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Review: E-waste in Indian Context Status, Strategy and Future Prospects of Urban Ore Recycling in India

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Abstract

The global pandemic has led to an increased dependency on Electrical and Electronic Equipments (EEEs) in our daily lives. The use of EEEs has thus grown exponentially compared to the previous years. It is one of the fastest-growing areas worldwide. The limited life span of electronic devices has led to the Waste Electrical and Electronic Equipment (WEEEs) increasing manifold. WEEE consists of several valuable elements, which are found in limited amounts in natural resources. Along with this, it has many hazardous elements, which are harmful to the environment and human health. India had adopted the Extended Producer's Responsibility (EPR) to recycle and minimise WEEEs in an organised manner, but due to several reasons the rules and regulations are not implemented properly. This review discusses the current status of WEEE generation and efforts made towards the development of eco-friendly and energy-saving recycling technologies with sustainable steps for WEEE recycling as secondary resources.

Keywords: *India E-Waste, Recycling, Status Recycling, WEEE*

1.0 Introduction

Globalisation and advancement have brought the world closer in this electronic era. Dependency on electronic and electrical devices like computers, mobile phones and different electronic equipment (refrigerators, televisions, washing machines and different industrial equipment) has risen. All these electronic devices have a limited life span, so the waste generated from these devices, WEEE, is increasing rapidly. In the previous decades, most of the WEEE was dumped into landfills or incinerated, creating a lot of pollution and other environment-related issues[1]. WEEE generated in the developed countries was also imported to India despite the international accords to limit international shipments. The substantial volume of WEEE generated annually necessitates a comprehensive examination of product and process design and the establishment of component reuse systems to facilitate enhanced materials recovery for WEEE[2].

Rapid technological advancements and the launching of lightweight attractive models with good features replaced the old models with new ones generating a huge amount of WEEE.

This type of waste contains a lot of hazardous and non-hazardous substances, which are generally mixed with municipal waste effluent and create huge pollution. WEEE contains both valuable and toxic materials containing more than 30% of metals (Fe, Au, Pb, Cu, Co etc.), 60% of non-metals and 2.70% other

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pollutants. There are strict environmental rules and regulations for the management of such kind of waste by reusing, reducing and recycling these WEEE. The ministry had notified WEEE management rules in 2016 which were further amended in 2018 to include different objectives such as the responsibility of electronic product developers to manage WEEE by a loop of collection, storage, transportation, environmentally safe dismantling and recycling under EPR authorisation, minimising illegal recycling operations and reduction of hazardous substances in electrical and electronic equipment. According to the Ministry of Environment, Forestry and Climate Change division update on 7 April 2022, there were 10,14,961.21 tones of WEEE generated till 2020 and only 2,24,041.0 tones were collected, dismantled and recycled or disposed of. There is an expected rise in dependency on electronic equipment like mobile phones, and computers in a post-pandemic world which has moved towards digitisation. This may have created WEEE in a larger proportion as compared to the previous year's data. The government has many norms for discarding limited quantities of pollutants into the environment. However, implementation of these norms is a major challenge due to restrictions, affordability and proper knowledge for handling and reusing of WEEE. In India, some proposed industries for the recycling of WEEE are Trishyiraya Recycling India Private Limited, Attero Recycling, Delhi, E-Parisaraa, Eco Recycling, Metaore Recycler, Kolkata, etc. These industries are operating in various areas of India including Delhi, Meerut, Firozabad, Chennai, Kolkata, Bangalore and Mumbai. India is stepping towards profitable stakeholders in the WEEE management business with the help of many integrated and interconnected networks of different research institutes working in this area.

In this paper, the changing trend of the generation and recycling of WEEE in India has been reviewed with a focus on the generation and recycling strategies of different WEEE like personal computers, laptops, mobile phones etc. and general procedure adopted by recyclers for the metal recovery from WEEE.

