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ROLE OF MODERN TECHNOLOGY TO MANAGE E- WASTE

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Introduction

The rapid global rise in technology, tied in with consumer pressures for upgrades in functionality and design, has generated advanced electrical and electronic equipment with short life spans. For instance, the lifespan of a mobile phone has reduced from 4 – 6 years since 1992 to 2 – 3 years in 2015.[1] Consequence of this is the production of electronic waste which, in 2018 amounted to 50 million tones, with a project annual growth of 2- 5 percent, three times more than other waste streams.[2] Despite problem in terms of quantity, e-waste itself is also hazardous. E- waste contains up to 1000 toxic substances. common hazardous substance found in e- waste includes toxic metals and metalloids such as arsenic, barium, beryllium, cadmium, cobalt, chromium, copper, iron, lead, mercury, nickel and zinc, and persistent organic pollutant such as dioxin, brominated flame retardants, polycyclic aromatic hydrocarbon, polychlorinated biphenyls, polybrominated dioxins, and alternative halogenated flame retardants. such variety of toxicants could cause environmental degradation and harmful to human health unless appropriate management procedure would be adopted in a time.[3]

Although, e- waste is simply categories as hazardous waste, it has significant potential for value recovery. E- waste in fact consists of several valuable materials[4] as well as precious metals[5]. It clearly shows that a hidden treasure lies beneath this huge ever- growing mountain of e- waste. if metals are extracted properly from e- waste, this will create a new business opportunity of recycling, remanufacture and refurbishment. Investment in this new sector will lead to a win – win situation for both company as well as nation. The resources in e- waste is normally recycled by both formal and informal procedure. Manual e-

[1] Majeti Narasimha Vara Prasad, Meththika Vithanage, Anwesha Borthakur, "Handbook of Electronic Waste Management" Butterworth- Heinemann an imprint of Elsevier, 2020

[2] balde, C.P, Forti V, Gary. V, Kuehr. R, Stegmann.p, "The Global E- waste Monitor 2017", United Nations University, International Telecommunication Union & International Solid Waste Association, Bonn/Geneva/Vienna. available at: https://www.ewastemonitor.info last visited on 2020

[3] supra note 1

[4] such as iron, copper, aluminum and plastics etc.

[5] such as gold, silver, platinum and palladium etc.

waste recycling inescapably leads to the released of hazardous substance into the environment and harming human health.[6]

The endeavor here is to establish a cause – effect relationship between the use of hazardous substances and the consequence effect on the health of people and on the environment. This relationship revealed the immediate need for a proper management and regulation of hazardous substances.

"Hazardous Waste means any waste which by reason any of its physical, chemical, reactive, toxic, flammable, explosive or corrosive characteristics, cause danger or is likely to cause danger to health or environment, whether alone or when in contact with other wastes or substances."[7] The term 'E- Waste' is generally understood to refer to an old, obsolete, end-of-life appliances using electricity which have been disposed of. There are several definitions given by different references but highlight that e- waste is the electrically powered appliance, which can come in any size and function and 'no longer desired' to be meant, that e- waste can be generated not only because the product has lost its service function or reached its lifespan, but also because of the behavior of the consumer or obsolete technology which decreases the lifespan of electrical and electronic equipment's. Electronic waste commonly refers to whitegoods, information and communication technology hardware, business and household electrical and electronic items, that have completed its useful life and are discarded.[8] It can be classified as any electrical powered appliance that has reached its end-of-life or a broader and growing range of the electronic devices range from large household items to personal computers that have been discarded after their end-of-life or the multifarious combination of ferrous, nonferrous, ceramic and plastic materials.[9]

Treatment strategies of E- waste

E – waste comprises of both valuable and hazardous compounds and these can be segregated and recovered by employing proper processes of recycling. The material recover can be reused in the manufacturing of new products or in refurbishment of the old one. The process of recycling has a potential to recover 95 percent of the useful computer materials and 45 percent from cathode ray and tube monitors.[10] The method employs in recycling processes vary according to the economic conditions of a country where these are to be carried out. Developed nation focus on more comprehensive solutions to deal with e- waste wherein majority of percentage of e- waste generated is duly collected by authorized collectors and sent to recycling units where segregation of both valuable metals and toxic substance take place. On contrary in developing nations informal recycling industry owns a dominant share and works as a source of employment and income for poor masses. This is so because their primary target is to recover the valuable metals from the e- waste leaving the trash to dump at any place at the cost of environment. These activities are most of the time carried

[6] Klaus Hieronymi, Ramzy Karnet and Eric Williams, "E- Waste Management: From Waste to Resources", Routledge (Teylore and Francies Group), London & New York, 2012

[7] Rule 3 (14), The Hazardous Waste (Management and Handling) Rules, 1989.

