capabilities, challenges & experience gained" (Conference Session). 6th Session of the OEWG Basel Convention, Geneva, Switzerland. http://archive.base.int/industry/sideeven030907/umicore.pdf

Another study done in Belgium compared the natural resource savings between landfilling and recycling of desktops and laptops. The study concluded that natural resource consumption of recycling is much less than in a landfilling scenario, where materials must be generated from virgin natural resources. Eygen (2016) claims, “Overall, recycling saves 80 and 87 percent of the natural resources in the case of desktops and laptops, respectively.”

3.3.3 E-waste contains a higher concentration of metals than ore

Furthermore, urban mining is more efficient than ore mining because e-waste streams hold a much higher concentration of valuable minerals than mined ores, making metals easier and less expensive to recover. “The average grades of Cu, Au, Ag, and Pd in e-waste are significantly higher than those grades in mined ores” (Tesfaye et al., 2017). In fact, Xavier (2019) claims that “the proportion of valuable metals that can be recovered from e-waste is up to ten times greater than the amount extracted from primary mineral deposits.” As can be seen in the chart below, the metal concentration in the precious metals is significantly higher than in ore. When averaging all electronics, gold concentration is 127 parts per million (ppm), whereas ore contains only 1.01 ppm; silver concentration is 1009 ppm in electronics compared to only 215.5 in ore; and palladium concentration in electronics concentration is 51.5 ppm compared to 2.7 ppm in ore. The percentage of copper by weight is also significantly higher in electronic waste at 13.8 percent compared to that in ore at only 0.6 percent. (Table 3.3.3.1 below)

Table 3.3.3.1 Metal Concentrations Comparison between Electronics and Ore

Product	**Copper (% by wt.)**	**Silver (ppm)**	**Gold (ppm)**	**Palladium (ppm)**
Television board	10	280	20	10
PC board	20	1,000	250	110
Mobile phone	13	3,500	340	130
Portable audio scrap	21	150	10	4
DVD player scrap	5	115	15	4
AVERAGE ELECTRONICS	**13.8**	**1,009**	**127**	**51.6**
ORE/MINE	**0.6**	**215.5**	**1.01**	**2.7**

Source: Kumar et. al. 2017. "E-Waste: An Overview on Generation, Collection, Legislation and Recycling Practices." *Resources, Conservation and Recycling* 122: 32–42. doi:10.1016/j.resconrec.2017.01.018.

Precious metals are the most valuable part of the e-waste stream even though they constitute only a small percentage of the overall weight of e-waste. Within the e-waste stream, the printed circuit board is the most valuable part and accounts "for over 40% of the total e-waste metal value" because it contains a larger concentration of precious and critical metals (Kumar, 2017).

3.3.4 Urban mining is more efficient than informal recycling

Finally, urban mining is much more efficient than the primitive recycling practices used in underdeveloped countries, which often waste material resources. A recent study estimated that the overall efficiency of a wet chemical process recovering gold from printed wiring boards in India was at most 20% compared to 95% in a state-of-the-art facility in the EU that recovers "not only gold but also 16 other precious metals with lower total emissions" (Cobbing, 2008).

3.3.5 Reduces countries' dependency on China for rare metals

Another economic benefit of urban mining is that it reduces countries' dependency on China for rare earth elements (REE) which holds about 90% of the world's supply of REE (Xavier, 2019). These elements are critical for the countries that use them in different applications, and unfortunately, these REE are concentrated in only a few countries including China, Brazil, Canada, Russia, and Congo (Xavier, 2019). If countries can mine their own REE through recycling and urban mining or purchase from other countries who possess the capability for urban mining, they reduce their dependency on China for these elements.

3.3.6 Helps create circular economies

One of the strongest arguments for urban mining is that it helps to create circular economies to recover the precious and special metals required to produce electronic equipment. The goal of a circular economy is to keep products and all their materials in circulation at their highest value for as long as possible. Xavier (2019) states, "The circular model aims to reduce the need for primary resource extraction, and it targets zero waste generation." One of the biggest advantages to recycling metals is that they can be recycled repeatedly without any loss in quality. In the VRBO documentary, "Urban Mining - Gold in Our Trash" (2015) the sales manager at Umicore, Thierry van Kerckhoven, claims no one can tell the difference between the gold recycled from e-waste and the gold mined from ore because they both possess the same properties and are both 99.99 percent pure. He calls the recycled gold "green gold" because the production has a much smaller impact on the environment.

