इलेक्ट्रॉनिकी एवं सूचना प्रौद्योगिकी मंत्रालय
MINISTRY OF ELECTRONICS AND INFORMATION TECHNOLOGY

सत्यमेव जयते

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EU-REI
Creating a Resource Efficient India

Report on Best Available Technologies

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EU-India Joint Study

Toxics Link
for a toxics-free world

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Report on
Best Available Technologies

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Foreword

'*Circular Economy*' is the new 'Mantra' for future development and growth. Circular economy approach is imperative to fulfill the need of resources for the growing economy, like India. It minimizes the wastage at each life-cycle stage and promotes 4Rs (i.e. reuse, repair, recover, re-manufacture) and also ensures regeneration of products and materials.

India is the third largest consumer of raw materials produced globally. If current economic trends persist, then India's material consumption would reach nearly 15 billion tonnes by 2030 and above 25 billion tonnes by 2050. In order to fulfill the resources need, it is essential to follow circular economy approach rather than the current linear economy principle of take-make-dispose.

This study report prepared under European Union – Resource Efficiency Initiative (EU-REI), India on circular economy in E-waste provides an international scenario on global best practices to be adopted by Indian Manufacturer and Recyclers. Promotion of eco-design & Green products, scientific extraction and reuse of SRM & CRM in manufacturing value chain would be a forthcoming step in the country. This report ensures an India-centric approach to understand the preparedness of circular economy business models, identify gaps and opportunities, as also to formulate evidence-based policy recommendations.

I compliment EU-REI team for this comprehensive well-researched report on Global best practices in circular economy in E-waste.

Best Wishes,

(S. Krishnan)

Dated: 22.9.2023
Place: New Delhi

आज़ादी का अमृत महोत्सव

Digital India
Power To Empower

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CONTENTS

1. INTRODUCTION

Electronic gadgets have become essential to support modern-day lifestyles, driving the massive production-consumption of EEE globally. The products have been constantly evolving and loaded with new features and improved functionality, enticing customers to consume and discard more. A few electronic products have short lifespan, with limited options for prolonging their lifespan, resulting in the generation of waste, which is termed electronic waste. As per the Global E-waste Monitor 2020 report, in the year 2019, 53.6 million tonnes (an average of 7.3 kg per capita) of e-waste were generated globally and it is projected that the global e-waste generation will grow to 74.7 Mt by the year 2030[1]. This pace of waste generation is a matter of serious environmental concern as this ever-growing volume of waste is extremely complex and difficult to handle and dispose.

53.6
million tonnes
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Rapid increase in production & consumption driven by market economics is proving to be highly unsustainable because of increased raw material consumption as well as subsequent waste generation. Raw material reserves are only finitely available on the planet and need to be judiciously consumed for it to be conserved for use by future generations. The current economic model of extraction of raw material, its use for the manufacture of EEE, and waste generation at the end of life of the product can be termed as a linear model, which is highly unsustainable. The concerns around depletion of raw material stocks, its fragmented deposits in a few geographies, cost, and resources required to extract, transport, and process these for use have serious environmental impacts. Many such concerns and conversations have clearly shown the need to shift from a linear to a circular economy model. The circular economy model attempts to address optimized resource utilisation, increase recycled content in EEE, and minimization of waste.

Shifting from a linear to a circular model will take time but will benefit the environment, economy & society. One of the elements in achieving circularity is effective and efficient use of technology. Technology will be a key determining factor in bringing CE, bringing various aspects, such as technology used in extraction, manufacturing, and recycling. In this context, this paper seeks to identify and assess the role of technology in the recycling and recovery stage of various materials and metals from e-waste. And also, its applicability in the Indian context.

1 https://ewastemonitor.info/wp-content/uploads/2020/11/GEM_2020_def_july1_low.pdf

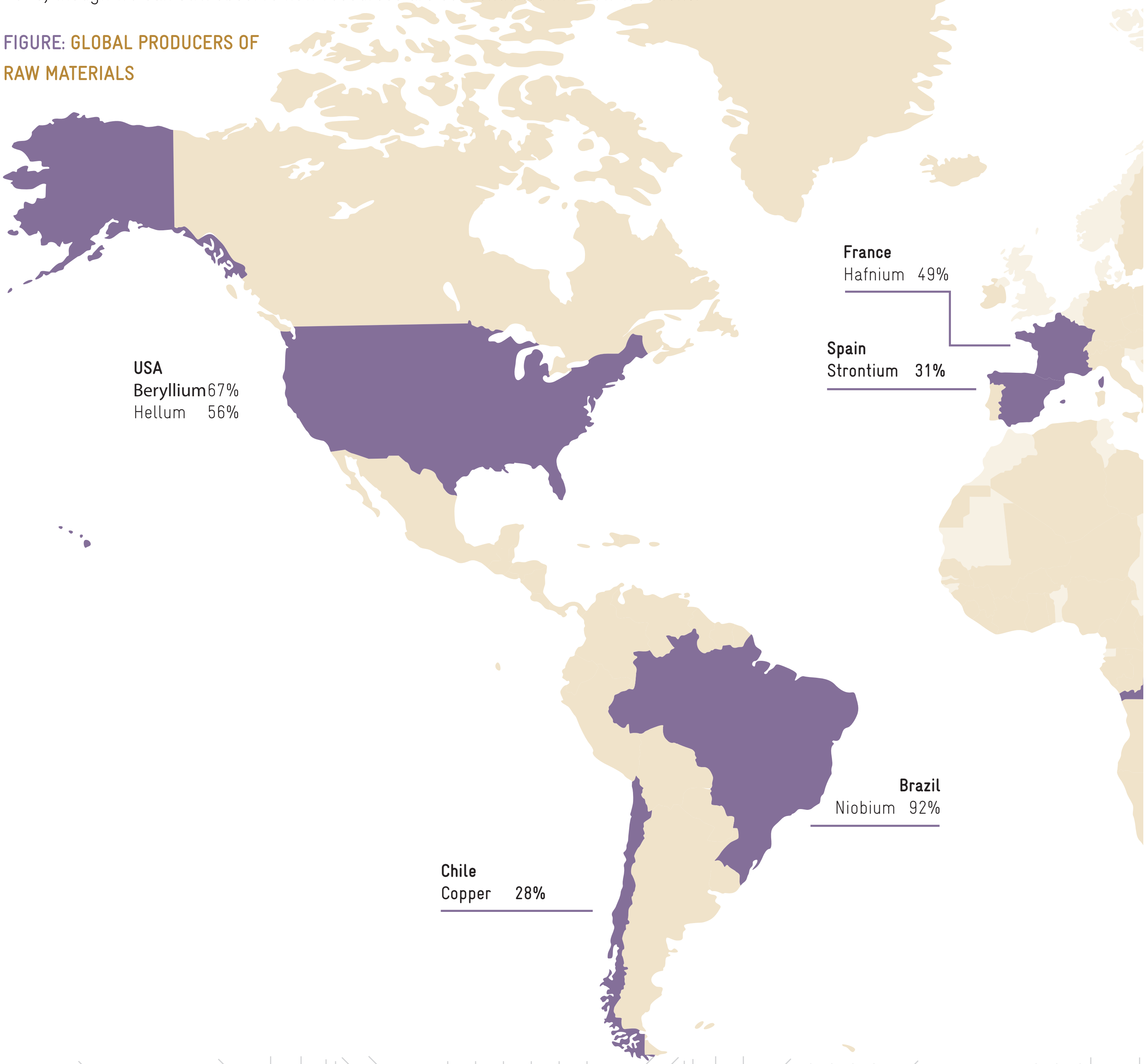
2. CIRCULAR APPROACH IN E-WASTE MANAGEMENT