[8] Pankaj Pathak, Rajiv Ranjan Srivastava and Ojasvi, "Environmental Management of E-waste"

[9] supra note 8

[10] Bret H. Robinson, "E- waste: An Assessment of Global product and Environment Impacts" Science of Total Environment, 2009, Vol. 408, PP. 183 - 191

out in small workshops or just in nearby open areas using primitive techniques of recycling where there is no control over the processes and emissions generated during the processes.

Informal recycling process involved manual disassembly and extraction of valuable metals, Acid Extraction, Burning, Shredding and Melting of Plastic, etc., Manual disassembly usually carried out manually using regular tools such as screwdrivers, chisels, hammer and bare hands.[11] Acid Extraction of metal is also known as "Backyard recycling" as it can be conveniently performed at shops and homes by unlicensed recycler.[12] This process is not only hazardous but is also inefficient as it is unable to extract complete value of processed products. The acidic wastes and sludges produced during process is often dumped in open grounds or drained in water streams leading to contamination of land, soil and water.[13]

Further, Dumping and Landfilling are the cheapest methods of waste disposal and huge amount of e-waste is disposed to landfills. Initially, dumping and landfilling was considered as a wised sources to deal with e- waste but later researches made it evident that there are many dangerous repercussions of this method.[14] large amount of e- waste that is thrown away with municipal waste is not recycled but is dump on field and open area adjacent to wetland and rivers. This dump material comprises of different electronic and electrical parts, toner cartridges, mixed and dirty plastics, burnt components, and residues from recycling operations. This landfill tends to contaminate environment and dangerously affect entire ecosystem.

In India, many researches revealed that e- waste is mainly recycled by the informal and unorganized sectors.[15]

Modern Treatment Strategies

Electronic waste covers a great variety of scrap and these e- waste should be processed in a sophisticated manner for two reasons:

a. To avoid negative effects on the environment caused by hazardous substances in e- waste; and
b. To recover values from the e- waste, usually by recycling metals or plastics.

Although, there have been a number of developments in recent years on the treatment options for WEEE, there is a need for additional new technologies that can further enhance the effectiveness of WEEE treatment in a more automated way that requires less manual intervention. Conventional treatments may typically involve some degree of manual separation followed by a variety of comminution and separation techniques.

E- waste contains many components that can be recycled and reused. these resources include: plastics and glass, non-ferrous metals, ferrous metals, hazardous materials. A typical process for managing e- waste includes collection from businesses and public drop- offs that are then sent to a recycling facility. the collected

[11] Deblina Dutta, Sudha Goel, "E- waste Generation, Management, Utilization and Recycling: A Review" Journal of Metallurgy and Materials Science, 2016, Vol 53, PP. 89 -98
[12] Ibid
[13] Ibid
[14] Darren Kell, "Recycling and Recovery" Electronic Waste Management, Design, Analysis and Application, 2009, Vol. 27, The Royal Society of Chemistry, Cambridge, UK available at: www.rsc.org last visited on May 15, 2022.
[15] Ibid

e- waste is then sorted, dismantled and categories into their basic material components, including plastic and glass, and component containing metals. [16]

A precondition for all recycling process is the collection of e- waste. Where no significant collection systems exist, institutional sources can be mobilized first. More and more companies are becoming interested in using a reliable disposal path for their old electrical and electronic waste to avoid ecological hazards in their downstream processes. The organization of e- waste is crucial for the recycling processes.[17] The more carefully collection and transport occurs, the less damaged the appliances are when they reach the recycling plant. Less damaged means more value can be extracted during recycling. Hence, for the proper implementation of collection system the concept of extended producer responsibility is adopted.[18]

Recycling and Recovery

Growing quantities of e- waste pose a major challenge for its recycling efforts. E- waste recycling can be intended as part of the formal or informal economic sector in many countries. Recycling and recovery of e- waste is concerned with the separation of individual materials into grades that are saleable on the open market or to other secondary processors. Large scale recycling started in the 1950s as the large telephone exchanges and other communications equipment began to be replaced by new technology.[19] This early recycling was driven by economics as people realized the inherent values of the metals contained in these facilities. Although, the e- waste contains potentially toxic metals, such as lead, mercury, cadmium, hazardous chemicals such as flame retardants, polycyclic aromatic hydrocarbons and plastic etc. Earlier, the primitive techniques including, stripping of metals in open – pit acid baths, chipping, melting plastics without suitable ventilation, burning cables in open air, disposing unsalvageable matters in the sites and dismantling devices are used at informal e- waste recycling site. Numerous studies have shown that the contamination of toxic substances from e- waste recycling sites release directly into the surrounding environment, and impact human health.[20]