Furthermore, circular economies aim to achieve not only sustainability but also profitability. Balde et al. (2017) states, "Closing the loop of materials implies the reduction in the need for new raw materials, waste disposal, and energy, while creating economic growth, new 'green' jobs, and business opportunities." The e-waste industry has the potential to create thousands of new jobs. Kumar et al. (2017) states that 300 to 600 new treatment facilities will be needed in China alone to deal with the total generated e-waste between 2020 and 2030, which can potentially provide jobs for up to 30,000 people.

3.5 Successful Urban Mining Operations

3.5.1 Boliden Rönnskär Smelter in Skelleftehemn, Sweden

The Boliden Rönnskär Smelter in Skelleftehemn, Sweden is one of the world's largest recyclers of copper and precious metals from e-scrap, most of which comes from EU and North America. The annual recycling capacity of e-waste at the Boliden Rönnskär Smelter is 120,000 metric tons (Boliden, 2020). Scrap is entered into the process at different stages depending on its purity. High copper-containing scrap such as printed circuit boards and mobile phones are fed directly into the converting process, but lower grade scrap is fed into the Kaldo Furnace, which is combusted with oxygen and oil. The process yields a mixed copper alloy, which is then sent to a copper converter for recovery of metals such as copper, silver, gold, palladium, nickel, selenium, and zinc. "The volatile metals such as Pb, Sb, In, and Cd are segregated into the vapor phase that is recovered by a separate process" (Tesfaye et al., 2017). To prevent environmental harm, the Rönnskär smelter is "equipped with advanced systems to clean process gases and discharge water. Wet gas purification uses water to wash out dust particles, which are returned to the refining process." (Boliden, 2020).

3.5.2 Umicore in Hoboken, Belgium

Umicore Precious Metals Refining in Hoboken, Belgium is another of the world's largest recycler of precious metals from e-waste. Umicore treats approximately 250,000 metric tons of different types of waste annually, 10% of which constitutes electronic waste (Cui and Zhang, 2008). The first step in the operation is feeding the e-waste into the Isa Smelt furnace, which "separates precious metals in a copper bullion from mostly all other metals concentrated in a lead slag, which is further treated at the Base Metals Operations (BMO)" (Cui and Zhang, 2008). The copper bullion is treated by copper-leaching, electrowinning, and precious metals refinery to recover the copper and precious metals (Cui and Zhang, 2008). The lead slag is treated at the BMO through three main methods: the lead blast furnace, which reduces the oxidized slag into impure lead bullion, nickel speiss, copper matte and depleted slag; the lead refinery, which recovers special metals from the lead bullion; and the specials metals plant, which recovers pure metals (Cui and Zhang, 2008).

After removing lithium batteries from mobile phones, Umicore treats materials directly in the integrated smelter without first shredding or sorting into fractions. Direct incineration "reduces the loss of valuable metals in side streams (plastics, Al, Fe, dust) from where they cannot be recovered" (Hageluken, 2007). The separated plastics are too impure for recovery, and the iron, aluminum, and dust are of minor economical value compared to the precious metals recovered. Instead, Umicore uses the energy content of the plastics to fuel the process (as discussed in section 3.3.2). Although Umicore removes lithium batteries from mobile phones, it does not shred any mobile phones or computer circuit boards, but rather dismantles and removes parts manually or mechanically to prevent loss of valuable metals.

Finally, Umicore's Isa Smelt plant uses an emission control system which cools and cleans hygienic gasses and process gasses, using bag house filters, electro-filters, and scrubbers. The system converts sulfur into SO_2, which is then transformed to sulfuric acid. Umicore, monitors its emissions, which are well below the European limits, continuously with a direct display of the measured values in the control room so operators can respond immediately (Cui and Zhang, 2008).

3.5.3 Horne Smelter of Xstrata Copper in Noranda, Quebec, Canada

The Horne Smelter of Xstrata Copper in Noranda, Quebec, Canada is another major commercial pyrometallurgical plant and the only smelter in North America. It has the capacity to process 840,000 tons per year of copper and precious metal bearing materials (Glencore Recycling, 2020). It recycles about 100,000 tons of e-waste each year (Tesfaye et al, 2017). The facility accepts a complex and wide range of electronic materials including computers, cell phones, circuit boards, lead frames, sweeps, insulated consumer wire, copper yokes, among others (Glencore Recycling, 2020).