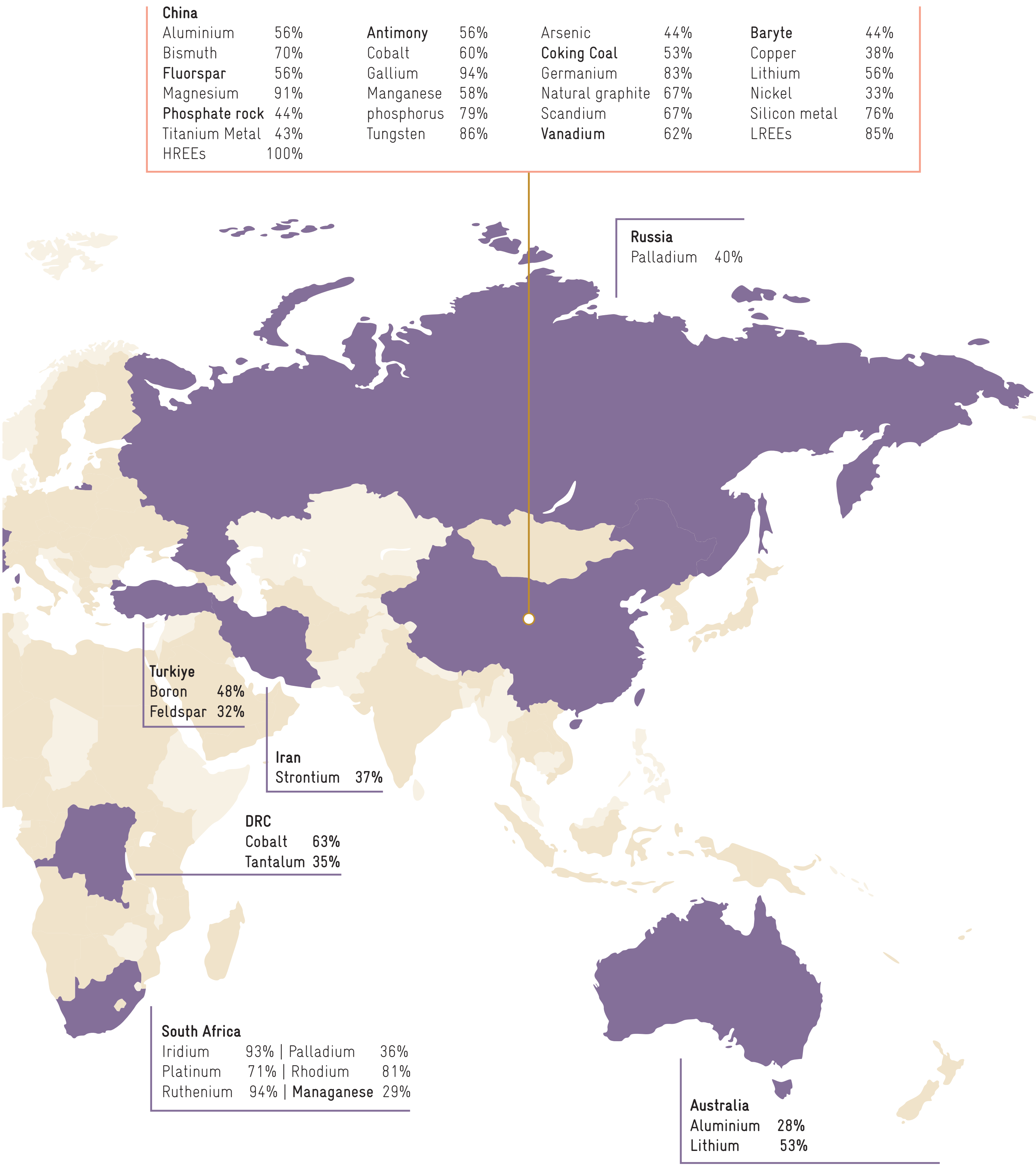
2.1 Increasing demand for raw material in the EEE sector

In light of advancements across various sectors, the global availability of raw materials might face increasing pressure due to rising demand and the potential for supply bottlenecks as geographically only a few nations have reserves for precious materials and metals. Our planet has a finite quantum of natural resources and the pace at which technology advancements are happening will lead to the depletion of these natural resources which will have environmental as well as supply risks for future generations to come.

The figure given shows the world map of the main global producers of the raw materials listed as critical for the EU in 2023, though we can still observe how resources are concentrated in a few locations.

FIGURE: GLOBAL PRODUCERS OF RAW MATERIALS




China
Aluminium 56%
Bismuth 70%
Fluorspar 56%
Magnesium 91%
Phosphate rock 44%
Titanium Metal 43%
HREEs 100%
Antimony 56%
Cobalt 60%
Gallium 94%
Manganese 58%
phosphorus 79%
Tungsten 86%
Arsenic 44%
Coking Coal 53%
Germanium 83%
Natural graphite 67%
Scandium 67%
Vanadium 62%
Baryte 44%
Copper 38%
Lithium 56%
Nickel 33%
Silicon metal 76%
LREEs 85%
Russia
Palladium 40%
Turkiye
Boron 48%
Feldspar 32%
Iran
Strontium 37%
DRC
Cobalt 63%
Tantalum 35%
South Africa
Iridium 93% | Palladium 36%
Platinum 71% | Rhodium 81%
Ruthenium 94% | Managanese 29%
Australia
Aluminium 28%
Lithium 53%

The concern over global resource security has become more pronounced, with governments worldwide prioritizing access to diverse precious materials and metals. These resources are integral to numerous industries and all stages of the supply chains, making economies heavily reliant on imports particularly vulnerable to supply disruptions.

The rapid pace of technological innovation and the emergence of economies such as India have further fuelled the demand for raw materials. India now stands as the third largest consumer of globally produced raw materials. It is estimated that India's material requirements will reach nearly 15 billion tonnes by 2030 and exceed 25 billion tonnes by 2050[2].

The demand for raw materials is increasing due to the growth in various sectors – one of them being the electronics sector. In India, the electronics market has experienced significant demand growth, with the market size expanding from US$ 145 billion in FY16 to US$ 215 billion in FY19. It is projected to reach US$ 540 billion by FY25, according to data provided by IBEF[3]. If we take a look at the growth of Indian appliances and consumer electronics industry[4], it was reported at US$ 9.84 billion in 2021, and is expected to reach US$ 21.18 billion by 2025. India's smartphone shipments witnessed YoY growth of 11% in 2021, with 169 million units exported and the market revenue crossed US$ 38 billion[5].

With this rise in demand for various raw materials, it's important to understand that traditional mining of natural resources imposes significant environmental burdens, as the mining of ores is among the most polluting industries. Compared to exploration, extraction, and refining activities involved in procuring virgin ores, using e-waste as a source of secondary raw material (also termed urban mining) presents several advantages. Not only does it minimize the need for capital investment, but it also helps mitigate environmental degradation, emissions, and human rights violations associated with conventional mining practices[6].

A compelling example of the benefits of urban mining is the extraction of gold and copper from circuit boards. On average, one metric ton of circuit boards can yield up to 1.5 kg of gold and 210 kg of copper. In contrast, conventional mining of gold from ore typically contains 5 grams per ton (g/t), while copper content averages around 5.25 kilograms per ton (kg/t) (Shahabuddin et al., 2022). These figures demonstrate that the concentrations of gold and copper recovered through urban mining are significantly higher, with values approximately 300 and 40 times greater than those found in ores, respectively.

Given the increasing demand for precious materials and metals, enhancing the recovery of these materials from e-waste has become a strategic priority to mitigate supply risks. The substantial volume of e-waste generated poses environmental threats, but it also presents a business opportunity for extracting valuable resources. Advanced e-waste recycling techniques offer a means to recover precious materials present in e-waste.

However, efficient e-waste recycling is not without its challenges, requiring the development of sophisticated informal networks, processes, and technologies. Efforts to optimize e-waste recycling and maximize the recovery of valuable materials play a vital role in achieving resource efficiency, reducing environmental impacts, and promoting a circular economy in the EEE sector.

2 https://www.meity.gov.in/writereaddata/files/Circular_Economy_EEE-MeitY-May2021-ver7.pdf
3 https://www.ibef.org/industry/electronics-system-design-manufacturing-esdm
4 Consumer durables entails (fans, kitchen and cooking appliances, lighting devices, as well as white goods such as washing machines, televisions, refrigerators, and air conditioners.)
5 https://www.ibef.org/industry/consumer-durables-presentation
6 https://wedocs.unep.org/bitstream/handle/20.500.11822/30809/FutEWSc.pdf?sequence=1&isAllowed=y

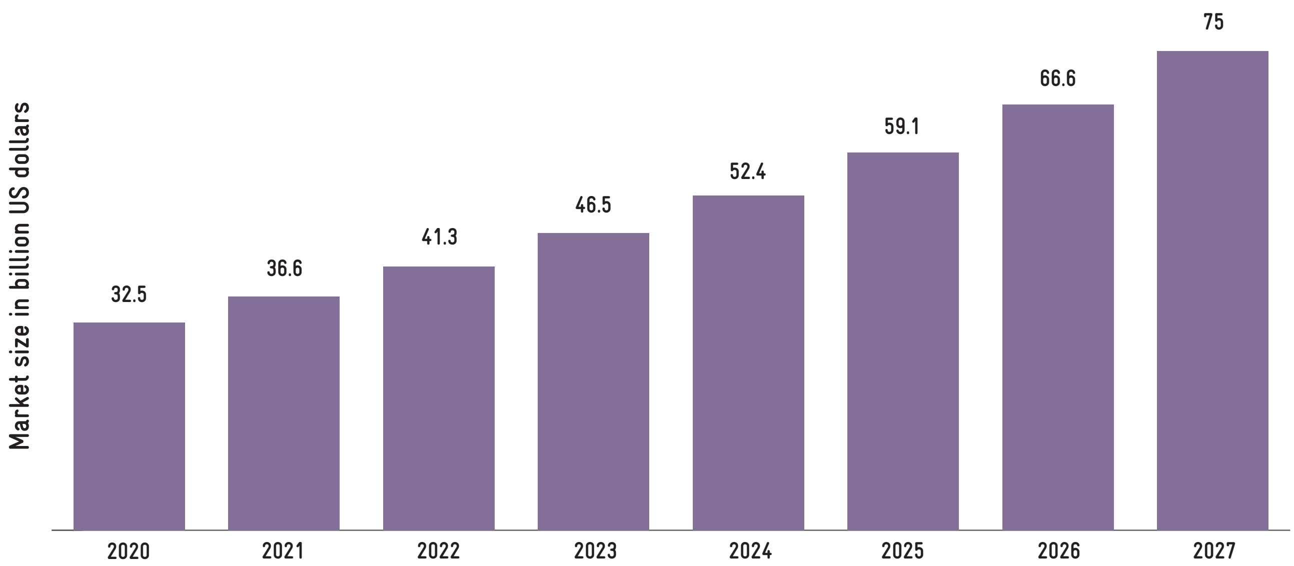
2.2 Current recycling scenario

2.2.1 Global scenario

2.2.1.1 Recycling market size

The global market for electronics recycling demonstrates the significant economic potential in this sector. In 2022, the electronic recycling market was estimated at US$39.8 billion, and it is projected to reach US$110.6 billion by 2030, exhibiting a compound annual growth rate (CAGR) of 13.6%. The figure given below maps out the size of the global electronic recycling market till the year 2027. We can observe that this substantial growth underscores the vast economic, environmental, and livelihood benefits that can be derived from effective e-waste recycling practices.