In many nations the legislation has been introduce which meant that significant effort is now going into the recovery of lower – value materials, particularly plastic, in order to meet the legislative targets. This has led to well developed technology to separate metal that is capable of extremely high recovery rates. Japan was one of the first countries to legislate for e- waste recycling through the Home Appliance Recycling Law (HARL), enacted in 2001. HARL covers only the four large group of appliances such as TVs/ monitors, refrigeration equipment, air conditioner equipment and washing machines.[21]

The core questions for the organization of an e- waste recycling process are; what are the requirement by the legal regulation? where is the value? what are the cost? what are the risks for the environment and human health?

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[16] Siegfried Kreibe, "Current and New Electronic Waste Recycling Technologies", E- waste Management from Waste to Resources, 2013 Routledge published in USA and Canada, PP. 25
[17] Ibid
[18] Ibid
[19] Darren Kell, "Recycling and Recovery" Electronic Waste Management, Design, Analysis and Application, 2009, Vol. 27, The Royal Society of Chemistry, Cambridge, UK available at: www.rsc.org last visited on May 15, 2022.
[20] Peeranart Kiddee, Jatindra Kumar Pradhan, Sanchita Mandal, Jayanta Kumar Biswas and Binoy Sarkar, "An Overview of Treatment Technologies of E- waste", Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 1 - 14
[21] Supra Note 69

The recycling and recovery process is broadly similar throughout the world and generally includes the following steps:[22]

- Separation and sorting
- De – pollution
- Size reduction
- Materials separation

Many of the processes, particularly size reduction and separation, are repeated to further upgrade the materials. With the objective of the highest recovery of the precious metals, e- waste recycling also includes stages like pretreatment, size reduction and separation including comminution and separation of materials using mechanical or physical processing and metallurgical or chemical refining or purification through pyro or hydro or electro or bio hydro metallurgical processes.[23]

Separation and Sorting

Physical separation techniques are conducted to separate metallic and non- metallic fraction without any loss of valuable metals. The physical properties such as size and shape of waste electrical and electronic influence the efficiency of physical recycling. Some types of equipment are collected separately because of the different processes required. Refrigeration equipment containing ozone depleting substances such as CFCs and HCFCs (Chlorofluorocarbons and Hydrochlorofluorocarbons) are collected and stored separately and used the established infrastructure set up.[24] Television and Monitors containing Cathode Ray Tubes (CRTs) are also collected separately due to the different process required. Some small high- value items are collected separately for logistical and economic reasons e.g., like mobile phone because of the small size and high metals value contained in them. Segregated mobile phone are a valuable commodity in the waste electrical and electronic equipment recycling market. Non – segregated waste electrical and electronic equipment must be sorted out at the treatment facility to remove equipment which may contain hazardous materials.[25] So, there are three different physical separation techniques are being practiced such as density separation or particle shape – based separation, electrostatic separation mostly Eddy current separation, and magnetic separation.[26] When the collected waste electrical and electronic equipment reaches the recycling facility, it may undergo various process before actual recycling take place.

The choice of approach to de – pollution is influenced by capacity, larger facilities tending to use less manual disassembly, and also by the preceding collection and transportation steps. Lack of segregation and front loader and bulk containers can preclude any significant manual disassembly because of the level of breakage during transportation.[27] The level of segregation of different materials and how completely

[22] Ibid
[23] Peeranart Kiddee, Jatindra Kumar Pradhan, Sanchita Mandal, Jayanta Kumar Biswas and Binoy Sarkar, "An Overview of Treatment Technologies of E- waste", Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 1 - 14
[24] Ibid
[25] Darren Kell, "Recycling and Recovery" Electronic Waste Management, Design, Analysis and Application, 2009, Vol. 27, The Royal Society of Chemistry, Cambridge, UK available at: www.rsc.org last visited on May 15, 2022.
[26] Supra Note 73
[27] Ibid

hazardous material are removed, is heavily dependent on the operators. training of operator is key to the effectiveness of de- pollution and segregation.[28]