The Horne Smelter first samples and assesses all materials at U.S. locations in either San Jose or Rhode Island before it sends them to Canada to be processed. After the initial assessment, hazardous components like batteries, cathode ray tubes, and mercury bulbs are removed and separated at sorting stations. The components are then shredded into scrap metals and fines, which are then separated even further using conveyors, shaker tables, cross-belt magnets, and eddy current separators (Glencore Recycling, 2020). Finally, the materials are to the Horne smelter in Noranda, Quebec for metal recovery.

There are three major places in which the smelting process occurs in the Noranda process: the reactor, the converters, and the anode furnaces. First, the materials are placed into the reactor and "immersed in a molten metal bath (1250 degrees Celsius), which is churned by a mixture of supercharged air (up to 39% oxygen)" (Cui and Zhang, 2008). Similarly, as in Umicore's process, energy costs are reduced by the combustion of plastics in the feed. The smelting process oxidizes iron, lead, and zinc into a silica-based slag, which is cooled and milled to recover precious metals before disposal. In the second step, the copper matte containing the precious metals is transferred from the furnace to the converters. In the third step, “the liquid blister copper is refined in the anode furnaces and cast into anodes with a purity of 99.1% copper” (Cui and Zhang, 2008). Only the remaining 0.9% contains precious metals such as gold, silver, and palladium, along with selenium, tellurium, and nickel.

In the final phase of the recycling process, the precious metals are recovered through electrorefining at the CCR Refinery in Montreal, Canada where the impure anode copper is dissolved and deposited on cathode sheets while the impurities contained in the anode are recovered as copper slimes. The electrorefining produces 99.99% pure copper cathodes which are sold on the world market, among other byproducts including gold, silver, platinum, palladium, tellurium, selenium, and nickel sulphate (Glencore Recycling, 2020).

4.0 CHALLENGES TO URBAN MINING

4.1 Economic Barriers

Urban mining faces challenges despite its clear environmental, health, and economic benefits. First, the initial cost of constructing smelters and state-of-the-art recycling centers is extremely high. Tesfaye et al. (2017) explains, “A large investment is required for installing integrated e-waste recycling plants that maximize the recovery of valuable metals and also protect the environment by controlling hazardous gas emissions.” Waste management and urban mining processes require expensive control systems, such sensors to gauge emissions, filtering, emissions controls, and protective carrying equipment (Kazancolglu, 2020).

Second, the uncertainty about the amounts and types of metal in waste streams and the possibility of low scrap value streams hinders initial investment decisions of investors because the value of e-waste is directly tied to the amount of valuable metals extracted during the process (Kazancolglu, 2020). Additionally, the volatility of valuable metal prices on the market, competition with regular metal producers, fluctuating demand for metals, and lack of market data all create barriers to economic investment in urban mining (Kazancolglu, 2020).

Finally, because the initial investment is so high, only a handful of smelters exist globally. The major recycling plants around the world are the Umicore integrate smelting and refining facility in Belgium, the Noranda process in Quebec, the Boliden Ronnskar smelters in Sweden, Kosaka's recycling plant in Japan, the Kayser recycling system in Austria, and the Metallo-Chimique N.V. plants in Belgium and Spain (Tesfaye et al., 2017). The lack of formal recycling centers around the globe means e-waste materials must be transported far distances, which increases operating costs.

4.2 Inadequate and Inconsistent Regulation

4.2.1 Globally

A diverse array of e-waste policies exists around the world today. Some are treaties ratified by governments, others are merely suggested guidelines that hold no one liable. Some countries have well-defined and elaborate legislation on e-waste, whereas some countries have no specific regulation at all. For instance, in Europe, The Waste Electrical and Electronic Equipment

(WEEE) Directive was developed in 2002 to manage EOL electronics by setting collection targets. The target collection rate was changed in 2016 to 45% of all EEE put on the market and to 85% in 2019 (Kumar et al., 2017). The Restriction of Hazardous Substances (RoHS) Directive restricts the use of hazardous substances in EEE, and because it represents the entire EU market, it has the clout to set higher standards for all electronic products sold in the EU. It also requires manufacturers to help pay for recycling, which has resulted in an e-waste recycling rate of 35% in the EU.

Japan is another country that has successfully implemented e-waste policies, which has resulted in a 75% recycling rate for products covered under the Home Appliances Recycling Law (HARL) and Small Appliance Recycling Law (Kumar et al., 2017). In Japan consumers are required to pay a fee for recycling products at EOL and to bring products back to the retailer where they purchased the product. Australia passed the National Waste Policy and the National Television and Computer Recycling Scheme to improve the recycling rate, but it has not been properly implemented and falls behind international best practices (Kumar et al., 2017). China also adopted the extended producer responsibility (EPR) practice in 2011 for WEEE recycling. India also developed guidelines for the sound management of e-waste which classified e-waste according to its components and composition in 2008. In 2011, India also developed guidelines for collection and recycling. In Indonesia, “there is no specific legislation for e-waste management” but both Indonesia and the Philippines are in the process of finalizing e-waste legislation (Kumar et al., 2017).