2.0 Sale, Scrap and Waste of EEE

During the pandemic, India's total consumer-based electronic appliances market from small appliances to larger appliances like washing machines and air conditioners has increased by 9% compared to the pre-pandemic era. The last two-quarter consumer reports suggest an exponential growth of the premium electronic product market, despite increased prices in all categories, inflationary market situation and work-from-home office employees due to pandemic restrictions. The sale of some essential electronic products like mobile phones, laptops, personal computers, televisions, coolers and air-conditioners was more between 2020 and 2022 as compared to 2019. According to market intelligence firm GfK India, television has shown vigorous growth over 2020. All categories including television have presented a strong growth over 2020, as per data from market intelligence firm GfK India. Computer sales in 2021 are beating 87% from 2019 levels, while the growth of large appliances including refrigerators, air-conditioners and washing machines increased by 10% over 2019. Small appliances and kitchen electronics like mixer-grinder

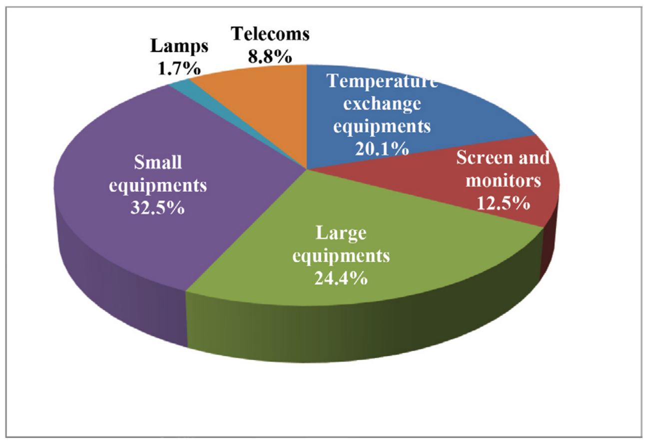

Figure 1. Electronic product distribution by percentage[6,9,33].

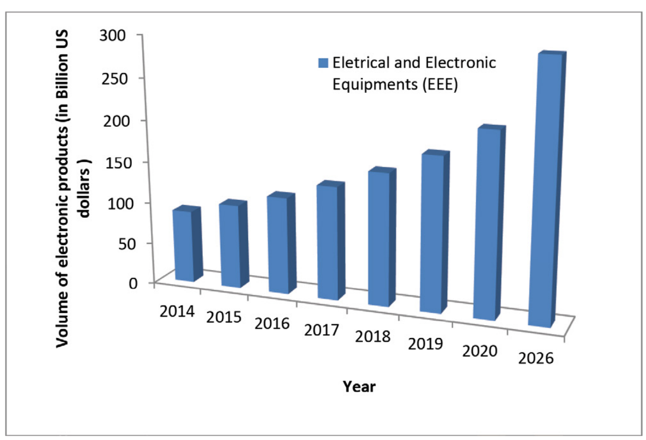

Figure 2. Market value of electrical and electronic products[4,5].

and microwave ovens grew by 13%, smartphone sales increased by 8% and mobile phones by 4%[3]. Figure 1 gives an idea about electronic product distribution by percentage.

The data presented in Figure 2 shows a review of the overall market value of WEEE which is an increasing trend. Data from 2014-2026 has been included in Figure 2.

In today's electronic world, there exists no such concept as a "Device for a life" which means a lot of WEEE gets generated by default due to its expiry. Table 1 indicates some of the electronic products with their expiry.

Table 1. Different electronic devices with their weight and life span[32]

Item	Weight (kg)	Expiry (Life Span) (Years)
Mobile Phone	0.1	2
Telephone	1	5
Computer	25	3
Television	30	5
Washing Machine	65	8
Refrigerators	25	10
Iron	1	10
Hair Dryer	1	10
Microwave	15	7
Kettle	1	3
Air Conditioners	60	15
Coolers	20-60	3-7

