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Solutions and Motivations for Better Electronic Waste Management

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ABSTRACT

With an increase in the production of advanced technological devices and appliances nowadays, there is a rapid growth of electronic waste (e-waste) across the world. E-waste has a toxic environmental and economic impact on our society. Fifty million metric tons of e-waste are disposed of, and this data continues to rise. As a result, waste management has become outdated in many parts of the world, especially in North America. Current disposal methods such as landfilling, incinerating, and recycling are analyzed; however, the consequences of such methods outweigh the benefits. These environmentally unfriendly methods cause significant harm to the human body and release dangerous chemicals into the water and land that people live in. New and potential procedures are then analyzed, which mainly include strengthening disposing of, collection, and recycling infrastructure and implementing new federal legislation. Through countries' governments, *Extended Producer Responsibility*, as well as Right to Repair, are taken apart to disclose the findings of its effectiveness.

Overview of Electronic Waste

Electronics have become an essential part of human life. Due to the introduction of electronics to society, the quality of living has soared in almost every aspect of people's lives. Communication has become instant, information is at the user's fingertips, and healthcare has improved significantly. Over the years, humans have grown reliant on electronics and have generated massive amounts of electronic waste, or e-waste, due to lack of proper waste management.

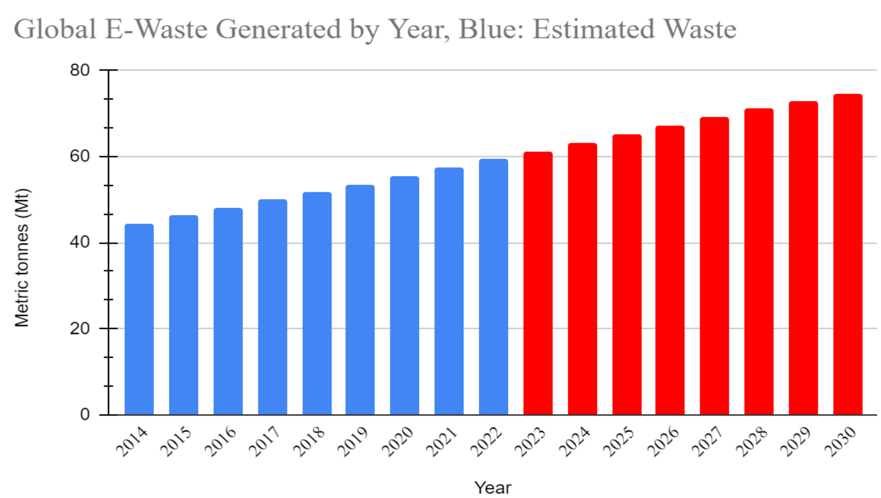

Figure 1. Global E-Waste Generated by Year; Blue: Estimated Waste, Red: Predicted Waste (Forti et al., 2020)

E-waste consists of any waste from electrical components with power cycling through them, such as phones and laptops. E-waste contributes to around 5% of today's overall pollution. It equates to 70% of the world's overall toxic waste, with 50 million metric tonnes, and almost 6500 Eiffel towers (Mt) of e-waste disposed of annually (Herat, 2007). Every year, the global e-waste generated increases by 2 Mt, or 2 billion kilograms. By 2030, it is approximated that there will be 74.7 Mt generated, a high 68% increase from 2014 seen in Figure 1 (Forti, Balde, Kuehr & Bel, 2020). Although a linear trend, e-waste pollution is continuing to be on the rise.

E-waste is made up of different materials depending on the product. In general, it is made up of a wide variety of materials, such as iron alloys, nonferrous metals (gold and silver), plastics, glass, wood and plywood, printed circuit boards, rubber, ceramics, and other things. Plastics make up 21% of the e-waste, nonferrous metals make up 13%, iron and steel make up 50%, and the previously mentioned components make up the remaining proportions of e-waste (Widmer et al., 2015). All of these components are dumped every year. In fact, 35,274 lbs of copper, 772 lbs of silver, 75 lbs of gold, and 33 lbs of palladium are mostly lost per every 1 million cell phones dumped (Vats and Singh, 2014). Without recycling these precious metals, a conservative estimate of 60 billion dollars is lost annually. Similar to the great impact electronic waste has on the global economy, electronic waste is threatening to the environment and the people.