Size of global electronics recycling market for 2020 to 2027



Source- Statista[7]

However, if we take a look at the quantum of e-waste recycled, based on the findings of the Global E-waste Monitor 2020 a mere 17% of the e-waste generated in 2019 was reported as collected and recycled globally. This means that the fate of the remaining 44.3 million metric tons of global e-waste flows was uncertain. The estimated value of this undocumented e-waste was a staggering $47.6 billion USD[8]. In contrast, the documented e-waste that was properly managed resulted in the recovery of raw materials worth $10 billion USD. It's also important to note that these values and data have been reported using specific methodologies that don't take into consideration the involvement of informal sector or illegal waste trade, these numbers in reality might be different from what is documented and reported.

According to several studies conducted to gauge the involvement of the informal sector in e-waste, bulk of e-waste, especially in developing countries like India, Africa gets recycled by the informal sector and these studies have reported that processes are not very efficient in terms of recovery of materials[9]. The loss of recovery of precious material and metals from WEEE, results in a loss of finance and resources incurred due to the use of inappropriate technology in e-waste waste management, this not only undermines economic growth but also poses a serious threat to the environment. These figures highlight the urgent need for effective and sustainable e-waste management practices globally.

7 https://www.statista.com/statistics/1309081/global-electronics-recycling-market-size/#:~:text=Indeed%2C%20in%202022%2C%20the%20size,growth%20rate%20of%2012.7%20percent.

8 https://ewastemonitor.info/wp-content/uploads/2020/11/GEM_2020_def_july1_low.pdf

9 https://i.unu.edu/media/ias.unu.edu-en/news/7916/Global-E-waste-Monitor-2014-small.pdf

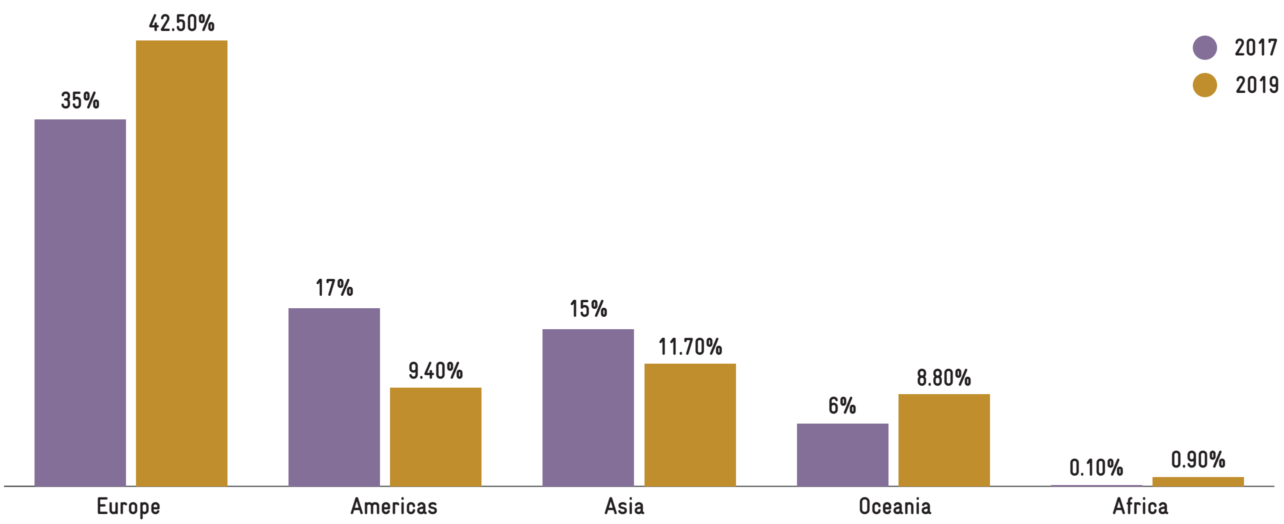
2.2.1.2 Recycling rates

Recognizing the inherent value of e-waste, it becomes crucial to prioritize efficient recycling practices from both economic and environmental standpoints. Examining the global recycling rates, it is evident that there has been limited progress in formal e-waste collection and treatment. In 2016, only 20% which accounts for (8.9 million metric tons)[10] of e-waste was formally documented and properly recycled. This figure slightly declined to 17% which accounts for (9.3 million metric tons) in 2019. Though the quantum of e-waste recycled increased roughly by 0.4 million metric tonnes for the year 2019, in relation to the generation of E-waste there was no significant increase in the overall recycling percentage. This indicates that the formal collection and treatment of e-waste have not kept pace with the overall growth of (EEEs) worldwide, as well as the increasing generation of e-waste.

A closer examination of e-waste collection and recycling rates across continents reveals varying levels of progress. In 2019, Europe emerged as the continent with the highest collection and recycling rate, reaching 42.5%. Asia followed closely behind with a rate of 11.7%. The Americas and Oceania exhibited similar rates at 9.4% and 8.8%, respectively, while Africa reported the lowest rate at 0.9%. Comparatively, the collection and recycling rates in 2017 were as follows: Europe – 35%, Americas- 17%, Asia – 15%, Oceania – 6%, and Africa – 0.1%[11], a summarised figure is given below depicting the change in global continent wise E-waste collection. Upon analysing the provided data, it becomes apparent that there have been minimal improvements in collection and recycling rates across continents in relation to the e-waste generated in these places. The Americas and Asia experienced a decline in their collection and recycling rates.

These statistics highlight the urgent need for concerted efforts to improve formal recycling rates and ensure that the recycling infrastructure keeps up with the growing volume of e-waste.

Continent-wise formal collection & recycling rates in 2016 and 2019



2.2.2 India scenario

The import of a few categories of electronic goods into India experienced a surge following the liberalization of the economy in 1991, which brought about changes in market dynamics, politics, and the economy. These factors, coupled with the rise of the middle class, led to an increase in consumerism and an improved standard of living. However, this growth also marked the beginning of the e-waste problem in the country. As per data provided by MOEF&CC, the quantum of e-waste generated in 2021-22 was estimated at 1.6 million tonnes or (16,01,155.36 metric tonnes)12.

Understanding the evolution of e-waste management in India requires examining how e-waste has been defined and the legal instruments drawn up to address and regulate this issue. These definitions and regulatory frameworks play a crucial role in

10 https://www.itu.int/en/ITU-D/Climate-Change/Documents/GEM%202017/Global-E-waste%20Monitor%202017%20.pdf
11 Calculation – Quantum of waste generated / quantum of waste collected and recycled X 100
12 https://pqars.nic.in/annex/259/AS5.pdf

shaping the strategies and approaches adopted for effective e-waste management. By exploring the evolution of e-waste in India within this context, we can gain valuable insights into the country's journey in tackling this complex waste stream.

2.2.2.1 Legal frameworks

The journey of e-waste management in India saw its first legal initiative a decade ago, marking a significant milestone in addressing this growing waste stream. Prior to its formal recognition, e-waste remained an overlooked waste category. Initially, e-waste was categorized as hazardous waste and fell under the purview of the Hazardous Wastes (Management and Handling) (HWM) Rules 2003. In 2008, the Central Pollution Control Board (CPCB) issued guidelines for the environmentally responsible management of e-waste. The subsequent development occurred in 2011 with the notification of the E-Waste (Management and Handling) Rules, which underwent revisions in 2016, 2018, and most recently in 2022.

The implementation of the E-Waste Rules brought about a significant change in the responsibilities of manufacturers through the concept of Extended Producer Responsibility (EPR). This shift made it mandatory for producers/manufacturers to take on the responsibility of ensuring the proper collection, recycling, and safe disposal of their electronic products at the end of their life cycle.