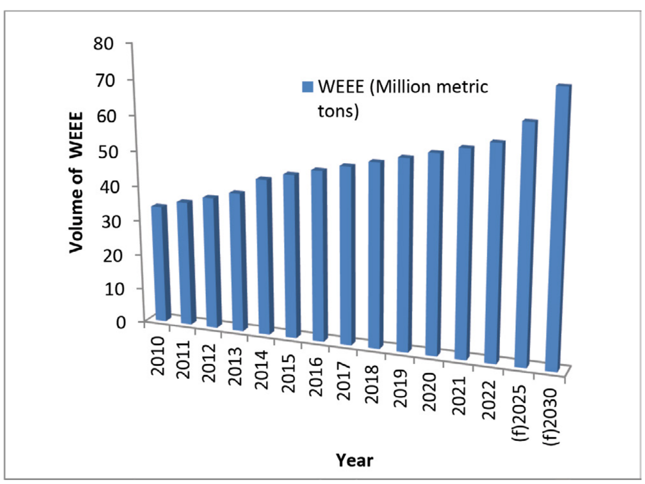

Figure 3. Volume of WEEE generated in million metric tons in the previous decade and forecast (f)[6,9,33].

Worldwide record shows that 59.4 million tons of WEEE was generated in 2022. The scale of this waste is accelerating every year showing a 25.5% rise in WEEE generation from 2014 to 2022 (Figure 3) and based on this trend, it is expected to rise to 74.7 million tons by 2030. WEEE generation is growing by an average of 2 Mt per year.

There will be over 347 Mt of un-recycled WEEE on the Earth in 2022. China, the USA and India produce the most WEEE. Only 17.4% of WEEE is known to be collected and properly recycled. There are 468 authorised recyclers (formal sector) present in 22 states of India which is much lesser compared to the WEEE generated, so maintaining balance and avoiding accumulation of this kind of waste is the real challenge. Table 2 indicates the top 10 countries which are producing WEEE with its volume in kilo ton.

According to statistical data of WEEE generation, it can be analysed that this is going to be a major issue in future which can affect the environment, human health, wildlife and their habitat. It is reported that WEEE can contaminate the air, water and soil by releasing heavy metals from landfill dumpings. In 2022, it was estimated that 88.9 million tons of carbon dioxide were released into the environment from dumped refrigerators and air conditioners alone. According to the National Library of Medicine, research has been done on the connection between exposure to WEEE and its effect on human health and it is concluded that WEEE can lead to a variation in thyroid function, adverse neonatal outcomes, changes in temperament and behaviour, cellular expression, function changes and decreased lung function. People living near

Table 2. Top 10 WEEE generating country[34].

Rank	Country	WEEE(Kilo ton)
1	China	10129
2	USA	6918
3	India	3230
4	Japan	2569
5	Brazil	2143
6	Russia	1631
7	Indonesia	1618
8	Germany	1607
9	UK	1598
10	France	1362

the WEEE recycling towns have shown evidence of DNA damage and mutation due to exposure to harmful elements like nickel, lead, and mercury. These are affecting the future generations due to a high risk of stillbirths.

The main source for the WEEE generation is the IT sector which is completely dependent on electronic devices like computers, hard disks and mobile phones. Government sectors, educational institutes, commercial sectors and households are other units that transfer WEEE generated to the formal and informal sectors for recycling purposes, according to the benefits given to them (Jha MK *et al.*,)[7]. Accurate information about the generation and collection of WEEE is not possible due to the large number of illegal businesses in the recycling sector that import WEEE from developer countries like America and the European Union. In recent years, there has been a lot of mishandling of WEEE waste management for profits without addressing environmental concerns[8].

In India, the collection of WEEE is majorly connected among the manufacturers, dealers, distributors, consumers, collectors and recyclers in the loop format. Unauthorised sectors are largely involved in collecting, dismantling and smelting of WEEE. Waste management of WEEE involves the use of acid/alkali in an inappropriate manner which can harm the environment. Developing countries like India differ from developed countries regarding rules and regulations about waste collection. Here waste pickers pay money to the consumers for collecting waste from them for their discarded products and there are no guidelines about advance recycling fees to be paid by consumers to retailers, retailers to manufacturers and lastly to the recyclers for their efforts to save the environment. The flow chart (Figure 4) below indicates about product life cycle and close loop system of WEEE.