The differences in laws across national boundaries creates confusion and difficulty regarding the enforcement of those laws. Even though a lot of the legislation across borders mandates

Extended Producer Responsibility (EPR), it is a complex undertaking to monitor, understand, and comply with the various legal stipulations because they slightly diverge everywhere. The globalization of electronics has created complicated supply chains, which means that companies must invest in staff with expertise in electronics EOL compliance and environmental legislation across different countries and regions. Ultimately the enforcement of legislation is the exclusive responsibility of competent authorities within each country, but "their executive power ends at the national boarder as they are not empowered to impose any sanction on a foreign manufacturer that sells products in their territory" (Hieronymi et al., 2103). Essentially, authorities in each country do not have the legal means to enforce compliance throughout global supply chain and sales channels.

One attempt to regulate the international realm of e-waste was the creation of *The Basel Convention on the Control of Transboundary Movements of Electronic Wastes and Their Disposal,* a treaty that was ratified in 1992 by 188 countries to prevent the exportation of hazardous waste to foreign countries (Basel Convention, 2011). It regulates the flow of hazardous waste by requiring prior notification between the two signatories' trade partners. The Basel Action Network (BAN) is an international charitable organization that acts as the non-governmental watchdog for *The Basel Convention.* BAN also started the *e-Steward* project which is an accreditation program for recycling companies to demonstrate that they comply with the industry's most rigorous environmental and social standards (BAN, 2020). Certified recyclers are not allowed to dispose of e-waste in landfills or incinerators, export e-waste, or use coerced or prison labor (BAN, 2020). "It is important to note that the U.S. and Canada, along with Japan, are the three governments most actively opposed to the Basel Convention and especially the overwhelming majority decision in 1995 (Basel Ban) to amend it to prohibit the export of hazardous waste from developed to developing countries" (Puckett, 2015).

4.2.2 United States

The United States lacks federal legislation mandating the recycling of electronic waste. Even though 28 states and the District of Columbia have enacted e-waste recycling laws, each state's laws differ in their approach. The lack of a unified federal law has resulted in several negative outcomes. First, because of the disjointed approach between states, no single state has the market share to force manufactures to design or produce more environmentally friendly products. Second, collection rates of electronics are low in the U.S. at only 27% per year (Tesfaye et al., 2017). StEP (2009) claims that a lack of national regulation has been shown to significantly hinder recycling rates in other nations. Third, a lack of federal legislation allows for e-waste to be exported to developing countries, which then increases unsafe and primitive recycling practices in those countries, reduces the e-waste stream going to formal recyclers, and increases the amount of e-waste ultimately deposited in landfills.

4.3 Insufficient Collection

To maximize the efficiency and profitability of urban mining, large quantities of e-waste are needed. Currently, the global collection rates do not match the growth in production of new electronic devices. The EU is globally the leading waste recycler with a rate of 35% per year (Tesfaye et al., 2017). "Practically, the most limiting factor of urban mining is volume of the collected e-waste, for which feasible options for recycling can be significantly limited" (Tesfaye et al., 2017). Collection is difficult for several reasons. First, because there are so few smelters near urban areas, e-waste must be transported far distances from the collection points to be processed. “Transportation cost is an important barrier because of the transportation costs of heavy and bulky waste materials (Kazancoglu, 2020). A more integrated supply chain network is needed to reduce distances travelled. Second, collection rates are low because of a lack of public awareness and involvement, which is due to the costs and inconvenience associated with discarding electronic waste. For example, in the U.S. only 10% of obsolete mobile phones are recycled “while the remaining 90% is stored at home by users or disposed in landfills” (Singh et al., 2019). Similarly, in China 400 million mobile phones were disposed of in 2015, but only 2% of those were recycled (Singh et al., 2019). Finally, collection rates remain low because a vast majority of e-waste is still sent to developing countries where it is recycled through informal methods. Collection rates are of great concern because even if the metal recoveries in the other steps of the chain are more than 90%, when only a small number of devices are collected, the overall recovery rate for the metals will be low.