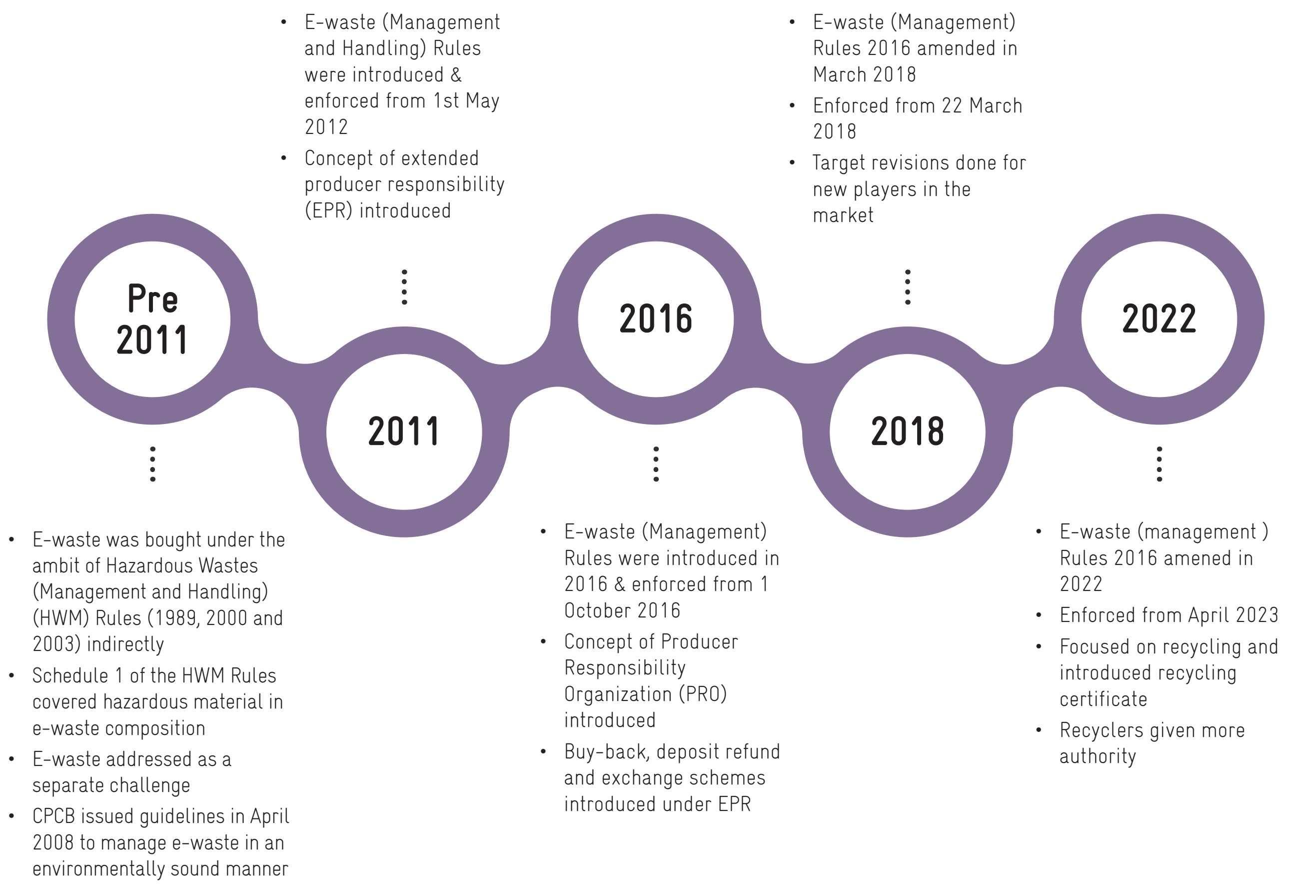


Figure- Timeline of Rules in India to address E-waste

2.2.2.2 E-waste Management Infrastructure

This policy change had an effect on the e-waste management landscape in India. It necessitated the development of a formal recycling infrastructure, as authorized recycling facilities became a requirement to meet the rules. As a result, authorized recyclers and collection centres emerged, equipped with the necessary technology and processes to handle e-waste in an environmentally responsible manner. It is interesting to note the growth in registered Dismantlers/ Recyclers, from a total of 100 Dismantlers/ Recyclers in 2012 with a total capacity of 2,92,457 MT/A; which has now grown up to 567 Dismantlers/ Recycler with a total capacity of 17,31,998.27 Metric Tons per Annum to handle e-waste as of June 2023 and the Producers registered are 2330.

From the data available it can be assumed that we are currently processing far below our capacity in year 2021 we have been able to collect and process a meagre 5,27.131.57 metric tonnes of e-waste. On further discussion with stakeholders, it emerged that there is serious shortfall in collection of waste in formal channels some of which could be because of waste flows in the informal sector. This is a serious challenge and undermines investment in recycling sector and a barrier towards the promotion of circular economy.

The year-on-year recycling capacity in the E-waste sector is placed in the table below.

Table- Recycling infrastructure dynamics in India.

Year	Capacity (metric tonnes per annum)	Recycled (Metric tonne)
2012-13	2,92,457 MT/A	No data
2013-14	2,93,057 MT/A	No data
2015-16	4,55,058.7 MT/A	No data
2016-17	No data	No data
2017-18	No data	69,413.619 MT
2018-19	5,10,950 MT/A	1,64,663.00 MT
2019-20	7,82,080.62 MT/A	2,22,436.34 MT
2020-21	10,68,542.72 MT/A	No Data

Source- Annual report by CPCB13 (for the selected years)

E-waste can be seen as a problem but can benefit the Indian economy greatly if appropriate measures are taken. With India's vision of Make in India, Digital India, and becoming a self-reliant economy, will require a steady supply of raw materials and must anticipate future demands. In this context, India can be one of the nations that can excel in the recycling industry, as the generation of E-waste in India is huge and the scope of recovering precious materials and metals efficiently.

13 https://cpcb.nic.in/annual-report.php

3. OBJECTIVE AND METHODOLOGY

Aim

The primary goal of this research is to identify, analyse, and compare the global best available technologies to promote recycling and recovery of SRM at the recycling and recovery stage. The paper will also seek to assess recycling and refurbishment technologies at a local and global level.

Objectives

1. To identify and assess global best available technologies to handle and treat e-waste
2. To evaluate applicability of various technologies in the Indian context

Methods

3.1 Secondary research on BAT

- To start with, a comprehensive review of published (Reports, Government documents, Research papers, archival documents obtained from the websites of companies, industry associations, developmental organizations, policy think tanks, NGOs, and governmental bodies) has been attempted in selected database to assess the best available technology to recycle and recover metals from e-waste. The list of important papers, reports, and other relevant documents have been annexed.
- The study also explored websites, technologies used, and the type of metals recovered by Indian recyclers to understand the e-waste recycling capacities and capabilities in India.

3.2 Stakeholder consultation

The identification of key stakeholders in this study was based on a comprehensive analysis of existing knowledge on the issue, supplemented by thorough secondary research. To gather the necessary data, semi-structured interview schedules and/or individual meetings with the identified stakeholders were employed. These methods have been chosen to ensure a comprehensive and insightful collection of data from individuals and organizations who hold valuable insights and perspectives on the topic under investigation.

Europe emerged as the continent with the highest collection and recycling rate, reaching

42.5%.

Asia followed closely behind with a rate of

11.7%.

The aim of the interaction was to understand several aspects of EOL e-waste management at recycling and recover stage such as: -

1. Emerging technology development in India
2. Adoption of international technologies
3. Bringing circularity in the WEEE sector
4. Key barriers in recycling, focusing on technology

The stakeholders identified are as follows.

Stakeholder consulted

1. Anand Kumar- CPCB Divisional Head, Waste Management -III Division
2. Greenscape Eco Management Private Limited- Mr Jeevesh Kumar
3. Exigo Recycling Private Limited - Mr A L N Rao
4. E- Parisaraa Private Limited - Dr P. Parthasarathy
5. Eco Recycling Ltd (Ecoreco)- Mr B.K. Soni
6. Umicore India Pvt. Ltd-Mr Vaibhav D. Adhyaru
7. Umicore India Pvt. Ltd- Mr Vinayak Bajoria
8. Cerebra Integrated Technologies Ltd. - Ms Preeti
9. Reminepvt ltd- Mr Vivek Goel
10. ResposeIndia – DB Prabhu
11. Anwesha Borthakur- Post-doctorate Researcher

Limitations

- Limited secondary literature on BAT for e-waste recycling globally and for India. The available literature explains in detail technology in general to treat e-waste, extensive research assesses only one particular type of e-waste category (i.e. PCB). Limited research was done to assess the best of 2 world technologies or comparative technology research.
- Stakeholders are reluctant to share information regarding technology used at their recycling facilities. Each stakeholder has their method of operation which might reveal certain processes and pose a disadvantage to the stakeholder.
- Limited information on websites for Indian recyclers regarding the type and purity of metals recovered, and the type of method used during pre-treatment and end processing.
- Data provided by various agencies can't be verified, thus inferences based on the data as reported.

4. TECHNOLOGIES TO HANDLE E-WASTE

4.1 E-waste recycling methods

Before we dive into the best available technology (BAT) present and in commercial use, it's important to understand that there are no permanent methods or technologies to recycle and recover metals from E-waste. Each method of the mentioned technologies or a combination can be used together in different phases of recovery and refining.

The following section briefly explains the methods/ techniques used in recycling and recovering precious materials from e-waste. There are several other ways in which authors, agencies, recyclers etc. have termed these methods/ techniques. For the purpose of this paper, these methods and techniques have been summarised and clubbed together to give an overview of the recycling chain.

The recycling chain for E-waste consists of three main subsequent steps:

- Collection
- Pre-processing or pre-treatment
- End-processing (including refining and disposal of hazardous elements).

The material recovery efficiency of the entire recycling chain depends on the efficiency of each step and how well the interfaces between these interdependent steps are managed.

4.1.1 Step 1 - Collection

This is usually a non-hazardous activity wherein e-waste of different categories are collected and stored in a safe manner to be transported to e-waste management agencies. There are sufficient guidelines associated with collection of e-waste.

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42.5%.