The electronic waste consists of many hazardous waste elements to the environment. Hazardous waste contains substances, including lead, mercury, arsenic, cadmium, selenium, hexavalent chromium, and flame retardants in quantities over the threshold limit. Nearly all e-waste contains these toxic additives, including brominated flame retardants (BFR), chlorofluorocarbons, and hydrochlorofluorocarbons (Forti, V., Balde, C. P., Kuehr, R., & Bel, G, 2020).

Chemicals and toxic fumes may weaken the immune system when exposed to the human body (Vats and Singh, 2014). With rising volumes, limited recycling rates, and unsustainable disposal and treatment methods, e-waste poses a danger to the environment and human health unless new procedures are found to properly and safely dispose of e-waste.

Current Disposal Methods

Currently, countries mainly dispose of landfills by incinerating or recycling waste. These practices are commonly used across the world, especially in countries like India and China. Whether it's legal or not, most companies and countries export their waste into these countries' underdeveloped regions for a cheap price (Annamalai, 2015). Waste management corporations in these waste-receiving countries take advantage of the lax pollution legislation to make money. Because disposing of the waste is their only goal, they do not take into account how the disposal methods are exercised or what the future short-term and long-term consequences may be. On the contrary, many experts have discussed these old and current methods, evaluated them and made necessary adjustments such as implementing cost-friendly and new environmentally friendly methods.

Landfilling

One of the most common disposal methods, landfilling, buries electronic waste under a thick layer of soil. Excavators are used to dig trenches into the ground where waste material piled in, and then covered up with the surrounding soil. The purpose of this method is to remove the waste from the dense populations in many cities and towns into regions where the waste can be dumped without harming the populations of those cities and towns. Countries producing large amounts of e-waste will export their waste to countries with large plots of landfills and relaxed pollution laws. Although landfilling is one of the most effective ways of getting rid of large amounts of e-waste, it comes with many flaws.

In the landfilled areas, they start to leak and contaminate the surrounding soil and groundwater over time. The leakage from the landfilled e-waste includes metals, such as lead, copper, nickel, antimony, cadmium and zinc (Akram et al., 2019). These metals of e-waste leakage, combined with other materials and organic compounds, cause unwanted chemical reactions where the products vaporize into harmful gasses and possibly even uncontrollable fires (Elliott et. al., 2001). Because of this, putting together non-biodegradable material with BFRs into the land does not seem like a viable solution.

Additionally, landfilled e-waste can detrimentally impact plant-life and the air seen in figure 2. The pollutants dissolve and leach into the soil near plants and these plants absorb these toxins via their roots. After long term exposure, all nearby plant life can hold this toxin in their stalks and leaves, making the plant itself dangerous for consumption by any animal or humans. Exposure and consumption of these toxins via plant life or animals that may consume these plants can cause gastroenteritis, a stomach virus, liver and kidney damage, and cancer in humans (Awasthi, Zeng & Li, 2016).