4.4 Products Not Designed with EOL in Mind

Most experts agree that investment in developing technologies for the manufacture of electrical and electronic equipment should equal investment for the proper e-waste management and for the recovery of valuable materials at EOL. Unfortunately, producers have not prioritized designing products for EOL. “As recycling techniques try to catch up with the ever-advancing product designs, design-for-EOL has not been the priority” (Parajuly, 2020). Extended producer responsibility (EPR) requires companies that make products to be responsible for the management and disposal of them at the end of their lives. The purpose of EPR is to encourage manufacturers to consider EOL management during the initial product design phase and hopefully turn waste materials into a resource for producing new products. The reasoning is that this will motivate them to “reorganize business models and product designs to reduce their EOL costs” (Parajuly, 2020).

However, the implementation of this goal has been limited to collection and there has been “no incentive for individual actors to improve resource recovery,” and therefore, “preparation for reuse of EOL products is almost non-existent” (Parajuly, 2020). The European Eco-Design Directive has begun to set requirements for products to include all stages of product lifecycle, including EOL. However, Parajuly (2020) states, “Classic design flaws are still found even in modern e-products.” Little evidence exists that recent designs support EOL resource recovery so far.

Furthermore, companies have not reduced the level of toxic materials in many electronics to mitigate negative human health and environmental impacts at EOL. For example, a recent study in China analyzed the content of toxic metals in both basic phones and smartphones that were manufactured between 2001 and 2015. The study found the metals with the highest concentrations in smartphones were copper, nickel, and aluminum, all of which exceeded the total threshold limit concentration (TTLC) as did the average levels of silver, barium, and beryllium (Singh e. al., 2019). While the total metals content in basic phones decreased between 2009 and 2012, the total metals content in smartphones increased steadily between 2007 and 2015. Additionally, the average lead mass was high in smartphones at 704mg/kg, almost four times higher than in basic phones, despite the European Union’s Restriction on Hazardous Substances (RoHS) direction that restricts lead levels in EEE (Singh et al., 2019). The increasing trend of total toxic metals content in smartphones reveals that the industry has not prioritized reducing toxic metals in their design process.

5.0 RECOMMENDATIONS

5.1 Enact and Enforce Regulations Mandating E-waste Recycling

Individual countries should enact legislation that promote circular economies in which e-waste is treated as a resource rather than waste and should strategically coordinate their efforts. Balde et al. (2017) states that countries "should promote the reusing, repairing, redistributing, refurbishing, remanufacturing prior to recycling of materials."

5.1.1 Coordinate e-waste legislation and compliance internationally

Individual countries need to coordinate and harmonize their environmental legislation and methods of compliance. "Since a major amount of e-waste from developed countries still ends up in developing countries, an international cooperation and support program will be important to achieve better management systems" (Kumar et al., 2017). As noted above, because of the differences in laws between countries and because the authority to enforce laws is constrained by national borders, problems surrounding e-waste management continue to exist. The single most important factor in implementing policies is the ability to enforce legislation. "Despite all of the political statements about a market-driven approach, the most important legal tool for environmental legislation is command and control, not the stipulation of economic and other incentives" (Hieronymi et al., 2013). This means that legislation must address which economic actors can require compliance and the means of enforcement. A harmonized approach between countries should define the scope of legislation, the economic actors involved, the measure and tools used to assure compliance, and the administrative procedures and enforcement run by competent authorities (Hieronymi et al., 2013). For instance, the EU should coordinate with national competent authorities at borders to implement the WEEE Directive. Another solution might be to create international institutions to deal with the control of environmental compliance.

5.1.2 Enact federal legislation in the U.S.

The United States should enact federal legislation regulating e-waste recycling and ratify *The Basel Convention.* Legislation could set collection target rates for the nation, ban landfills, ban the export of e-waste to developing countries, establish financing plans to support collection systems and recycling plants, offer tax breaks or rebates to companies that process their used devices to encourage them to design products with EOL in mind, and offer tax breaks to companies that help prevent the export of e-waste to developing countries. The federal government could also lead by example by using e-Stewards certified recyclers. Finally, the Environmental Protection Agency (EPA) could implement enforceable guidelines for an e-waste program. Currently, the EPA does not have the authority to penalize those who do not comply with e-waste guidelines.