As India is a developing country, it does not have adequately efficient technology, manpower or infrastructure to handle WEEE generated every year. In the last decade, the Indian government has given due attention to the issue and framed some rules and regulations for WEEE management in 2011 which was implemented immediately for the sustainable development of the country. These rules were modified in 2015 and further in 2016 according to requirements. However, a lack of knowledge and community awareness of these rules leads to poor implementation. Due to this improper collection, transportation, processing and disposal of WEEE are major emerging issues in the implementation of a sustainable waste management system. The rising problem of WEEE management is a complex one and needs more attention and intervention from the government along with the involvement of intelligence, NGOs, entrepreneurs and recyclers for proper planning design and implementation of a comprehensive and sustainable WEEE recycling programme.

3.0 Sustainable Management of WEEE

The need of the hour is to plan strategically for better handling and recycling of WEEE. Waste management depends on the strategy of reusing, reducing and recycling the waste for minimum disposal in the landfills for further degradation. For sustainable development in the electronic era, it is very important to plan and design routes for minimum disposable of waste generation[10].

Electronic devices can be reused by donating them to the needy who cannot afford such expensive devices. There are many electronic gadgets which do not work due to damage of software malfunctioning. Instead of contributing to the scrap, the damaged component can be substituted with a new one, thereby enhancing the operational capacity and longevity of the device. Defective parts which are replaced with new parts can

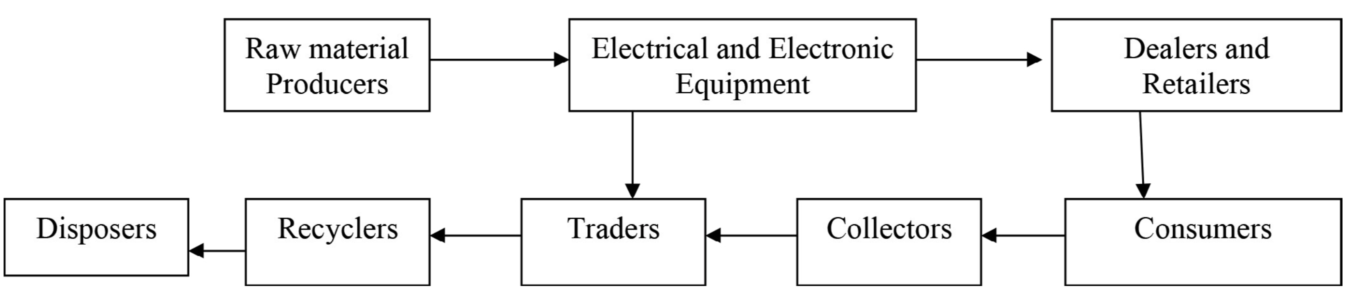

Figure 4. Product life cycle of electrical and electronic equipment[7].

be sent to the recycling unit for further dismantling to recover valuable elements and for further safe disposal. Governments, NGOs and recycling units should work in collaboration to spread awareness, sensitivity and information regarding the handling of WEEE and the process to dispose it without harming the environment and human health[11].

EPR also involves designing products by considering their entire life span for sustainable development. This is done by producing electronic devices which use fewer resources and minimum harmful substances.

3.1 Recycling Technologies

WEEE processing techniques developed at the Council of Scientific and Industrial Research - National Metallurgical Laboratory (CSIR-NML) are environment-friendly and effective. NML has developed strong collaborations with international agencies like the Korean Institute of Geosciences and Mineral Resources (KIGAM), the Russian Academy of Sciences (RAS) and different Indian government agencies like the Department of Science and Technology (DST), Department of Energy (DAE) etc. Several Indian industries operating in recycling areas like M/s. E-Parisaraa, Bangalore, M/s ADV Metal Combine Pvt. Ltd., New Delhi and M/s Eco Recycling, Mumbai are also working in collaboration with NML for E-waste recycling.

Different techniques and procedures are involved in WEEE recycling. Hydrometallurgy, pyrometallurgy, a hybrid of hydro and pyrometallurgy and biometallugy are developed for the recovery of various metals from the WEEE. Electrometallurgy techniques are also reported by some research articles. Amongst all the techniques, the hydrometallurgy technique is the least hazardous and most efficient route for metal recovery. Sustainable management requires the recycling of e-waste with safe and modern technologies which are low cost and specific and efficient techniques for complete recovery of metals.