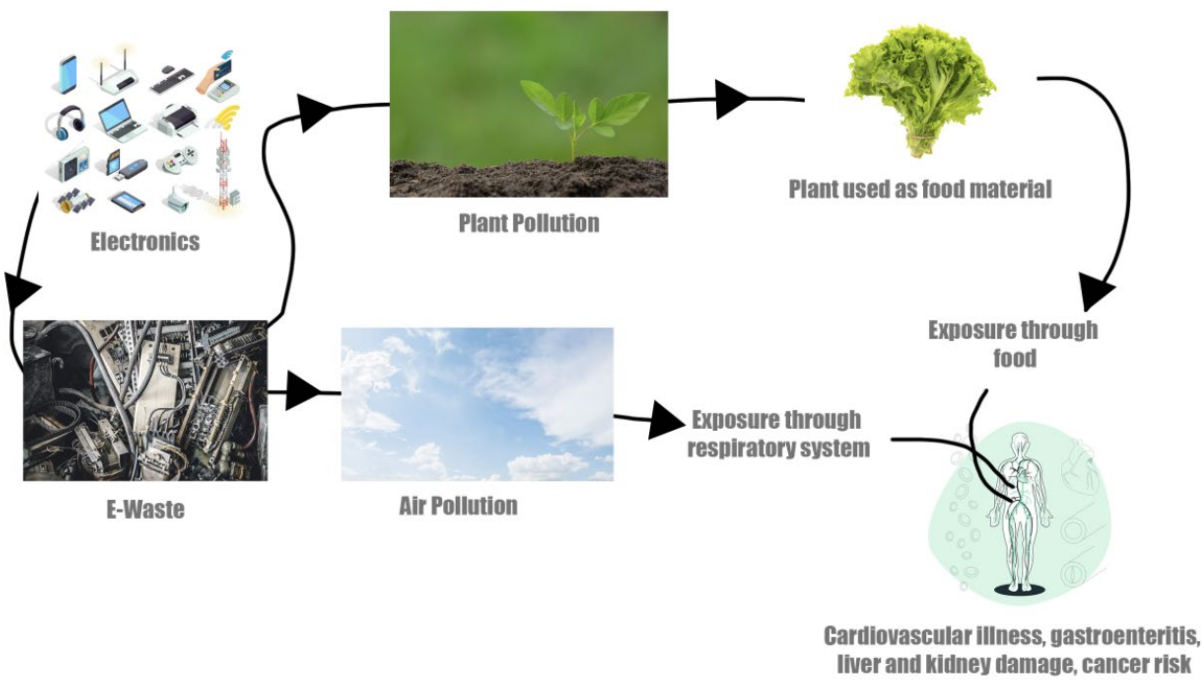

Figure 2. E-waste Effects on Soil Environment

Moreover, landfilling is lessening in overall "effectiveness". There is rapidly decreasing space for landfilling on Earth. Due to the lack of space, countries have to place landfills in close proximity to human civilizations and communities, essentially contradicting their initial purposes. Globally, there are over 100,000 landfills affecting the environment around them (Brand et al., 2018). The amount of landfills is still increasing, but many experts predict that the world will soon run out of space and will not be able to contain the spiraling amount of waste. Presently, to divert the waste from the landfills, incineration and recycling are used, but these methods come with their own problems.

Incinerating

Incineration, or the act of open burning waste, is one of the most primitive disposal methods of waste. Incinerating is the open burning of e-waste to destroy to obtain basic metals like aluminum, copper, and steel (Annamalai, 2015). Incineration is a controlled combustion process with the purpose of reducing waste volume and the utilization of the energy content of combustible materials. Every time these open burnings happen, the electronics react with heat and explode, releasing all sorts of chemicals into the air (Devika, 2010). This is the main disadvantage to incineration. Gases that escape into the air have an extreme effect on greenhouse gasses with toxic emissions like cadmium and mercury being released to the environment.

Dioxins, an environmental pollutant formed from heavy metals, contaminate the air and water. From these pollutant-motivating processes, dioxins, furans, and heavy metals (Cu, Pb, Cd and Cr) are released to the environment, not to mention the average greenhouse gases (Awasthi, Zeng & Li, 2016). When these toxic fumes are exposed to the human body through the air, ground, and water, there can be growth abnormalities, altered learning and behavioral outcomes, and may potentially impair the immune system. Furthermore, people can experience rapid onset of blood coagulation, cardiovascular regulatory changes, gastroenteritis, liver and kidney damage, and cancer risk with sufficient exposure to the electronic pollution (Vats and Singh, 2014).

Heavy metals penetrate the world's food chain and spoil the underground water reserves with pollution. The pollution causes millions of premature deaths, more specifically 11 million deaths (Landrigan & Fuller, 2015). Figure 3 compares pollution to AIDS, tuberculosis, and malaria, pollution, concluding that it is several times deadlier. E-waste even causes a financial burden, estimated to 8.1 trillion in world pollution costs in 2019.