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11.7%.

4.1.2 Step 2- Pre-treatment

After collection of e-waste through various means, pre-treatment or pre-processing is usually the first step in treatment and processing of e-waste. Pre-treatment can be done through manual or mechanical or a mix of both (Electronic Waste, 2015) (Kaya, 2016).

A) Manual pre-treatment

This step usually consists of various steps to prepare the material for recycling. These steps are, sorting, separating, cleaning, and dismantling, of electronic devices.

- **Sorting/separating –** During collection, E-waste is sorted for a first time according to different product groups. This is crucial as identifying different products and channelling them to the appropriate treatment route, makes it efficient for downstream processing stages and makes it easy for workers to handle the incoming e-waste. The products are generally sorted as – Screens and monitors, Lamps, Large equipment, small equipment, including telecommunication and IT appliances.
- **Depollution -** E-waste must be cleaned before the appliances can be processed. for example, lamps, containing hazardous substances or presence of gasses in cooling & freezing equipment. Depollution becomes crucial for such appliances before further manual or mechanical processing takes place. Cooling gases and used oil from gadgets can be highly hazardous and need to be handled with utmost care and disposed of as per the current guidelines and protocols. All hazardous waste thus segregated in this process will also require to be handled with care and disposed of in TSDF.
- **Dismantling-** The depolluted e-waste is dismantled to remove various components from the equipment. The dismantling process could be manual or mechanized in nature, usually comprises the following steps:
  1. The appliance needs to be opened, and the case is separated from the rest of the appliance.
  2. Depollution of components
  3. The remaining components are dismantled, separated (based on the material type ie plastic, glass or other materials).

Pros and cons of manual pre-treatment

Pros

- **Sorting and Segregation:** Manual pre-treatment allows for precise sorting and segregation of different types of e-waste based on their composition, size, or recycling requirements. This facilitates precise product range and brings in ease in downstream processes.
- **Component Recovery:** Manual pre-treatment allows for the selective extraction and recovery of valuable components, such as circuit boards, memory chips, connectors, and other reusable parts. This helps maximize the recovery of valuable materials from e-waste. Generates additional revenue
- **Refurbishment:** This process also allows for identification and separation of serviceable /partially serviceable gadgets, which can be further upgraded and reused. Generates additional revenue
- **Quality Control:** Manual pre-treatment enables visual inspection and quality control of e-waste materials. Workers can identify any visible damage, defects, or contamination, ensuring that only suitable materials proceed to the next processing steps. It also ensures consistent quality of feed.
- **Depollution:** Identification and removal of hazardous substances, including heavy metals and toxic chemicals. Does not allow mixing of toxic and safer materials.
- **Livelihood:** Opportunity in job creation as well, can be situation specific.
- **Cost effective:** abundance of cheap labour will make this process cost effective. (Situation specific)

Cons

- **Limited risk:** Involves direct contact with e-waste, which may contain hazardous substances. This poses potential risks to workers if the right safety measures and protective equipment are not used.
- **Labour-Intensive:** it is process that requires skilled workers to handle and disassemble e-waste. This can be time-consuming and costly to the recyclers, particularly when dealing with large volumes of e-waste. (Situation / country specific)

Source- Compiled from different sources

B) Mechanical processes

Mechanical pre-treatment can be done as the first step and can also be done after incorporating few of the manual methods mentioned above such as basic sorting and separating different category of items. Mechanical processing which is normally done to obtain concentrates of recyclable materials in a dedicated fraction and also to further separate hazardous materials and various streams such as metals, glass, and plastics. Typical components of a mechanical processing are shredding or crushing, sieving and separation.

- **Shredding/Crushing -** crushing or comminution processes are generally intended to achieve a suitable liberation level. The main objective is size reduction and also exposure of valuable materials in e-waste. There are different types of shredders for different types of e-waste, for instance- hammermill, rotary cutter etc.
- **Sizing-** After passing through the comminution phase, the material generally has to be classified. Size classification is based on the separation of particles according to their different size. One of the simplest and most widely used forms for size separation is sieving. This is done with sieves that consist of perforated surfaces over which the particles are moved. The smaller particles pass through those perforations while the larger particles remain on the sieve. This process separates the material only by the size of its particles.
- **Sorting –** in this process the materials are sorted into fractions, i.e., divided into two or more products of different material composition. This is done by making use of the different physical or physical-chemical properties of the respective particles. different sorting methods such as sorting by magnetic field, by electrical field, by density can be used. The separation technologies are explained briefly along with the challenges which occurs while processing.

a) **Magnetic separation** where ferrous metals and nonferrous metals in E-waste can be separated through the use of magnetism (Goel, 2017).

b) **Density separation /Flotation** uses the different density of materials in solvent to achieve the purpose of separation (Ogunniyi and Vermaak, 2009).

c) **Gravity separation** based on the different weight of materials in E-waste powder, the various materials will be separated (Das et al., 2009; Yoo et al., 2009).

d) **Electrostatic separation** a variety of metals and nonmetals will be separated because of their conductive and non-conductive characters.

e) **Near-Infrared (NIR) Sorting:** Near-infrared (NIR) sorting utilizes infrared sensors to detect and identify materials based on their spectral characteristics. NIR sensors can analyse the reflectance and absorption of light by different materials, allowing for the identification and separation of various plastics, including different types and colours. NIR sorting is highly effective in separating mixed plastic fractions in e-waste.

f) **X-ray Sorting:** X-ray-based sorting technologies use X-ray radiation to analyse the internal structure and composition of materials. By measuring the attenuation of X-rays passing through objects, these technologies can identify and separate materials based on their elemental composition and density. X-ray sorting is useful for separating metals, as well as identifying and recovering valuable components like printed circuit boards (PCBs).

Pros and cons of mechanical pre-treatment

Pros

- **Material recovery:** Mechanical methods can produce feedstock of uniform size make downstream processes more efficient.
- **Efficiency:** Mechanical processes, such as shredding and sorting, can handle large volumes of e-waste quickly and efficiently, thereby increasing the overall processing capacity.
- **Economical:** Can be economical and this would be situation specific.

Cons

- **Mixing of material:** Mechanical processes may result in mixed fractions of materials, as bulk e-waste gets treated in one go. Further refining or separation processes may be required. Making it challenging to achieve high levels of purity.
- **Risk of damage:** Some delicate components of electronic devices may be prone to damage during the mechanical process, potentially reducing the overall value of the recovered materials.
- **Energy consumption:** Mechanical pre-treatment processes, particularly shredding and crushing, can consume significant amounts of energy, contributing to the overall environmental footprint of e-waste recycling
- **Cost:** The overall cost of installing and equipment is usually high.
- **Loss of resource:** Many serviceable components and systems are lost in mechanical processes.
- **Hazardous substance release:** Certain e-waste items contain hazardous substances, such as mercury or brominated flame retardants. Mechanical methods can release these substances into the environment if not handled properly, posing risks to human health and the ecosystem.

Source- Compiled from different sources

4.1.2 Step 3- End processing

The next step followed by manual and mechanical pre-treatment is end processing to recover and process metals, synthetics and glass.