The typical flow chart for recycling mentioned below (Figure 5) indicates that WEEE gets segregated according to the original products after dismantling. Components like batteries, cables, solders etc. are recycled to recover different metals like copper, nickel, cobalt, lithium, tin etc. The remaining parts undergo mechanical shredding for further separation of ferrous and non-ferrous metals and plastics. Hazardous metals like lead, mercury and zinc cannot be processed in the same unit. These are sent to hazardous waste treatment plants for further recovery. After crushing and segregation of different types of WEEE they are sent to the global market for further recovery of precious metals from it.

Heterogeneous WEEE has different sizes, shapes and composition materials which can be segregated depending on different properties. WEEE is dismantled first and then segregated according to their sizes. Then shredding is done with different teeth-sized scutter cutters depending on the need. A size fraction of 1 to 0.5 mm is obtained from the pulverisation process. After pulverisation, the powdered material undergoes other physical separation methods based on density, particle size, surface properties, magmatic susceptibility, electric conductivity etc. The pulverised material is further processed based on air classification, eddy current, heavy media, magnetic fraction, etc. Light fractions like plastics, rubber and ceramic materials are separated in this manner. Along with this, some light metals like aluminium, magnesium and non-ferrous metals get separated at this stage. Non-ferrous metallic material obtained from this undergoes different hydrometallurgical techniques like leaching, solvent extraction, precipitation and evaporation to get pure metal depending on the availability and applicability.

The maximum volume of WEEE recovery includes different metal parts, heat sinks, ferrite and ceramics components, ferrous and non-ferrous metal scraps. Recyclers in India have adequate intelligence to produce new raw materials from WEEE. Plastic material obtained from WEEE can be utilised as a filler in road construction and in some cases as an alternative fuel option. Approximately 27% of plastic parts from electronic waste can be recovered and utilised. Glass recyclers also efficiently use glasses recovered from the WEEE. They convert them to usable raw material. Glass cullet is used to produce fresh glass parts like panels, funnels, TV units etc. Cathode Ray Tube (CRT) glasses also undergo a process of lead extraction. Physically separated material from WEEE is further treated for Printed Circuit Boards (PCB) recycling, recycling of Li-ion batteries, converting plastics to value-added products, copper recovery from wires, Liquid Crystal Display (LCD) screen processing, recovery of different hazardous substances, etc.

Hydrometallurgy techniques mainly include extracting metals from the ore in an aqueous solution. The primary stage of the hydrometallurgy technique is leaching which involves the dissolution of metals into the