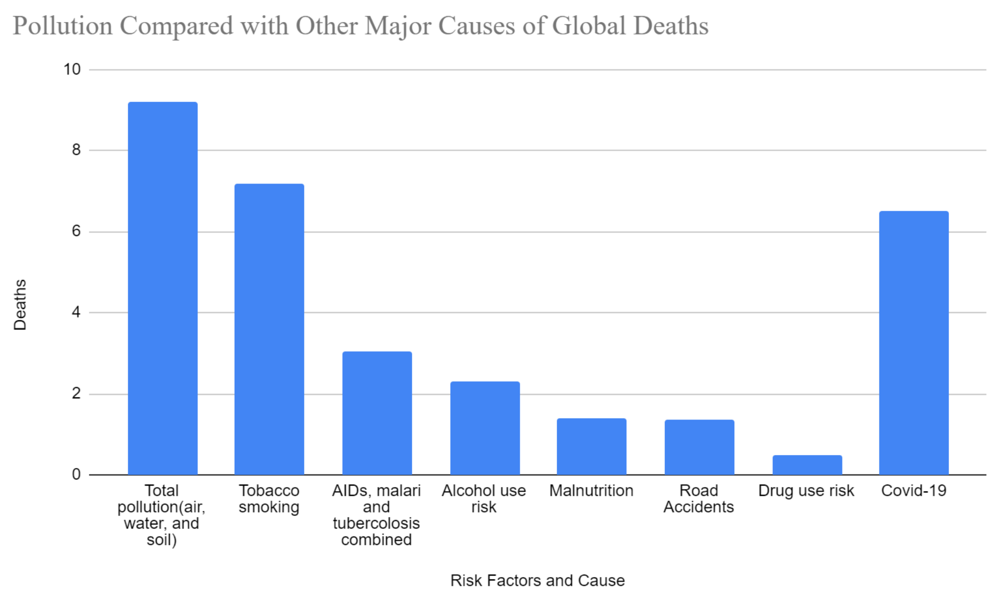

Figure 3. Pollution Compared with Other Major Causes of Global Deaths (Landrigan & Fuller, 2015)

To keep workers safe under these environments, they are advised to keep masks on at all times. Most incineration facilities are in slums where laws are laxed therefore, the workers may lack the education in maintaining safety and avoiding the dangers of incineration. Many are diagnosed with cancer or with other deadly diseases that affect the brain and body.

Recycling

Out of all the common e-waste management methods, recycling is the most sustainable option for end-of-life or unwanted electronics. The recycling process is the dismantling and separating of the ferrous and nonferrous metals and circuit boards (Favot & Grassetti, 2017). This is done to get rid of the substances that are in almost every electronic device.

Just like all of the other methods, recycling has its drawbacks. Most countries do not have a solid infrastructure for recycling to support the rising e-waste. E-waste management is still a relatively new category for all countries, but most are not doing anything about it (Rene et al., 2021).

For example, the recycling model that Egypt has disregarded became one of the largest waste mismanaged countries in the world. Most recycling processes are carried out informally which is not by the government, who should be responsible. Because systems for data collection and preprocessing are in need in Egypt, there is a limit on how well the country can manage waste and recycling firms. There are not any official government programs that consider the problem of e-waste, even private sectors have little to no interest. Because of this, little waste is recycled and most are not recycled properly. The waste then ends up in landfills or are sold independently to recyclers, second-handed equipment shops, or other parties that would benefit from the materials (Abdelbasier et al., 2018).

The scene in Egypt is similar to many countries across the world. As shown in figure 4, in countries like the United States, Canada and Mexico, the percent of recycling are all below 9.4% however, European countries seem to care much more about the environment, with most ranging to the 42.5% range (Gunarathne, 2019). Germany, South Korea, and Austria are currently the best in recycling, being around 60% each in recycling, although Asia as a whole are at a 11.7% rate (Gunarathne, 2019).

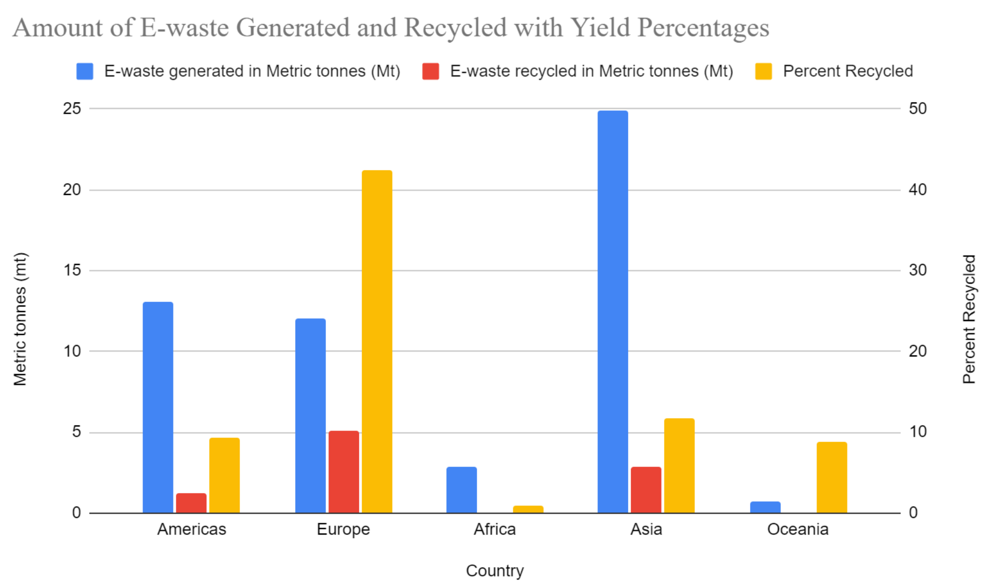

Figure 4. Amount of E-waste Generated and Recycled with Yield Percentages (Gunarathne, 2019)