Most of the Mixed waste electrical and electronic equipment is processed in a facility based on mechanical separation. Many of the processes, particularly size reduction and separation, are repeated iteratively to further upgrade the materials. Size classification and dust removal are also important in the separation process.[29] Manual sorting is also a common operation used to remove large identifiable items such as circuit boards, stainless steel and cables. The number of iterations, the quality of manual sorting and the operation and layout of the plant, all have a large impact on the efficiency of the process and quality of the output materials.[30]

Treatment or De - Pollution

Different processes exist for different types of equipment, such as CRTs and Refrigerators are dealt with in specialized dedicated facilities to cope with the hazardous or environmentally damaging substances present.[31]

- Dismantling

Dismantling or disassembly is mainly conducted to remove hazardous components in order to minimize the toxic materials into the recycling stream and to separate reusable parts. Dismantling can also be performed manually or mechanically where mechanical disassembly further classified semiautomatic or automatic dismantling.[32] Desoldering is done via heating the solder above the melting point and separated reusable items for reselling. Removal of components, parts or a group of parts attached through fastening by screws, clinks and rivets, inserting, welding, binding, wrapping, coating and plating in a systematic manner from e- waste is called as dismantling.[33]

There two basic forms of dismantling which are selective and simultaneous disassembly. In selective dismantling, look and pick specific components and removed. Simultaneous dismantling is an efficient process, however, there is a risk for the components to be damaged and, also requires an additional sorting that increases the time and cost. In simultaneous disassembly, desoldering is done by heating the whole unit in a tin furnace.[34]

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[28] ibid

[29] Peeranart Kiddee, Jatindra Kumar Pradhan, Sanchita Mandal, Jayanta Kumar Biswas and Binoy Sarkar, "An Overview of Treatment Technologies of E- waste", Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 1 - 14

[30] Ibid

[31] Sammani Ramanayaka, Santhirasekaram Keerthanan and Methika Vithanage, "Urban Mining of E- waste: Treasure Hunting for Precious Nanometals", Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 19 - 24

[32] Ibid

[33] Ibid

[34] Kalyani Korla and Chanchal Kumar Mitra, "Biochemical Hazards Associated with Unsafe Disposal of Electrical and Electronic Items", Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP.55

- Crushing, Shredding and Milling

After physical dismantling, the remaining waste electrical and electronic equipment undergoes crushing, shredding and grinding to pulverize the waste to powder.[35] Shredding or crushing is conducted to strip metals from waste electrical and electronic equipment. Further, reduction of dimensions of WEEE is made through shredding. Double shaft shredder is widely used in e- waste recycling.[36] After shredding, crushing or pulverizing is done with dust collection systems. Subsequently, density separation isolates the non – metals and metals. Comminution of waste electronic and electrical equipment and effective detachment of metals from non – metals are the prerequisite.[37] Low speed high torque shear shredders are considered as the best for the primary crushing. Crushing can generate hazardous dust due to the strength and tenacity of the waste electrical and electronic equipment.[38] Hence, an efficient dust collection system is a must. Grinding process makes metal to be turned into a spherical shape due to their malleability and ductility, whereas non- metals like plastic and glass fibers remains non- spherical in shape. After crushing process, pulverizing of waste electrical and electronic equipment is done using ball and disc milling. Various types of mills have been described for the finer comminution where swing hammer types appearing to be the standard.[39]

Size Reduction or sieving and separation

Sieving is carried out in the physical recycling process to classify the different sized particles based on the various sizes of sieve apertures to the desired particulate size for separation. Sieving is not only been utilized to prepare a uniformly sized feed but also to upgrade metal contents.[40] The screening is essential as the particles size and shape of metals are different from that of plastics and ceramics. Rotary screen is used mainly for metal recovery in waste electrical and electronic equipment recycling process.[41]

Based on the variation in shape, density and electric conductivity of metallic and non- metallic materials in waste electronic and electrical equipment, electrostatic separation is considered as a promising way to recover metals from pulverized waste printed circuit boards. Recycling industry basically used shape separation by tilted plate and sieves. [42]

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[35] Ibid
[36] Ibid
[37] Ibid
[38] Supra Note 81
[39] Ibid
[40] Sammani Ramanayaka, Santhirasekaram Keerthanan and Methika Vithanage, "Urban Mining of E- waste: Treasure Hunting for Precious Nanometals", Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 19 – 24
[41] Ahamad Ashiq, Asitha Cooray, Srikanth Chakravartula Srivatsa and Meththika Vithanage, "Electrochemical Enhanced Metal Extraction from E- waste", Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 119
[42] Ibid

Magnetic, electrostatic and density separation are mechanical separation techniques that have been widely used.[43]