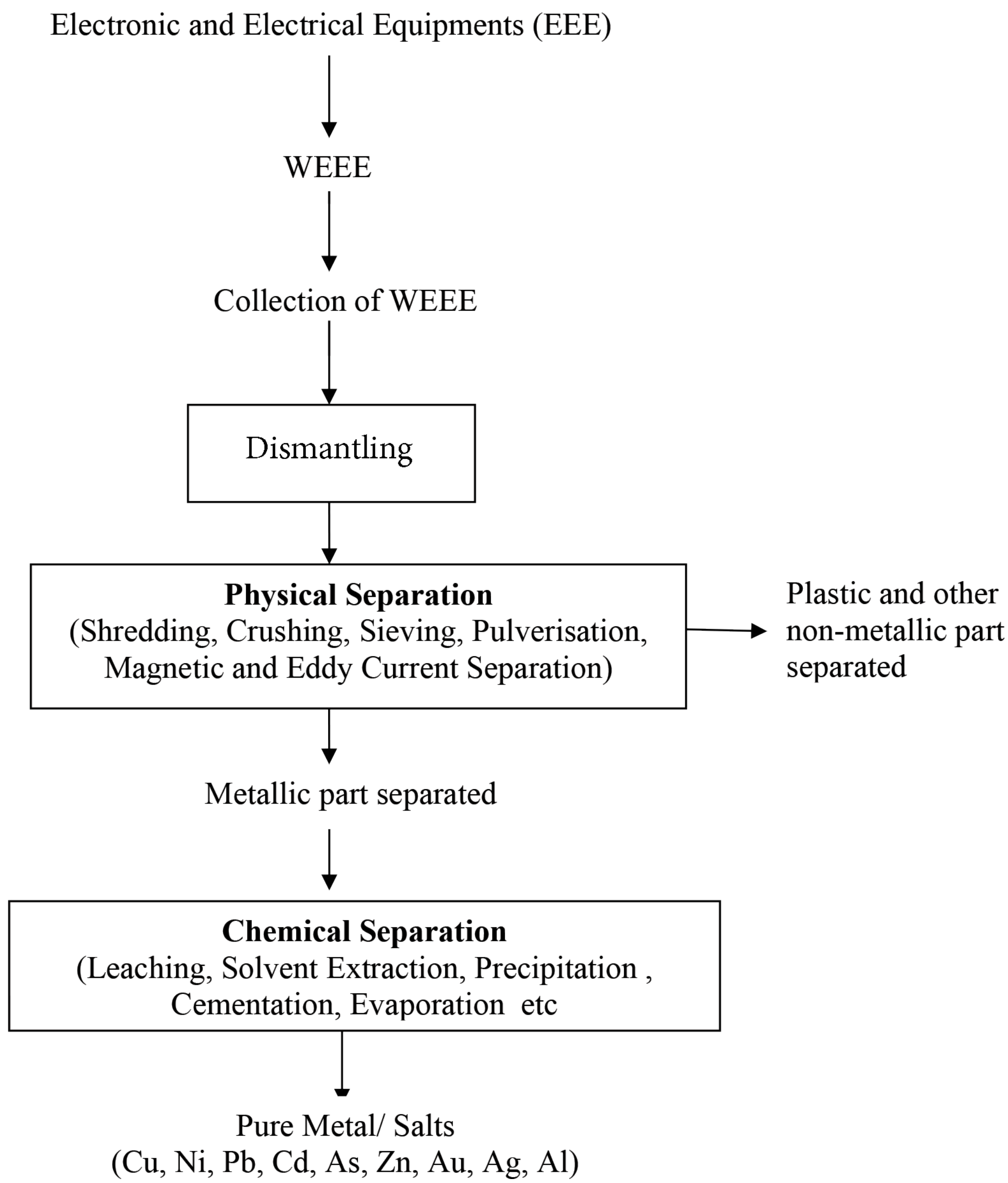

Figure 5. Process for recovery of non-ferrous metals from WEEE[32].

aqueous solution or a specific solvent. After the leaching process, the extract is mostly subjected to further purification and concentration before precious metals are recovered in metal form or compound form. Techniques include solvent extraction, precipitation, adsorption, distillation, cementation etc. The final recovery stage may include evaporation, precipitation, cementation or electro-winning process. More often ore must be pretreated with various mineral processing steps before being subjected to the hydrometallurgy techniques.

WEEE is leached using different acidic or basic reagents such as sulfuric acid, nitric acid, ammonia etc for the dissolution of metals into the aqueous form. Oxidising agents are utilised for the increasing rate of the reaction. After this stage, leach liquor containing valuable metals is filtered and undergoes liquid-liquid extraction (solvent extraction) by using organic extractants like di-(2-ethylhexyl)phosphoric acid (D2EPHA), dialkyl monothiophosphinic acid (Cyanex), 2-hydroxy-5-nonylacetophenoneoxime (LIX84) etc. Different organic-to-acid ratios can be taken at different pH for selective separation of metal in solution. Lastly, the purified metal solution is crystallised or electrowon to form a purified metal compound or metal sheet.

3.2 Recycling of PCB's

A very complicated mixture of valuable and precious metals is available in PCB which is an important part of every electronic device. PCB's recycling technologies have been developed in CSIR-NML to recover these valuables. PCBs are concentrated, with metals consisting 6% of the entire WEEE. In these techniques, after the pulverisation of PCBs, different physical processing techniques are undertaken to separate metals from epoxy resins. PCBs are ground to reduce them to the desired size using different mechanical processing techniques like shredding and fragmentation, granulation, physical impaction etc. Further separation of metal-containing PCB powder is done by different mechanical processes like magnetic separation which is used to separate iron, nickel and cobalt which have magnetic properties while aluminium is separated using eddy current. Plastic-rich particles from the mixture are separated using an electrostatic separation technique to concentrate metal-rich PCB powder. An approximate feed concentration of 23% pulverised PCBs would get enriched to 78% metal by using these physical separation methods. After using physical separation techniques, metal-rich PCB powder undergoes roasting at a higher temperature and is then leached by using sulfuric acid and an oxidising agent (hydrogen peroxide) at optimised temperature and atmospheric conditions. A total of 93-97% of metals can be recovered using these optimised conditions of leaching using a minimum concentration of acid in the shortest time. Copper, nickel, cobalt, zinc, aluminium and iron are recovered from PCBs using this technology. Autoclave under oxygen pressure gives maximum recovery of metal in PCB's leaching technology.