New and Potential Solutions to E-Waste Management

Creation of a Circular Economy

Although the concept of a circular economy was around decades ago, it is only now that countries are taking the idea into play. A circular economy is an economy that benefits the manufacturing of products and electronic footprints of companies through reusing, refurbishing, and recycling. Of the three aforementioned methods, currently, only recycling takes into account the reusability of products, despite products are reused to a certain extent in all three methods (EPA, 2022). With the use of a circular economy, current methods can be improved on by better utilization and better valuation of used products or down-right discarded based on their practicality. A circular economy has many parts to it, including proper recycling infrastructure, Extended Producer Responsibility, Right to Repair, and product design innovation with the goal of reducing electronic waste.

Convenient Recycling

The first steps toward a circular economy require the improvement of e-waste management facilities and the convenience of recycling. The awareness level of consumers directly relates to the availability of recycling and collection services and facilities. Raising awareness by educating communities on the importance of recycling is one of the key factors in promoting a successful e-waste management system and circular economy. There has to be a benefit in recycling for consumers, efficient recycling technology, and a high collection rate in order for recycling to continue to work in the future. On a global scale, less than 10% of people actually recycle their mobile phones after their life cycle (Tanskanen, 2013). In countries such as the UK, the rate is around 15%, but in developing countries, that number is substantially smaller, standing at a low 1%. It is even seen that the average individual already owns 5 mobile devices.

The main barrier to convenient and better recycling is the lack of education provided to the people. One of the biggest motivations to discarding devices versus recycling is the fear of leaving data and information on devices due to improper recycling. In any case, if society was well informed on how to properly recycle their devices, this large amount of waste in each household would be less of a problem.

Motivating people to recycle electronics can return huge ecological benefits. One study performed a survey on the knowledgeability of regular people about e-waste management. From the survey 12.0% of those polled said they understood the harmful effects of e-waste pretty well, followed by 64.3% of those with a basic grasp (Tanskanen, 2013). Citizens with an unconscious or even irresponsible attitude make up the remaining 23.7% of the population. In another study, simply 5.38% of those surveyed claim to be well-informed about the avoidance of e-waste pollution, with the remaining 30.3%, 52.8%, and 11.5% only knowing a little or nothing at all (Tanskanen, 2013). It shows that efforts to spread awareness about e-waste have not been made with all of the public's might. As anticipated, 88.3% of respondents said they would participate actively in pertinent promotions and events.

These studies show that people are not informed about how accessible recycling is to them. 87.1% of respondents were ignorant while 20.1% realized that recycling and collection centers are close to them. When considering sending their products to certain collectors, almost 50% consider just the price, but only 10% consider it environmentally friendly. The other 40% consider the convenience of the location of the specific collector. Most people are oblivious to how much e-waste is affecting their environment, and only how it affects them (Tanskanen, 2013).

Framing recycling as a hobby for the community may change the attitudes of recycling and enable community members to see it as enjoyable and environmentally friendly. Having campaigns that give back phones to companies support this idea. When campaigns give e-waste to companies, the companies use their resources in order to properly dispose of the e-waste. This process utilizes the community's recycling infrastructure, therefore supporting the infrastructure and pushing it to be better (Tanskanen, 2013).

Right to Repair

The Right to Repair Act protects consumers' rights to diagnose, service, maintain, and repair their own devices (Grinvald & Tur-Sinai, 2019). Prior to this Act, consumers did not have full ownership of items they bought. People had to pay absurd prices in order to get their products serviced by the manufacturers, while these manufacturers make it difficult for any other party or individual to service it themselves. Now, the act seeks to give full ownership to customers, giving them the ability to have full access to any part of their product.