- **Magnetic separation**: Magnets positioned over conveyor belts separates most ferrous material. This technique is robust and cheap. However, the maximum weight of a particles that can be removed from the belt is mainly limited by three factors: a) The distance of the magnet from the conveyor belt; b) The strength of the magnet; and c) The ferrous content of the particles.[44] Steel alloy with low iron content can be separated only with strong neodymium magnets and smaller distances between magnet and particles. As a result, neodymium magnets are usually positioned close to the inner surface of a rotating drum.[45] As the particles stream flows over the magnetic drum, the magnet attracts steel particles, which are then separated from the rest of the waste. In mechanical separation plants for e-waste, several magnetic separators are usually installed after the crushing systems.[46] removal of as much steel as possible is important not only to enhance the yield of ferrous matter but also because steel can cause damage to fine crushing units and separators as well as disturb other separation techniques.[47] Low intensity drum separators are the standard method of magnetic separation for the recovery of ferromagnetic metal form non- ferrous metals and other nonmagnetic waste. Magnetic separation is generally performed first, followed by shredding or grinding to fine particles size, and after that electrostatic separation applied.[48]

- **Electrostatic separation**: Electrostatic separators are used mainly to separate metals from particle mixtures. Usually, corona electrostatic separators are employed for e- waste treatment.[49] These machines put an electrostatic charge on the particles with electrodes and then lead them over an electrically grounded drum. poorly conducting particles such as most plastic retain their charge and stick to the drum, whereas particles with good conductivity such as metals are discharged quickly and thrown away from the drum.[50] Electrostatic separation is considered as advantageous compared to the other physical techniques as it is smooth operation, less hazardous and requires less energy. As above mention, Electrostatic separation is based upon electrical conductivity and separates the non-conductive materials form the conductive ones.[51] Although, the electrostatic separators were initially recovered non- ferrous metals from automobile scrap or municipal solid waste, now widely used for waste electrical and electronic equipment utilized explicitly for the recovery of copper and aluminum

[43] Sammani Ramanayaka, Santhirasekaram Keerthanan and Methika Vithanage, "Urban Mining of E- waste: Treasure Hunting for Precious Nanometals", Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 19 – 24
[44] Ibid
[45] Ibid
[46] ibid
[47] ibid
[48] Peeranart Kiddee, Jatindra Kumar Pradhan, Sanchita Mandal, Jayanta Kumar Biswas and Binoy Sarkar, "An Overview of Treatment Technologies of E- waste", Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 1 - 14
[49] Supra note 93
[50] Ibid
[51] Darren Kell, "Recycling and Recovery" Electronic Waste Management, Design, Analysis and Application, 2009, Vol. 27, The Royal Society of Chemistry, Cambridge, UK available at: www.rsc.org last visited on May 15, 2022.

from chopped electric wires and cables and recovery of cooper and precious metals from printed circuit board scrap.[52] It has been observed that the multistage process in needed to separate conductors from non- conductors. Both corona discharging and eddy current based electrostatic separation have received significant attention in the separation of ferrous and non- ferrous metals and the separation of the plastics from the plastic and metal mixture.[53]

- **Eddy Current – based electrostatic separation:** When particles of non – ferrous metals pass over a rotating magnet at high speeds, eddy currents are created in the non- ferrous metal, which generated a magnetic field around them. when the polarity of that magnetic field is the same as the rotating magnet, the non- ferrous metal is repelled form the magnet and it is this action that enable separation of such metals from feedstock materials.[54] Practical deployment of an eddy current separator is generally by action on granulated material, the material is transported on a conveyor belt which move over a pulley which generate a high intensity permanent magnet rotating at high speed, thus generating an alternative magnetic or primary magnetic field.[55] An eddy current is generated in conductors which are exposed to this field, with a resultant repulsive force existing between the drum magnet arrangement and the conductor which in turn moves the conductor away from the drum.[56] The generation of such a lifting force affects the trajectory of particles leaving the belts, this affords the practical means of separation of non- ferrous particulates. The Introduction of eddy current separators, whose operability is based on the use of rare earth permanent magnets, has been one of the most significant developments in the recycling industry in recent years. High – frequency eddy current separators, where the magnetic field changes very rapidly, are needed for separation of smaller particles.[57]
- **Density Separation:** Density separation is also known as gravity separation is considered as the best physical separation option for non – metals from the metals by different specific gravities. Density separation is dependent on the density and the size of the components. Gravity concentration separates materials of different specific gravity by their relative movement in response to the action of gravity and one or more other forces, such as the resistance to motion offered by water or air. Density separation techniques that have extensively been used in the mineral processing industry are now applied into e- waste recycling as waste electrical and electronic equipment consist of many plastics, light metals, and heavy metals.[58]