A) Pyro-metallurgy

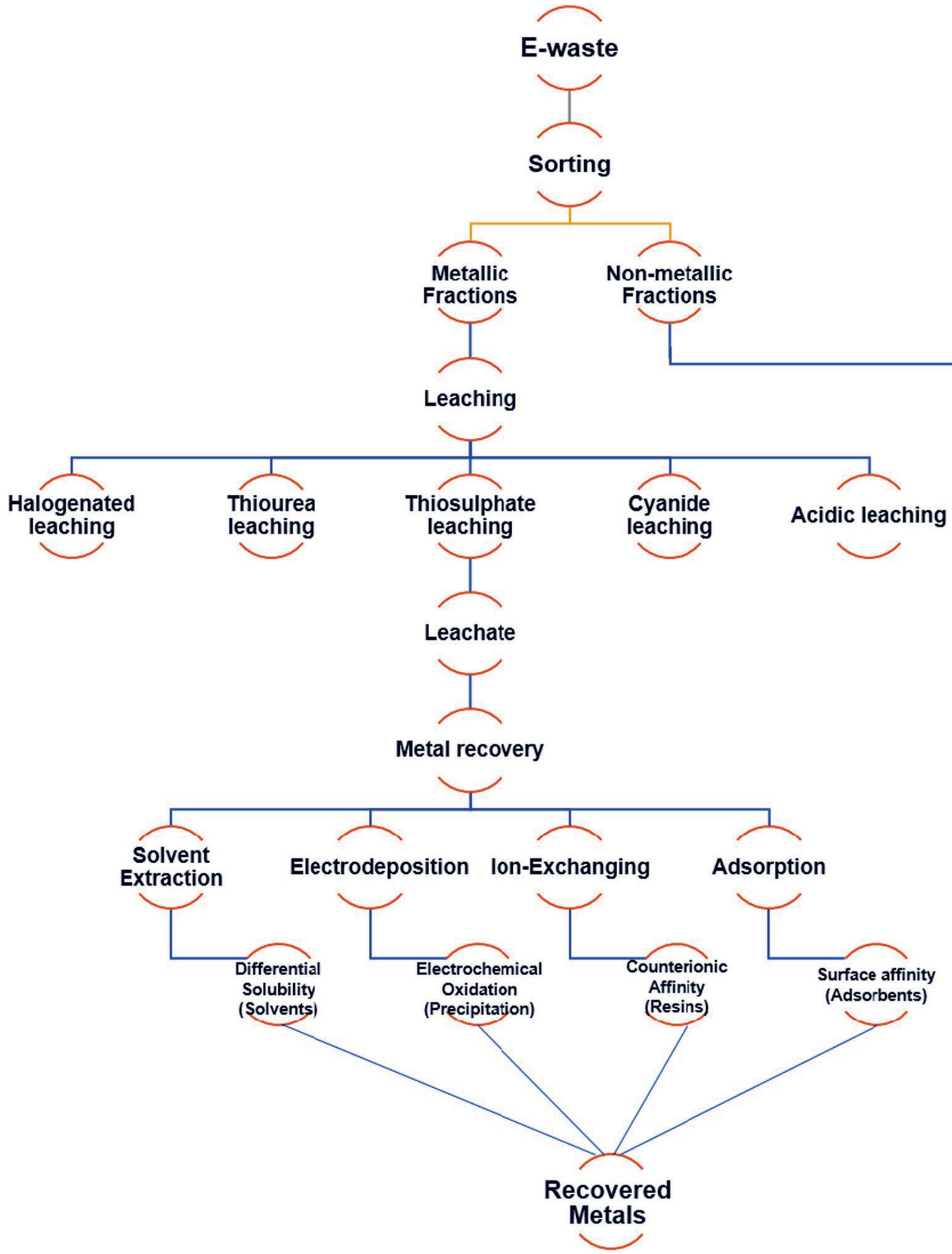
The pyrometallurgical process involves melting the materials/concentrate at a high-temperature furnace (usually at 600 to 1200 °C) to obtain a mixture of desired metals. Most common pyro routes include roasting, smelting, pyrolysis, chlorination, incineration and out of these routes smelting is considered as the most favoured step in achieving final metallic products. This route is mostly used to recover copper, gold, silver and palladium while Iron and aluminium usually get oxidized and report to the slag (Namias, 2013). The conventional pyrometallurgical processing mechanism consists essentially of concentrating metals in a metallic phase and rejecting most other materials in a slag and/or gas phase. Pyrometallurgy is one of the known and go to method of recycling and recovery of e-waste and other complex feed; for instance, Aurubis in Germany, Noranda in Canada, Boliden Rönnskar in Sweden, the Umicore in Belgium are some of the companies using pyrometallurgy as one of the processes.

B) **Hydro-metallurgy**

Hydrometallurgy is a route in which strong acidic or caustic watery solutions are used in order to selectively dissolve and precipitate metals. The aqueous solution includes chemical reagents, such as organic acids and inorganic acids for dissolution of metals present in E-waste i.e., leaching of metals in the solvent and then purification process. Leaching can be done the use of Thiourea, acid, thiosulfate, cyanides, and halides etc. The leachate is purified, the purification process includes several techniques, such as ion exchange, solvent extraction, precipitation, cementation, absorption, and electro winning (Birloaga and Vegliò, 2016). While for the non-metallic parts is not processed in these particular processes and hence channelised to concerned agencies handling non-metallic parts.

To give a brief overview of the processes which are involved in hydrometallurgical routes is given below.

FIGURE - A TYPICAL HYDROMETALLURGICAL PROCESS.



There is another way which are present and is used at one of the stages of recovery i.e. Electrometallurgy. While another route namely bio metallurgy is in lab scale or research level.

Most electrometallurgical processes associated with the recycling of electronic waste are steps of the electrowinning process that ultimately seeks to recover a pure metal. Electrochemical processes are usually performed in aqueous electrolytes or molten salts and can be used to recover metals from various types of waste. Metal concentrates obtained by hydrometallurgical processes (e.g., selective dissolution, ion exchange or solvent extraction) can be electrodeposited from aqueous solutions on the cathode.

Bio metallurgy- In this method, microorganisms are used to extract metals from different sources. The microorganisms oxidize or use the inorganic and organic substrate to transform the metal present, in its soluble form from where it can be extracted easily.

Advantages and disadvantages of technology (pyro and hydro metallurgy) discussed

Process	Advantages	Disadvantages	References
Hydrometallurgy: Leaching with acids (HNO_3, H_2SO_4, aqua regia etc.)	• Exact • Predictable and controllable technique; • Standard mineral processing technologies; • High levels of material recovery.	• Slow and time consuming; • Material loss during mechanical processing; • Relatively expensive, • Some leachants dangerous, e.g., cyanides; • Generation of secondary waste, spent acids and solvents; • local area contamination.	Khaliq et al. (2014); Kogan (2006); Sadegh et al. (2007); Cui and Zhang (2008).
Pyrometallurgy: Lead and copper smelting routes, incineration, combustion.	• Economic, • Eco-efficient and high recovery of major, minor and precious metals; • Commercial scale recycling of e-waste and PCBs.	• Difficult to recover plastics, iron, aluminium; • Significant infrastructure requirements; • High capital costs; • Complex operations, • High energy consumption; • Hazardous emissions, dioxins, furans generated from plastics at lower temperatures.	Cui and Zhang (2008); Khaliq et al. (2014); Cayumil et al. (2014); Saini et al., (2017); Ellamparuthy et al., (2017); Hagelüken (2006)

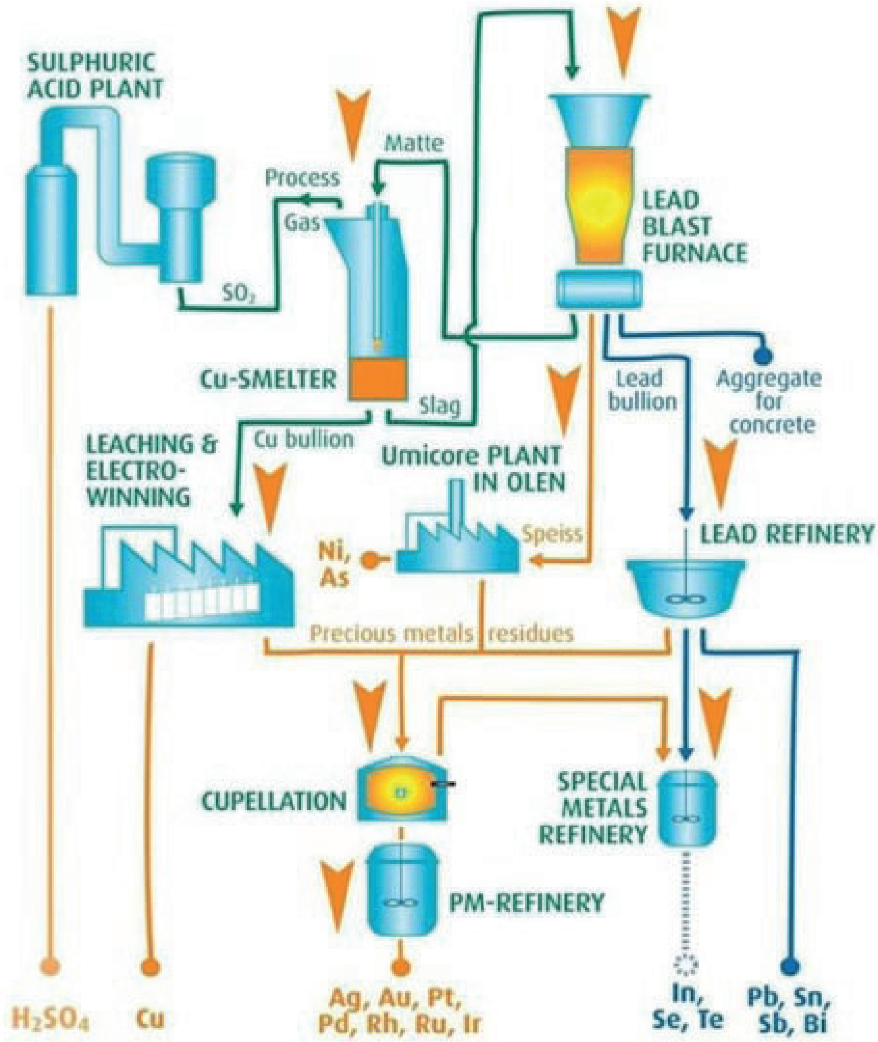
4.2 Globally used technology

Although there is numerous research on different techniques to recycle e-waste and their efficiencies, not all of them have come to practice due to various reasons. The viable procedures are often based on pyro, or combination of hydro and pyro techniques. Some of the processes are originally for mineral processing but adjusted to accept complex feed such as e-waste, scrap metals etc. The following section will briefly explain technology being presently used globally by recyclers/refiners to handle e-waste.

It is important to note that, these companies don't employ only one technology and in fact use a combination of technologies and methods. For the purpose of the study only those organisations are considered who have mentioned in their website key details of their technology and relevant information.