Prior to the act, companies took advantage of their consumers, requiring them to repair their devices at their retail shops or get service from certified technicians. Simple fixes such as cracked screens became very expensive because the company had complete control over repair prices, blueprints and parts. Most companies have taken this sly approach towards consumers, with companies like GM and Ford (automotive companies) setting in this practice of getting rid of the people's ability to repair their "property". For decades, these manufacturers pushed consumers to purchase new cars instead of repairing used ones or charged exorbitant prices for repairs (Grinvald & Tur-Sinai, 2021). Unfortunately, this methodology is carried onto today's modern companies like Apple and Tesla, primarily those that are involved in the electronics business. The Right to Repair Act is trying to fix the problem of companies taking advantage of their consumers and e-waste, but many disagree on the way the act comes into play in the United States legislation.

However, the Right to Repair Act has its own downsides. One of the most concerning problems is user safety (Montello, 2020). Companies do not want the safety of consumers to be on their hands when a battery explodes while a person is trying to take it out. Even if consumers are knowledgeable about their devices, shrinking technology is continuously making them impossible to repair, without proper tools and repair environments. With more integrated and small dense mechanics, it naturally makes it harder for people to repair. Additionally, the act oppresses a company's will to innovate because the companies were required to offer schematics and tools in order to fix any problem of the device. Additionally as engineers want to create the next big thing, it is possible that taking account of user reparability may halt their progress or make their project impossible to pursue. There are products like the Apple Airpods (an innovative product in its category) that are almost impossible to repair, but if Apple had tried to implement the feature, it would have changed the product altogether, possibly making it a worse product. For this reason, it will not let companies take risks, putting more effort into the thought of reparability (Mirr, 2019). Though, these are simple problems that can be fixed with time even with the act enacted. It just depends on how companies go upon this rule.

However, although it comes with downsides the right to repair act has caused significant changes in the accumulation of waste. Ever since 2001, when the first right to repair act came out, while mainly focusing on automobiles, the right to repair act has been seeing more publicity. In recent times or 2008, the US Supreme Court approved a class action lawsuit for the digital right to repair. More good news came to follow, where the same bill was passed in South Dakota, and 20 states are considering the possibility of the people's right to repair (McSherry, 2014). Even now in 2022, New York has passed the Right to Repair Law calling it the "Digital Fair Repair Act, forcing all electronics makers to provide repair information, software and components to consumers and third parties (Reisman, 2022). With these bills enacted, it will ensure that the same device will be in people's hands longer, therefore reducing the amount of e-waste. In just one small US state, if marylanders hold on to phones for 1 year long on average, it would reduce e-waste by taking an equivalent 11600 cars off the roads, around 350,000 kg of raw mineral per day (Kunze, 2021). Having these types of laws all over the country and the world could take an exponentially increased amount of cars off the road, with a great deal of raw materials being saved for something else more valuable.

Extended Producer Responsibility (EPR)

The Extended Producer Responsibility, also known as EPR, is the most useful and flexible solution to e-waste management. EPR is a policy where producers are given financial and physical responsibility for post-consumer products, disposing of them in the most sustainable way possible (OECD, n.d.). First introduced in 1988, EPR was created to

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make the circular economy concept possible. EPR is the last step of the circular economy that loops back into the first step of the whole process as seen in Figure 5. It is the step that maintains reduced waste and makes sure that companies return their original product (Gupt & Sahay, 2015). During the time it was founded, many European countries such as Germany and Switzerland did accept the policy, but it was only through the last decade where the policy really took off (OCDE, 2014).