The use of air to separate material of different density has long been established and air tables are used extensively within the food industry for grain separation and within the metals industry for applications such as refining of crushed slag in foundry output. In recent years both air and water-based gravity tables have been

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[52] Ibid
[53] Ibid
[54] Darren Kell, "Recycling and Recovery" Electronic Waste Management, Design, Analysis and Application, 2009, Vol. 27, The Royal Society of Chemistry, Cambridge, UK available at: www.rsc.org last visited on May 15, 2022.
[55] Ibid
[56] Ibid
[57] Sammani Ramanayaka, Santhirasekaram Keerthanan and Methika Vithanage, "Urban Mining of E- waste: Treasure Hunting for Precious Nanometals", Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 19 – 24
[58] Ibid

adopted for the sorting of electronic scrap and form an integral part of a number of electronic recycling plants operations.[59]

Material separation through Chemical techniques

Chemical processes that are used in resources recovery of waste electrical and electronic equipment includes three processes:[60]

a) Pyrometallurgical processes
b) Hydrometallurgical processes
c) Bio metallurgical processes

Most common chemical techniques for precious metal recovery form waste electrical and electronic equipment are Pyrometallurgical and Hydrometallurgical processes. Pyrometallurgy is the most traditional and standard treatment process where hydrometallurgy is a recent advancement.[61]

Pyrometallurgical Process:

The technique of recovering metal from electronic trash via high – temperature processing is known as pyrometallurgy method. pyrometallurgy method involves incineration, smelting in plasma arc or blast furnaces, sintering, melting and gas – phase reactions at the high temperatures.[62] Presently, waste electronic and electrical equipment recycling is dominated by pyrometallurgical routes. After the reduction of size via physical techniques, WEEE essentially transferred into smelters for separation and recovery of copper and other precious metals. In the pyrometallurgical process, the liberation of valuable metals is achieved by smelting in furnace at high temperatures.[63] Typical e- waste is rich in iron (Fe) and aluminum (Al) followed by copper (Cu) and lead (Pb). Therefore, WEEE may undergo Lead smelting and copper smelting routes in order to separate Pb, Cu and precious metals.[64] Recent techno- economic analysis of pyrometallurgy has revealed that the e- waste recycling process embedded in copper smelting has potential value and is economically feasible.[65]

The Pyrometallurgy method involves the following steps:[66]

- **Pre – Treatment:** To get rid of non – metallic components and other pollutants, the electronic trash is shredded and separated.

[59] Peeranart Kiddee, Jatindra Kumar Pradhan, Sanchita Mandal, Jayanta Kumar Biswas and Binoy Sarkar, "An Overview of Treatment Technologies of E- waste", Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 1 - 14
[60] Ibid
[61] Ibid
[62] Sammani Ramanayaka, Santhirasekaram Keerthanan and Methika Vithanage, "Urban Mining of E- waste: Treasure Hunting for Precious Nanometals", Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 19 – 24
[63] Ibid
[64] Ibid
[65] Supra Note 112
[66] Kalyani Korla and Chanchal Kumar Mitra, "Biochemical Hazards Associated with Unsafe Disposal of Electrical and Electronic Items" Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 55 - 67

- **Pyrolysis:** The pre – treated e- waste is heated in a reactor at temperature between 300 – 600 degrees Celsius in the absence of oxygen. This causes the organic material to break down and release gases, leaving behind the charred residue containing metals.
- **Smelting:** The charred residue is then mixed with a reducing agent like coke, and smelted at the temperatures between 1200 to 1400 degrees Celsius. This causes the metals to be separated from the charred residue and form a molten metal alloy.
- **Refining:** The molten metal alloy is then refined to removed impurities and recover individual metals such as, gold, silver, copper palladium.

Although, the pyrometallurgy is traditional and commonly used in metal recovery in the past centuries, it has borne some merit and demerits. The ability to accept any form of WEEE scrap since the organic matters in WEEE has been used as fuel during the incineration process is one of the main merits. However, there are some demerits of pyrometallurgy process have been reported as follows:[67]

- Pyrometallurgy process cannot recover metal like aluminum and iron since these are oxidized to metal oxides and shifted into the slag.
- It produces a large quantity of slag.
- It is impossible to recover some certain products such as plastic, ceramic and glass since these are provided thermal energy to the burning process.
- The combustion of the plastics generated environmentally toxic fumes such as furans, polybrominated diphenyl ether and dioxins and individual attention needed to be controlled this harmful emission.
- Uncontrolled combustion of WEEE during the incineration process.
- lengthy process, at the end of the process the precious metals such as gold and silver residue obtained and it is very challenging tasked to recover the precious metals from the residue.