Another alternative to the physical separation of PCBs was developed by the collaborative work of the Indo-Korean research team to overcome the feasibility issue. Organic swelling techniques of PCB separate the encapsulated thin layer of copper sheet and the outer layer of epoxy resin, which is helpful in metal-free epoxy resin to use as filler material and easy separation metals like copper, lead and tin[7,14,17,18,23]. Joint efforts in collaboration with NML and M/s Eco Recycling Company, Mumbai have developed hybrid techniques of pyro and hydrometallurgy in which pyrolysis, beneficiation and leaching techniques are used for recovery of low-density oil and copper metal sheet[24,25].

After extracting various metals from PCBs, gold recovery from waste mobile phone PCBs is attempted. Gold is present in the outer layer of PCBs of mobile phone scarps and small electronic equipment using the chemical leaching method. Adsorption or cementation technique is used for purification with subsequent heat treatment[26-28]. Recently the process for the recovery of silver from integrated circuits obtained from the PCBs has been further refined. The leaching technique was developed using a standardised condition that is 3 M HNO_3, 50 g/L pulp density, 80 °C temp and 1 hour mixing time. It had leached more than 90% of Ag, Cu, Pb and Ni leaving Au, Pt and Pd in the leftover material. Further silver was extracted by precipitation technique using 1M KCl in 30 minutes. Other metals were recovered by precipitation, solvent extraction and cementation process[27]. Another project on PCB processing has been implemented at C-MET, Hyderabad in collaboration with well-established recyclers M/s E-Parisaraa, Bangalore. They have used a vibratory centrifuge to separate small components of PCBs. It includes small outline transistors, crystal oscillators, chip capacitors, ICs, grid arrays, chip resistors and connectors which were depopulated and separated from the PCBs. De-capsulated bare PCBs undergo pyrolysis in a specially designed system having a 500kg batch size capacity. After this, the pyrolysed metals undergo air calcination to produce fragile material to reduce 40-50% of the mass[27].

3.3 Recycling of LIBs

Lithium-ion batteries consist of metals, organic chemicals, plastics and rich sources of lithium and cobalt. The process has been developed to recycle LIBs from scrap mobile phones through collaborative work of CSIR-NML and the Russian Academy of Science, Russia. Different experiments were performed on a bench scale in which black cathodic material obtained by physical processing of scarp LIBs from mobile phones is leached using minimum acid concentration at an elevated temperature for 1 hour. The Leach liquor obtained is further put for solvent extraction to generate pure lithium and cobalt solution at optimised pH. Further, using the evaporation technique cobalt sulphate and lithium sulfate salt are produced which are valuable products in the market[14,15,16,20,21,22]. In this technology, Batteries are crushed into scutter cutter and wet scrubbing is used to separate fine particle size of black powder from plastic and casing material of LIB. Beneficiated cathodic black powder consists of cobalt along with lithium, copper, manganese, iron etc.. Leach liquor obtained by this method is precipitated to obtain manganese and iron. The remaining filtrate containing copper is recovered using a solvent extraction technique. Cobalt is then recovered using Cyanex 272 and a concentrated pure solution of cobalt in a sulfate medium which generates $CoSO_4$, $7H_2O$ form. Electro-winning techniques are used to prepare the cobalt sheet and lithium present in the raffinate and recovered in a salt format using a solvent extraction technique. 97% Co and 99.999% Li salt is obtained by this technique with other metal recovery like copper, iron and manganese. 2M H_2SO_4 and 10% H_2O_2 are used to separate Co and Li for 2 h leaching at room temperature. This technology was transferred to a Delhi-based industry named M/s ADV Combine Pvt. Ltd.[29].