5.2 Increase Collection Rates

Without successful collection, e-waste will continue to be stored in homes, offices, and warehouses and will never reach recycling centers where resources can be recovered. The most important factor to achieve good collection rates is consumer participation. If consumers must spend time and money to locate, pay for, and travel to electronic waste collectors they are less likely to participate. Therefore, efforts should be made to increase collection rates of all types of electronic equipment, including smaller devices, which consumers tend to either throw away or keep stored. In addition to enacting legislation as noted above, two main ways to increase collection rates are to increase public awareness and to create convenient and inexpensive recycling option for consumers.

5.2.1 Increase public awareness

Raising awareness in the public through educational programs and advertisements is key to successful e-waste management and recycling. Consumers must be educated about the health and environmental risks of sending e-waste to developing countries and about the environmental and economic benefits of recycling and urban mining. Also, because of the differences in regulations regarding e-waste and the array of options available for collection, the public must be informed about the correct processes they should follow and what options are available to them in their jurisdictions. “Providing up-to-date information and increased publicity on prevailing recycling practices is needed in order to raise public awareness related to e-waste recycling” (Tesfaye et al., 2017). Another way to increase public awareness is to label electronic items with compositions to let the buyer know what is in them. Listing the harmful and valuable materials in electronics informs consumers of their value and of the environmental hazards if they are discarded improperly. This awareness may incentivize more consumers to recycle their products responsibly.

However, awareness does not always equate to increased collection rates. For instance, a survey made in Finland indicated that the EU consumers’ awareness levels of the existence and importance of e-waste recovery is high, but “this awareness has not been translated into recycling behavior due to inadequate waste management systems that promote return of <10kg EOL devices such as mobile phones and tablets” (Tesfaye et al., 2017). To increase collection rates and facilitate a circular economy, a fundamental change needs to occur in consumer behavior, which may require behavioral interventions. Parajuly (2020) explains, “This will require addressing not only the extrinsic attributes (infrastructure and incentives), but also intrinsic attributes (values and personal norms) of human behavior. Conventional approaches include information campaigns, economic incentives, and stricter regulations, whereas the use of behavior insight in such initiatives is still rare." One such behavior intervention technique is "nudging," which gives people a gentle push in the right direction without compulsion. In recent years, nudging has been used as low-cost solution for promoting pro-environmental behavior and has proven to be effective in trials promoting the purchase of greener mobile phones (Parajuly, 2020).

5.2.2 Create inexpensive and convenient recycling options for the public

Cost and convenience are two basic factors in any person's willingness to participate in a recycling program. Even though many states and cities provide drop-off locations and curbside pick-up, the costs associated with these options tend to dissuade consumers. Therefore, providing free collection services, including transportation of EEE to collection or recycling centers may improve the collection rate. One good example of this is the recycling company, Kuusakoski Oy, in Finland, which provides free collection services for consumers who call in EOL equipment delivery and allows customers to turn in all EOL electronics for free to the retailer if they purchase a new corresponding device (Tesfaye et al., 2017). Because smaller products such as mobile phones can easily be discarded with municipal waste or stored by consumers over longer periods of time, it is essential to provide a convenient and inexpensive manner for consumers to turn them to be recycled.

Best Buy also offers an extensive electronics recycling program in which customers can drop off three items per household per day no matter where the customer bought it, how old it is, or who made it (Best Buy, 2020). Customers can also trade in their electronic equipment, including phones, ipads, gaming hardware, laptops, notebooks, watches, cameras, and streaming devices, among others for a Best buy gift card. Best Buy will also come haul away old televisions and appliances for $24.99 and exercise equipment for $49.99 when a replacement product is purchased, or for $99.99 without a qualifying purchase (Best Buy, 2020). Apple also takes back old electronics in exchange for either credit towards a new purchase or for an apple gift card, and if no value is assigned, Apple will recycle products for free (Apple, 2020).

Another way to incentivize customers to participate in takeback programs would be to impose a surcharge on products at the time of purchase, similar to the way glass bottles and metal cans are charged, which would then be refunded to the customer when they turned in their products for recycling. Recycling centers could give a percentage of the initial collected fee to places like grocery stores that typically accept bottles and cans for recycling in exchange for also accepting electronics. This would provide an additional income stream for the local stores, and it would provide more options for consumers to drop off their electronics because grocery stores are more numerous than Best Buy stores.

Another example of a successful take-back program is the Dutch non-profit organization, Closing the Loop, which integrates the informal sector with formal recycling. The group collects dead phones from citizens in Ghana and pays them 2.5 euros for every ten phones they turn in, which offers some incentive for them to turn in the phones rather than discard of them improperly. The collected phones are then transferred to the Umicore processing plant in Belgium (VPRO Documentary, 2015). Perhaps Closing the Loop could coordinate with local vendors and marketplaces as mentioned above to establish more collection points for citizens across the country. This could benefit the local stores while also providing more readily available collection points to Ghana citizens.