Hydrometallurgical Process:[68]

A procedure called hydrometallurgy extract metals from electronic trash using water solution. Compared to pyrometallurgy, hydrometallurgy is considered to be better as the technique can be conducted in a controllable, more exact, predictable conditions through an environmentally friendly manner. This process involves the use of chemical reaction to dissolve metals from e- waste and then recover them through precipitation, ion exchange or electrochemical techniques. The hydrometallurgy process for e- waste treatment typically involves the following steps:

- **Shredding and sorting:** To get rid of non- metallic components and other pollutants, e- waste is shredded and separated.
- **Leaching:** The shredded e- waste is then place in a reactor containing a leaching solution, which dissolves the metals from e- waste. Acid like sulfuric acid or hydrochloric acid as well as alkaline solution like sodium hydro – oxide is frequently used as leaching agent.

[67] Ahmed Ashiq, Asitha Cooray, Srikanth Chakravartula Srivatsa and Meththika Vithanage, "Electrochemical Enhanced Metal Extraction from E- waste" Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 119
[68] Supra Note 117

- **Separation:** After leaching, the resulting solution is separated from the solid residue, which contained non- metallic materials and other impurities.
- **Purification:** The solution is then purified to remove impurities and recover the dissolve metals. Techniques like precipitation, ion exchange, or solvent extraction can be used to accomplished this.
- **Recovery:** The individual metals like gold, silver, copper and palladium are then extracted from the purified solution through further processes. techniques like precipitations, electrolysis can be used to accomplished this.

Earlier, leaching from cyanide is standard practice in gold mining. However, due to its high toxicity, it is not in practice at today's industry. It has been found that thiourea and thiosulfate leaching as the least hazardous techniques for the recovery of precious metals, however, are not cost effective. In the case of thiourea, the stability is poor whereas, the leaching kinetics of thiosulfate is slow and hence require large amount of reagent, make it unrealistic in large scale use.[69]

Recently, the organic acids also have used to recover the metals from e- waste, especially cellphone batteries. The organic acids are considered as potentially harmless to the environment, efficiently leaching the metals, less corrosive, and biodegradable green chemical.[70]

Bio metallurgical Process:

Bio metallurgy process has received recent attention due to low investment cost, low environmental impact, and low energy consumption and therefore has become a well-established pathway for recovering precious metals from WEEE. Bio metallurgy involves two processes: Bioleaching and Biosorption.[71]

- **Bioleaching:** Bioleaching is a simple process for the recovery of metal particles from e- waste, with the use of micro – organisms such as bacteria, fungi and actinomycetes. This particular process has considered as low energy consuming, highly efficient, environmentally friendly, and a low operational cost process that can be carried out at room temperature and atmospheric pressure. Acidophilic bacteria, most frequently Acid thiobacillus ferroxidase are used in bioleaching. The chemical makes up of culture medium, the size of the pulverized PCBs and the pH level of the solution, all have a big impact on bioleaching. The particles size has an impact on the leaching time. The Bioleaching is an effective manner to recover the precious metals form the WEEE. Therefore, it is necessary to study further in order to improve the leaching abilities and discover new species of microorganisms.[72]
- **Biosorption:** Biosorption is another technique, which can be used in recovery process of precious metals from WEEE. The bio sorbent used in this process can be either dead or alive or product biomasses of bacteria, fungi, algae and protein etc.[73] The adsorption of metal take place due to the

[69] Viraj Gunarathne, Sameera R. Gunatilake, Sachithra T. Wanasinghe, Thilakshani Atugoda, Prabuddhi Wijekoon, Jayanta Kumar Biswas and Meththika Vithanage, "Phytoremediation for E- waste Contaminated Sites" Handbook of Electronic Waste Management: International best Practices and Case Studies, 2020, Butterworth- Heinemann is an Imprint of Elsevier, UK PP. 141 - 147

[70] Darren Kell, "Recycling and Recovery" Electronic Waste Management, Design, Analysis and Application, 2009, Vol. 27, The Royal Society of Chemistry, Cambridge, UK available at: www.rsc.org last visited on May 15, 2022.