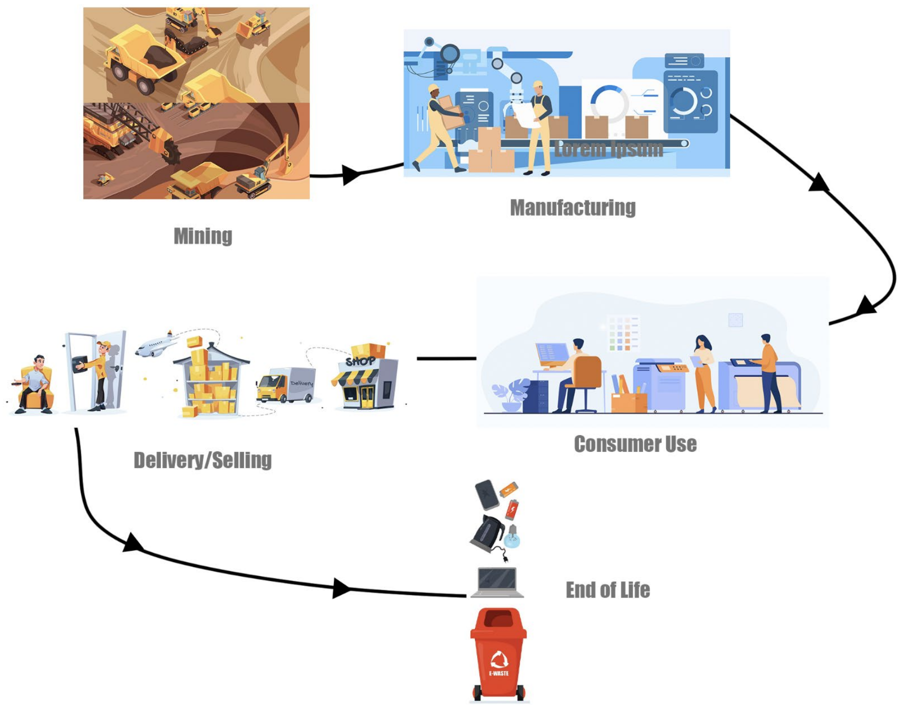

Figure 5. Life of Electronics (Ramirez et al., 2021)

EPR has many different versions of it throughout many countries. As said, EPR is a policy with one goal that accepted countries have to follow. Pursuing this goal, countries are able to create their own laws and policies regarding EPR. Similar to the Right to Repair Act and many other e-waste related acts, European countries usually have stricter laws, while countries like North America have local-level laws that moderately reach the policy's standards.

The two most important factors of EPR are regulatory provision and take-back responsibility (Gupt & Sahay, 2015). First, countries need regulatory provisions to address the issue of e-waste management. Countries that do not have management policies and laws are not able to have any success in EPR. Illegal and informal disposing methods will continue to run in developing countries if nothing is set by the government. Secondly, the take-back program's purpose is to negate the negative impact of the manufacturing and selling of their device. Most of the end-of-life consumer items do end up in landfills, where they end up decomposing for a long period of time, but having take-back programs will ensure, the devices will end up back in the producers hands, with the ability to send the materials back into manufacturing and refurbishing or into reselling. Although these two factors have high importance, financial flow into the EPR system also has an impact in EPR as it makes sures companies are fulfilling their responsibility by making them pay and submit reports on the amount of devices they have sold, received, and recycled. Even the previously mentioned parts to a circular economy have taken affect here too, as companies need to think about the feasibility of the take-back program, making it easier for themselves in the post-consumer process (Islam et al., 2021).

New Federal Legislation

Federal legislation will make it exponentially easier for countries to implement superior e-waste laws. In these laws, countries consider the need, applicability, impact, and feasibility in order to make sure the laws have a definitive purpose. UN negotiators under the United Nations Environment Program (UNEP) came together to encourage proper e-waste management to help the environment across the world and developing countries (Korcheva, 2021). This became known as the Basal Convention in which Europe made most European countries swear to a treaty where the EU introduced the Waste Shipment Regulation, prohibiting the export of toxic e-waste to non-OECD (The Organization for Economic Cooperation and Development that develop policies to promote economic growth) countries. In response to this convention, many import and export bans were placed in countries all over the world. Later, the EPR and the Right to Repair Acts took more precedence.

Treaties and policies make it essential that countries follow certain rules to create a better environment for the world. Countries in the EU such as the UK have been including more policies in order to tackle the e-waste problem while many others, especially the US do nothing to retaliate. The US is the biggest country that does not have any federal legislation regarding e-waste, and it shows through their low percent rate of recycling.