Another example of a company that has created a convenient way for customers to turn in electronic products is EcoATM, which enables customers to turn in electronic products and receive payment on the spot at automated self-serve kiosks. Kiosks are installed at public places like shopping centers, Walmart stores, and grocery retailers at over 2700 locations nationwide at which customers can turn in products. The kiosks use artificial intelligence and electronic diagnostics to evaluate electronics and pays customers immediately for their device. EcoATM has collected over 25 million devices since its inception (EcoATM, 2020). Kiosks like this could be installed around the world at local stores and markets to increase collection rates in developing countries.

Similarly, the internet company Baidu worked with United Nations Development Programme China (UNDP) to create a smartphone application called “Baidu Recycle” in which consumers choose the type of product they want to recycle, take a photo of the item, enter their phone number and address, and within 24 hours, an accredited recycler comes to pick it up (UNDP, 2020).

5.3 Incentivize Producers to Design Products with EOL in Mind

The ideal procedure is for companies to initially design products for reuse and repair, and eventually for ease of recycling once they reach end-of-life. “Implementing the circular economy (CE) principle involves integrating steps where all industries design with the CE model in their initial project conception” (Xavier, 2019). However, as noted above, companies have not been incentivized to design products with EOL in mind. Solutions for how to achieve this goal on a global scale, however, are elusive because of the complexity of international laws and the lack of a single international entity to enforce compliance. Governments of individual countries should set standards that encourage circularity of products and offer economic incentives such as tax breaks and rebates to producers who meet those standards.

5.3.1 Improve product design to make pre-processing easier

Solutions to e-waste should include designing electronic equipment to enable easier "disassembly and reuse of components" (Balde et al., 2017). For years, researchers have been working on ideas to improve "the ability to efficiently dismantle and separate the various components" (Bleiwas, 2001). This could mean using consistent types of screws and labeling plastics and other hazardous components. During the initial design phase of electronics, engineers should incorporate product specifications that will facilitate dismantling and separation at EOL.

5.3.2 Design products with fewer toxic materials

Not only should products be designed for easier dismantling, but they should also be designed with less toxic materials so that they pose less human health and environmental risks at EOL. "The material used and the design of EEE make recycling challenging, as they are designed using hazardous compounds such as mercury lamps in LCD screens, PVC, flame retardants, and other toxic additives in plastic components" (Balde et al. 2017). An example of an effort towards an eco-friendly design is that of a fully biodegradable electric circuit designed by scientists at Stanford. The first of its kind, this biodegradable circuit uses natural dyes that dissolve in acid with a pH100 times weaker than that of common vinegar or lemon juice. It is resistant to heat, water, and mild basic solutions, but dissolves within an hour of exposure to the low-level acidic solution. Further, it is "thinner than a human hair, and about 40 times lighter in weight than a piece of office paper of the same surface area" (Stanford Magazine, 2017). Further research like this should be done to develop more environmentally friendly electronic devices.

5.4 Improve Recycling Processes

5.4.1 Improve pre-processing methods

Valuable resources can be lost during the pre-processing phase, either through dismantling, crushing, shredding, etc. One example of a recent innovation to help dismantle products more safely and efficiently is a robot designed by Apple named Daisy. Daisy is 33 feet long, has five arms and can deconstruct up to 1.2 million iPhones a year at a rate of 200 per hour. Daisy removes the screen, battery, screws, sensors, logic board, and wireless charging coil from the phones, leaving just the aluminum shell. Once materials have been recovered, they are recycled back into the manufacturing process. Daisy's dismantling method enables Apple to recover high quality materials that traditional recyclers cannot (Martin, 2019).

Another example of improved process design is that of Ronin8, which has developed a new way to recover both metals and non-metals from circuit boards. Other techniques destroy the entire non-metal portion to extract the metals. Ronin8's process reduces the size of the material and then circulates it in recycled water through a sonic chamber. "The sonic vibrations liberate the metals from the non-metals. Once the metals and non-metals have been size- reduced and liberated, they can be separated into different streams of concentrate" (Ronin8, 2020).