1. Umicore[14] has a plant which is based out of Hoboken, Belgium and is dedicated towards handling various type of feed including e-waste. The recycling operations at the Hoboken are streamlined along two processes: The Precious Metals Operations (PMO) and The Base Metals Operations (BMO). **Though one of the major steps before end processing is Umicore's pre-processing stage.**

IMAGE- DETAILED DIAGRAM FOR PYROMETALLURGICAL PROCESSING (UMICORE)



Source: https://www.umicore.com/storage/migrate/2012SeptHobokenSiteVisitEN.pdf

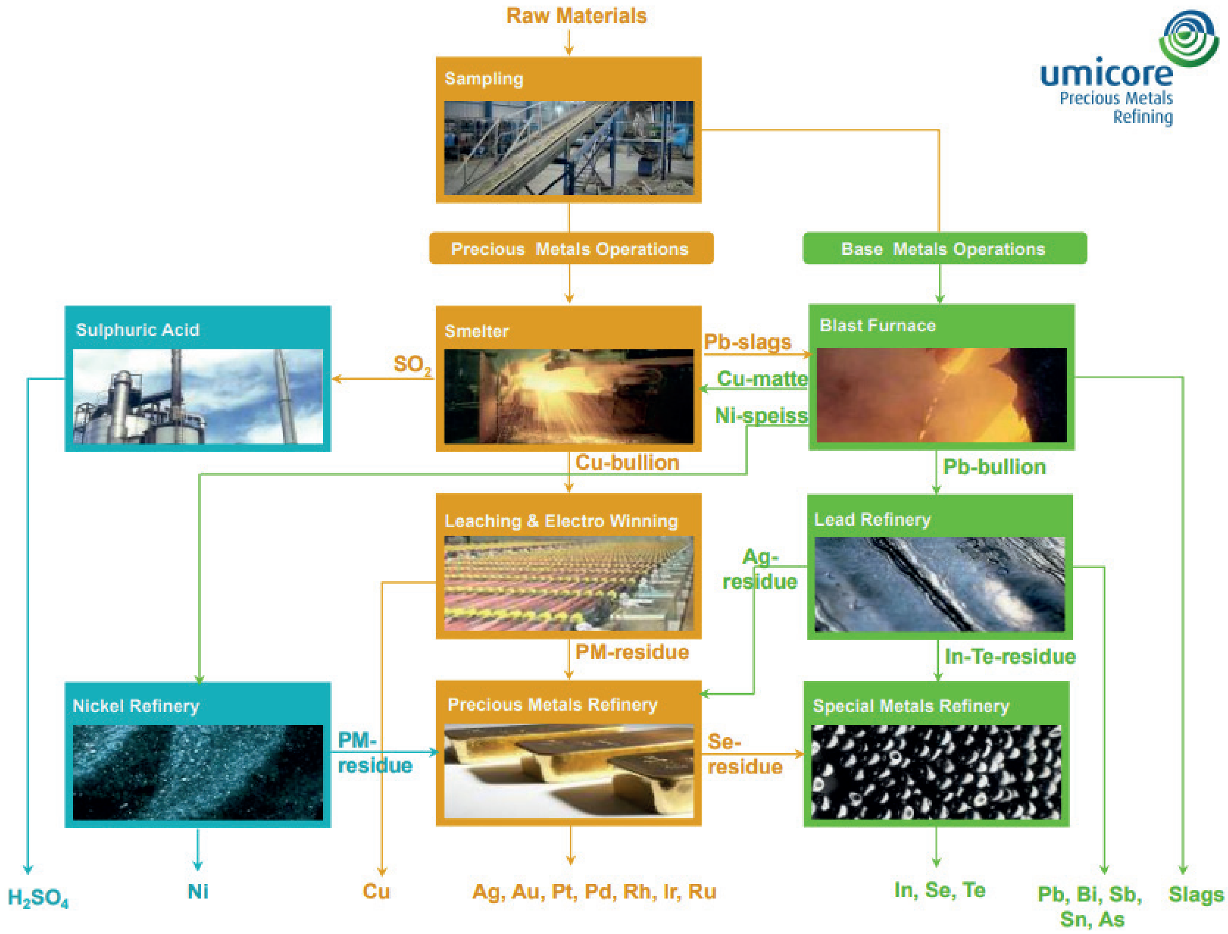
Various industrial wastes and by-products from other non-ferrous industries (e.g., drosses, matters, speiss, anode slimes), sweeps of precious metals and bullions, spent industrial catalysts, as well as consumer recyclables such as car exhaust catalysts or PCBs are accepted for the integrated metals smelter and refinery process. The mix of complex feed materials mentioned above makes sampling and assaying a key factor for sustainable precious metals recycling at Umicore. An accurate determination of the exact composition and the precious metal content of the feed is crucial. For instance, in case of circuit boards, 100% of the boards are shredded down to a size of 4 x 4 cm, the primary sample from this first step is then re-shredded to 7 x 7 mm, after which a secondary sample is taken and further prepared to obtain a lab-sample for analysis.

The main processing steps of the Precious Metals Operations (PMO) are smelting, copper-leaching & electro winning. The PMO focuses on the recovery of PMs from copper matte by smelting, leaching and electrowinning. The feed from e-waste and other industries is smelted in an IsaSmelt furnace which is a **submerged lance combustion technology**. This involves injecting oxygen-enriched air and fuel in a molten bath and adding coke as a reducing agent for the metals. The plastic and organic constituents in the feed partially replace coke as a reducing agent and a source of energy during smelting. The smelter then separates precious metals in copper bullion and the rest in the lead slag, which is further treated at the BMO. Copper is leached out from the copper bullion and recovered by the electrowinning process. The residue of the copper electrowinning process is further treated at a PMs refinery for the recovery of PMs.

The main processing steps of the Base Metals Operations (BMO) that treats by-products from PMO, are the lead blast furnace, the lead refinery and the special metals plant. The oxidized lead slag and third-party residues high in lead are treated in the lead blast furnace that produces impure lead bullion, nickel speiss, copper matte and depleted slag. The Harris process (lead refinery) is used to refine the impure lead bullion that contains fewer PMs. Pure lead, sodium antimonite and special metals (indium, selenium and tellurium) are produced during the Harris process. Bismuth and tin are sold to dedicated companies to produce pure metals. The flowchart for Umicore's refining operation is given below.

14 https://pmr.umicore.com/en/

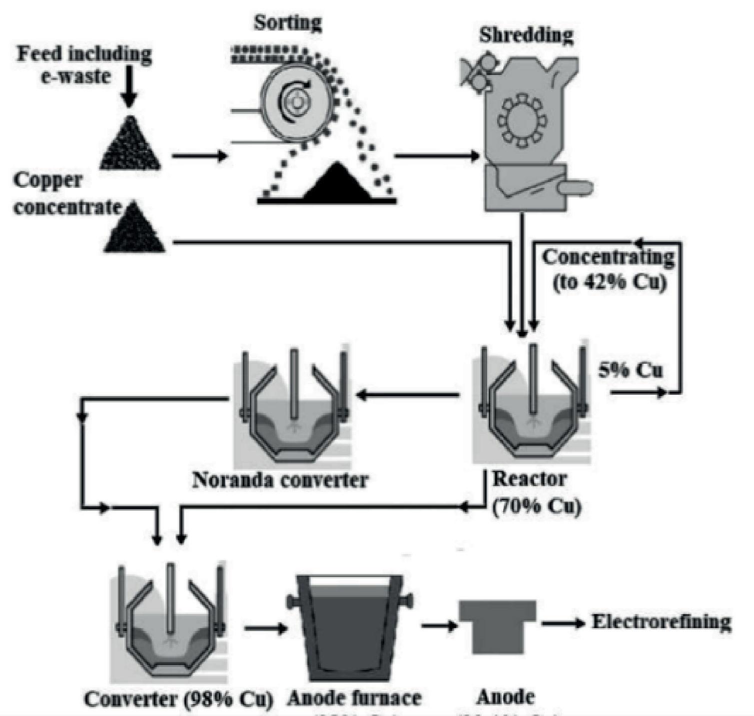
IMAGE- SIMPLIFIED PROCESSING OF E-WASTE USING PYROMETALLURGY



Source- https://www.umicore.com/storage/migrate/2012SeptHobokenSiteVisitEN.pdf

2.Glencore15 Copper's Horne Smelter (Noranda) is another commercial pyrometallurgical process for the recovery of metals from e-waste. The feed material for this process is composed of e-waste and mined copper concentrates. A blend of e-waste and copper concentrate is fed into the molten bath at 1250 °C and the process temperature is maintained by injecting supercharged oxygen. The energy cost is partially reduced by combusting the plastics and other combustible materials from e-waste. During the oxidation process, impurities including iron, lead and zinc are converted into oxides and segregated into a silica-based slag. The slag is cooled and processed for the recovery of metals before disposal. PMs are segregated in

IMAGE- DETAILED DIAGRAM FOR PYROMETALLURGICAL PROCESSING (GLENCORE)



Source- (Mihai, 2016)

15 https://www.glencore.ca/en/what-we-do/metals-and-minerals/copper

liquid copper that is processed into a copper converter for higher purity. The blister copper is refined in the anode furnace and casted into anodes with 99.1% purity. The remaining residue (0.9%) contains PMs such as gold, silver, platinum and palladium, and some other recoverable metals such as nickel, selenium and tellurium. Finally, PMs are recovered by electrorefining of anodes (Mihai, 2016).