The process has been further optimised for manganese recovery from the same. Using 10% D2EHPA at an optimum pH of 4.5, 98% Mn was extracted from the filtrate before lithium precipitation[20]. Recently the team has worked on the recovery of lithium from cathode active material from discarded lithium ion batteries. Different process parameters like roasting temperature (750°C), mass ratio ($LiCoO_2/Na_2SO_4$: 1/0.5.) and time (2 hours) were standardised for the lithium sulfate conversion from lithium oxide from the complex mixture of lithium cobalt oxide from batteries. 99.1% of lithium was leached from the roasted product in De-ionised water at 75°C for 2 hours[21].

3.4 Recycling of Other WEEE

Other WEEE also contains valuables which need to be extracted in an eco-friendly manner using a well-optimised technology. The uniqueness of Rare Earth Metals and their availability in WEEE make it more interesting to recover them. The CSIR-NML are working on this project, to recover rare earth metal neodymium from the hard disk of personal computers. In this technology, magnets are initially removed by the demagnetisation process and crushed for size reduction and dissolution in an acid-containing medium at a suitable temperature. The precipitation technique obtains neodymium salt after leaching. This salt can be further leached using hydrogen fluoride to get the value-added product of neodymium fluoride[12,13,19,30].

This technique was further refined by the team in which different hydro metallurgical techniques were used in which Nd, Pr, Dy, and Fe were 100% leached from the demagnetised magnet in 2M H_2SO_4, 75 °C temp, 60 minutes mixing time and 100g/L pulp density. It shows 99.1% Nd, 94% Pr, and 99.9% Fe recovered from leach liquor using 35% Cyanex 272, 1/1 O/A ratio within 10 minutes. Multistage solvent extraction techniques were developed for selective rare earth metal recovery[30].

Fluorescent tubes from WEEE are also rich sources of Rare Earth Metals like lanthanum, yttrium, terbium, europium, cerium etc which can be recycled. To recover these, fluorescent lamps are broken into a closed system with a vacuum device and phosphor powder is collected. That powder is leached in an acid-containing medium at an elevated temperature. After leaching solvent extraction method is used to separate the pure solution of individual rare earth metal[30,31]. Along with this team has also worked on the electric vehicle containing nickel metal hydride batteries for rare earth metals recovery by leaching, solvent extraction and precipitation technique, REMs like Ce, La, Nd leached in 2M H_2SO_4, 75°C temp, 60 minutes mixing period and 10% H_2O_2. This mixture is further selectively separated by solvent extraction (10% PC88A, O/A 1/1) and precipitation method (pH 1.5 to 2) for 99% recovery of REMs[31].

4.0 Future Prospects of WEEE Management in India

There is immense potential growth guaranteed in the WEEE market in India. Along with high potential research and the right partnership, it seems to be riding the wave in accelerating the growth rate by considering environmental safety initiatives. There are some important factors to improve WEEE management like licences to co-operatives and groups of illegal recyclers, connectivity with municipalities, government subsidiaries, easy loans, providing proper land, rewards to recyclers, improving collection network in WEEE, new electronic equipment recycling like solar panels, electronic vehicles etc., eco-friendly technological development, improving safety for WEEE recycling and motivating informal sectors of the WEEE management sector for partnership with the formal sector for the benefit of both the sectors and saving the environment.

5.0 Concluding Remarks

From the detailed analysis of WEEE management in the Indian context, it can be concluded:

- There is a huge gap between the generation of WEEE, its reusability and recycling. 95% of the total WEEE recycling sectors are working informally due to the presence of attractive precious elements in the WEEE.
- Lack of awareness among the consumers and producers regarding the hazardous effects of WEEE and the lack of strict implementation of environmental rules and regulations has resulted in the mass handling of WEEE by informal sectors.
- For sustainable WEEE management, different strategies mentioned in this paper need to be followed for the recovery of different valuable elements which has increased the importance of the WEEE due to its guaranteed potential growth. It will reduce the load on landfills which is the need of the hour considering the larger business value in coming years.

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