5.4.2 Explore non-toxic hydrometallurgical methods

As mentioned in section 2.4, despite their benefits, pyrometallurgical and hydrometallurgical methods can pose environmental and health risks. The smelting of flame retardants and polyvinyl chloride present in e-waste creates dioxin and furans, which require special emissions control. Further, the cyanide often used in hydrometallurgy is hazardous and requires high safety standards for operators. Another option that should be further explored, especially in countries lacking commercial smelters, are *non-toxic* hydrometallurgical methods. Advanced Technology Materials, Inc. (ATMI) has developed the first cost-effective, all chemical process that recovers valuable materials from wiring boards (PWB) and integrated circuits using a "green chemistry" technology. This process does not require shredding or grinding, thus reducing the loss of precious metals, and it does not need to use cyanide or aqua regia like other traditional methods. Metal recovery is greater than 99% with greater than 99% purity. In addition, the closed process eliminates "human exposure to lead, tin, and hazardous materials" and "the non-toxic chemistry is recycled with no toxic byproducts or hazardous air, water or solid waste discharge" (Jiang et al., 2012). ATMI's process requires low volumes of chemicals, uses low-energy, and leaves a low carbon footprint. Another major benefit to ATMI's process is that it is scalable and can be sited near sources of e-waste, thus reducing transportation costs (Jiang et al., 2012). Non-toxic hydrometallurgical processes like ATMI could offer a solution to countries that do not already have major smelters, thus eliminating the need to transport e-waste far distances and reducing environmental impact.

5.5 List of Recommended Actions to Improve E-Waste Recycling

1. Coordinate legislation and methods of compliance among countries around the globe, specifying which economic actors can require compliance and the means of enforcement.

2. Enact and enforce federal regulations mandating e-waste recycling in the United States that would do the following: set collection target rates for the nation, ban landfills, ban the export of e-waste to developing countries, establish financing plans to support collection systems and recycling plants, offer tax breaks or rebates to companies that process their used devices and to companies that help prevent the export of e-waste to developing countries.

3. Increase public awareness through educational programs and advertisements, informing consumers about the health and environmental risks of sending e-waste to developing countries and about the environmental and economic benefits of recycling and urban mining.

4. Label electronic products indicating both the harmful and valuable materials so that consumers know the value they contain and the environmental hazards if they are not recycled responsibly.

5. Inform the public of the correct processes they should follow and what options are available to them for e-waste recycling in their jurisdictions.

6. Impose a surcharge on electronics at time of purchase, which would be refunded to consumers when they return products for recycling or reuse when they no longer want them.

7. Make collection points more accessible by installing kiosks in malls, grocery stores, and Wal-marts, which would refund consumers on the spot for turning in their devices.

8. Provide free collection services, including transportation of EEE to collection or recycling, especially in cities where consumers may not own a vehicle or have means to return the product.

9. Provide financial incentives such as tax breaks or rebates to companies that design products with more eco-friendly materials.

10. Invest in research to improve pre-processing methods by designing products that are easier to dismantle, and by expanding the use of robots to efficiently recover valuable materials.

11. Invest in research to improve non-toxic hydrometallurgical processes.

6.0 CONCLUSION

Despite its challenges, urban mining offers a viable solution for the world's growing e-waste problem. The rapid growth in e-waste globally poses serious threats to both human health and the environment, and the increasing demand for raw materials needed to produce new electronics threatens to deplete the world's supply of precious and rare earth elements if they are not recycled. Urban mining plays an important role in solving the e-waste problem for the following reasons: (1) it uses significantly less energy, releases fewer harmful elements, and generates less CO_2 emissions than primary mining; (2) it reduces the need for new material and recovers rare earth elements that are considered non-renewable; (3) it reduces the amount of e-waste directly deposited into landfills and the amount of toxins released into the environment through unsafe and primitive recycling methods, and in turn, reduces human exposure to these toxins; (4) it decreases the world's dependency on China for rare earth metals; (5) it holds the potential to generate massive profit because of the high concentration of valuable metals in e-waste and because its processes are more energy efficient than primary mining; and (6) it supports circular economies by recovering and re-using valuable materials.

For urban mining to succeed, however, coordination and cooperation must occur between several key players including government agencies, non-governmental organizations, lawmakers, product designers, manufacturers, waste collectors, primary recyclers, end-processors, and the public. Each of these entities plays an important role in facilitating the overall success of the process. Barriers to urban mining can be overcome by enacting and enforcing federal legislation in the United States, by coordinating laws and methods of compliance internationally, by increasing collection rates, by incentivizing producers to design products with EOL in mind, and by improving and expanding all phases of the recycling process. Section 5.5 outlines a list of definitive actions that could be taken by the key players to improve the overall effectiveness and efficiency of e-waste recycling.

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