[71] Bruce A. Fowler, "Metals, Metallic Compounds, Organic Chemicals and E- waste Chemical Mixtures", Electronic Waste: Toxicology and Public health Issues, 2017, Academic Press an Imprint of Elsevier, UK, PP. 17 - 29

[72] Ibid

[73] Ibid

physiochemical interaction between the metals in solution and surface of bio sorbents, while complex formation, microbial oxidation and reduction, chelation between bio sorbent and metals, and microprecipitation are taken place as the chemical interactions. The physical Interaction includes ion exchange and electrostatic forces.[74] The Biosorption capacity of metals are affected by several factors such as, temperature, solution pH, the dosage of bio sorbents, and charge of metals. Due to their ability to bind with and concentrate metal ion from solutions, decomposing and inactive biomass material are frequently used.[75]

There are some demerits of the biosorption of metals, it needs to be leached out the solid waste prior to carry out the biosorption, and the bio sorbents are necessary to undergo a chemical surface modification to achieve maximum biosorption capacity.[76] Due to these limitations, the biosorption process is carried out at the small scale and laboratory levels. Further implementation is needed for the biosorption process to industrial and commercial levels. [77]

Product Design and Engineering Intervention

In Europe, the Electrical and Electronic Equipment, in addition to including precious and other valuable and scare metals, contains toxic substances. after the turn of e- waste, governments started legally restricting the use of well – known hazardous substances such as lead, cadmium, mercury and hexavalent chromium.[78] Besides substance restrictions, the REACh regulation in particular contains stipulations and tools that increase the pressure on producers to replace hazardous substances that are yet to banned.

Despite the obligation to collect and treat e- waste separately from private households, significant parts of waste electrical and electronic equipment will continue to be found in the current disposal routes. Even if WEEE were collected separately and submitted to recycling processes, its content of mercury, cadmium, lead, chromium, Polybrominated biphenyl and polybrominated diphenyl ether would be likely to pose risks to health or the environment, especially when treated in less-than-optimal conditions. Taking into account technical and economic feasibility, the most effective way of ensuring a significant reduction of risks to health and the environment is the substitution of those substance in EEE by safe and safer materials to enhance the possibilities and economic Profitability of recycling of WEEE and decrease the negative impact on the health of workers in recycling plants.[79]

The solution for the e- waste crises lie in "prevention at the manufacturing sources or the precautionary principles". It is a precautionary measure demanding the avoidance of hazardous substances in the production stage of products in order to protect health, safety, and the environment and to improve the end- of – life situation of electrical and electronic equipment. This can be done by employing waste minimization

[74] Siegfried Kreibe, "Current and New Electronic Waste Recycling Technologies", E- waste Management: From waste to Resources, 2013, Routledge Tylor & Francis Group, London and New York, PP. 25
[75] Ibid
[76] Ibid
[77] ibid
[78] The European Restriction of Hazardous Substances Directive, 2011/65/EU (RoHS 2), a template to lesser degree is the Restriction, Evaluation, Authorization and Restriction of Chemicals (REACh) Regulation, (EC) 1907/2006.
[79] Otmar Deubzer, "reduction of Hazardous Materials in Electrical and Electronic Equipment", Waste Electrical and Electronic Equipment Handbook, second edition, Woodhead publishing an imprint of Elsevier, UK, PP 208 - 230

techniques and by a sustainable product design as well as legal mechanism focuses on waste reduction rather than only emphasis on waste production and disposal method. for an example: EU has adopted a directive called Restriction of Hazardous substances Directive.[80] The Directive restricted the use of follow metals in EEE: cadmium (0.01%), hexavalent chromium (0.1%), lead (0.1%), mercury (0.1%), polybrominated biphenyl (0.1%), polybrominated diphenyl ether (0.1%), the bracketed percentages are threshold limits for their substances.[81] The Directive also direct the producers of EEE to find alternative to avoid using the six substances. A restricted substances can be either substituted or eliminated. Elimination means shifting to a technology that does not require the restricted substances.[82]

Hazardous substances are used because they have specific uses that are strongly related to their physical and chemical properties. substitution may thus be impossible in some cases, and alternative technologies that avoid restricted substances may not be available. for this case, the Directive have to allow the continued use of restricted substances. Such exemption can be granted:[83]

a) If the substitution or elimination of the restricted substance is scientifically and technically impossible;
b) If substitutions are not reliable;
c) If the substitution or elimination causes higher overall adverse impacts on the environment, health and safety than does the continued use of these substances.

[80] 2002/95/EC/RoHS, was adopted in February 2003 by the European Union. short for Directive on the Restriction of the use of Certain Hazardous Substances in Electrical and Electronic Equipment.
[81] Supra Note 129
[82] Ibid
[83] Ibid