Table 1. Summary of E-waste Legislation

Country	Laws	EPR?	Summary on Laws
China	Solid Waste Law, 2020 Minor ones: Law on the Prevention and Control of Environmental. Pollution by Solid Wastes. 2002, 2012. Law on Clean Production Promotion.	Yes	These laws reduced the generation of e-waste and even banned e-waste imports. China implemented the EPR law to legally hold companies and manufacturers responsible for their products using their own recycling facilities.
Japan	Law for the Promotion of Effective Utilization of Resources (LPUR) and the Law for the Recycling of Specified Kinds of Home Appliances (LRHA) (Patil & Ramakrishn, 2020)	Yes	LPUR is very similar to the EPR in which both promote the producers to be responsible for their e-waste generation. LRHA is more double sided, where it focuses on the manufacturers and the consumer of electronic products
South Korea	Waste Deposit-Refund System (Hong, 2018), the EcoAssurance System (ECOAS) (Rhee, 2016)	Yes	The Waste Deposit-Refund System required the consumer to pay a small fee to recycle their electronics. After the materials are extracted, the consumer is refunded. The ECOAS promotes recycling by removing hazardous substances in all electronics. For Korea's EPR system, producers are required to recycle their end of life products and submit their statistics to the government.
EU	Restriction of Hazardous Substances (RoHS) Directive 2012/95/EC WEEE directive 2012	Most countries	The directive laid down the proper disposal methods for specific recyclable materials of e-waste. Through this directive, countries are not set to mandatorily follow a certain set of steps to reduce e-waste, but make their own national rules to control e-waste management in accordance with their local ecosystems.
United States	No Federal Laws - Several Local/State Laws	Lower form of EPR in some states and none in most	Only some of the states have implemented e-waste laws, but all lack the high strict standards that come from the EU's WEEE directive. Just a few states have similar give-back programs like Europe, but these laws just lead to the exportation of most US e-waste into countries like Mexico, China, and Africa (Patil & Ramakrishn, 2020). Unlike their allies, the US does not ban foreign e-waste trade and exportation.
Canada	No Federal Laws - Several Local/State	No	Canada is in a very similar situation as the US, where they only have

Country	Laws	EPR?	Summary on Laws
	Laws		a few local e-waste regulations. Because of the lack of laws, environmental pollution has been heavily increasing and there has still been an illegal shipping of e-waste out to developing countries.

Conclusion

In conclusion, it is evident that methods of removing e-wastes are necessary to become environmentally friendly and alleviate adverse health conditions of individuals. However, these methods are not enough in today's society in consideration of increased usage of advanced technological systems. The common methods of e-waste management and disposal are becoming less and less effective, as there are less landfill spaces on the earth, more pollution in the air, and more crippling recycling infrastructures. In other words, the means to use these archaic methods are diminishing faster than the production of electronic waste. Utilizing these methods are doing more harm than good, therefore the methods at which we discard these goods should be well thought out and innovated just as fast new products are innovated.

The purpose of this paper was to give insight on current methods and hardships with e-waste management, and emphasize the need for new methods and disposal methods to be used to solve the increasingly challenging problem. Using strict-waste regulations in European and Asian countries as a model/template, the U.S. and other countries with lax recycling laws may benefit from an improved environment and improved human health. They are on-top with problems, searching for new ways to help their nation. They have introduced e-waste concerning acts such as the Right to Repair Act, and even introducing and implementing the EPR act. Although the Right to Repair Act will definitely be helpful to the environment, EPR will take a big step towards solving the situation as a whole. Making the producers responsible for their own products will be essential in how those nations will recycle and dispose of e-waste in the future. Soon, countries like the United States will see their demise in the clear problem of pollution. By the time the federal government tries to do something, it will be too late.

Standardization in technology is another act that governments want to set in. If everything uses identical interfaces, there are less differences between how devices interact with each other, therefore leading to less waste like wires, ports, and “dongles”. The European Union has even put out a statement on making it mandatory that all mobile devices switch to USB-C, a universal port (Shaikh & Thomas el al., 2020). In that statement, Apple iPhones, which use the lightning port, were at the middle of the situation, because they were causing so much unnecessary waste. The bill was so important that it was even passed in the EU, and will start to have its effect in 2024. Even with electric cars, although they are new, they are already using multiple different connections to power the car. All of these different ports and wires will exacerbate the current issue of pollution.

Furthermore, it should be recommended in order to create a circular economy that an electronic device should be used until the end of its useful life, then recycled for parts and metals. If it is necessary for someone to get a new device, it is highly recommended to donate to someone that may need it or repurpose the device, instead of disposing of it. Repurposing this device would help it fulfill its complete purpose until the end of its useful life, rather than laying in the dump, waiting to be decomposed for hundreds of years. This solution not only would require campaigning and awareness of the consequences of disposing of electronics, but also require producers and governments to push legislation and policies. It is crucial in the upcoming years to see recycling percentages gradually increase to keep up with the amount of e-waste being produced. As pollution and waste piles up on the Earth there needs to be more awareness brought to it and action taken to prevent irreparable damage to the environment. It is important to innovate methods and technologies of disposing, create awareness for recycling and generate new policies in order to create a more manageable future for e-waste.

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