IMAGE- DETAILED DIAGRAM FOR E-WASTE PROCESSING (BOLIDEN)

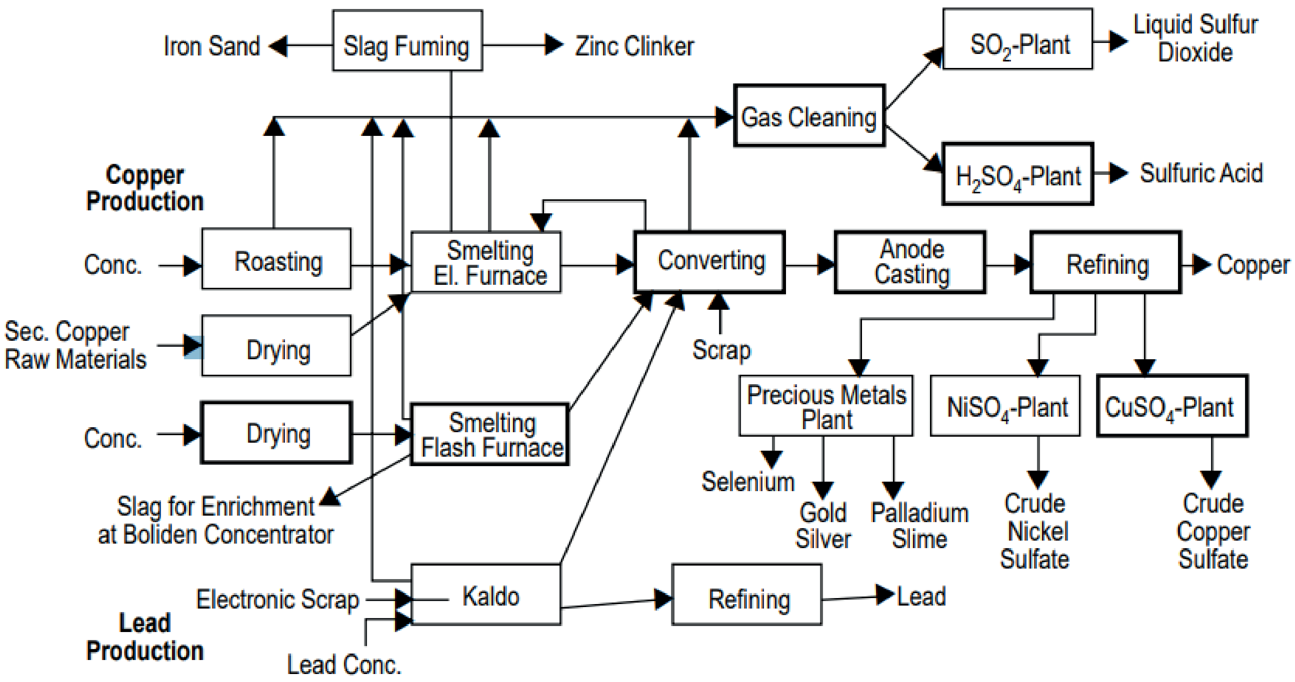


Image source - Boliden website

3. Boliden's16 smelters in Ronnskar, Sweden is another example of pyrometallurgy operation to handle e-waste and other scrap materials as well. The feed (e-waste) with low copper content is mixed with lead oxide concentrate and coke, then it is treated in a tilted furnace called Kaldo. The Kaldo furnace is essentially a slightly leaning cylinder which rotates during the smelting process. A mixture of air and fuel is also sparged over top of the melt to reduce the toxic fumes. The produced copper from this step and copper-rich e-waste are directed to a convertor. In almost all smelters, the volatile metals such as (Zn, Pb, Sn) are generated, which can be trapped and recycled; in the Ronnskar procedure, this step is easier as the combustion is complete and no organic fume is associated with the condensed metals. (Kaya, 2019; Ebin and Isik, 2016). The flowchart for Boliden's refining operation is given below.

4. Arubis17 a producer and distributor of non-ferrous metals, based in Germany is another operation which uses pyrometallurgy inone of its plants in Lünen to recover various precious materials. The feed at the plant consists of copper scrap, electronic scrap and residues. The Kayser Recycling System is well suited for utilizing recycling materials with low copper andprecious metal contents and very complex materials such as electric and electronic scrap.

At Lunen before the end processing, the feed is prepared and if necessary, processing begins with sampling, followed by a material preparation step. Depending on consistency and composition, the raw materials are then crushed, treated in a material preparation plant or directly conditioned into input mixtures. Aluminium and plastics are separated from the materials in some cases and sold to other recycling companies.

The next step is Pyrometallurgical preparation which begins in the Kayser Recycling System (KRS). The central operation is a submerged lance furnace. A special feature is the use of a submerged combustion lance, which is immersed into

16 https://www.boliden.com/4a6fb9/globalassets/operations/smelters/ronnskar/leach-plant-2021/facts-sheet/fact-sheet-leaching-plant.pdf
17 https://www.aurubis.com/en/products/recycling/technology

the furnace from above and supplies the process with heating oil, oxygen and air. The reduction process is very fast in the submerged lance furnace. Charging times are short. The iron silicate sand extracted in that step of the process has very low residual copper contents. Copper, nickel, tin, lead and the precious metals contained in the raw materials are enriched in an alloy with a copper content of about 80 %. In a top blown rotary converter (TBRC) the copper content is further enriched to 95 % and tin and lead are separated into a slag. The tin-lead slag is subsequently processed into a tin-lead alloy in the directly connected tin-lead furnace. During the KRS process, zinc is enriched in the KRS oxide, a flue dust.

The use of hydrometallurgy is also a known method for recovery of precious materials, though only a few companies are using it commercially and mostly are dealing with battery waste.

1. **Li circle** is a lithium-ion battery recycler in North America which uses a combination of safe mechanical size reduction and hydrometallurgical resource recovery specifically designed for lithium-ion battery recycling18.
2. **Lithion Recycling is a Canada-**based Company that responsibly manages of lithium-ion batteries. Their operations are based around pre-treatment of batteries through shredding and then the use of hydrometallurgy to recover battery-grade lithium, cobalt, and nickel as well as graphite and manganese19.
3. **Duesenfeld-** The company is based out of Germany which handles battery waste and combines mechanical, thermodynamic and hydrometallurgical processes in a patented process. The process achieves the highest material recovery rates with low energy consumption.

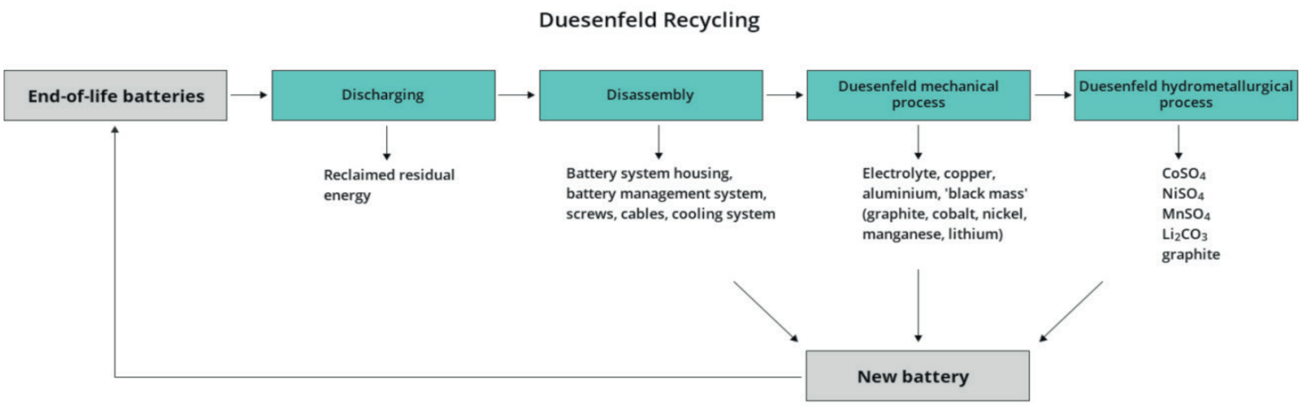


Image source- https://www.duesenfeld.com/recycling_en.html

4. **Fortum20-** Uses a combination of mechanical and hydrometallurgical technologies to recycle the battery materials. Our industrial scale, low-CO2 processes allow to recover lithium, cobalt, manganese and nickel from the battery for reuse in the production of new batteries. The general process followed by them are mechanical processing where lithium-ion batteries are first disassembled and treated during a mechanical process at Fortum's plant in Ikaalinen, Finland. The mechanical processing enables to recover plastics, aluminium, copper, and black mass. The battery's black mass, containing critical metals, is collected and then taken for hydrometallurgical processing at Fortum's plant in Harjavalta, Finland. Other recovered materials are recycled in separate processes.
5. **American battery co21-** Their recycling process utilizes an automated deconstruction process combined with a targeted hydrometallurgical, non-smelting process that deconstructs battery packs to modules, modules to cells, cells to subcell components, and then sorting and separating those subcell components.

18 https://li-cycle.com/technology/
19 https://www.lithiontechnologies.com/lithium-ion-battery-recycling-process/
20 https://www.fortum.com/services/battery-recycling/lithium-ion-battery-recycling-technology
21 https://americanbatterytechnology.com/solutions/lithium-ion-battery-recycling/

4.2 Key takeaways

The analysis of Best Available Technologies (BAT) reveals that companies employ a combination of pyrometallurgical and hydrometallurgical routes in their e-waste treatment processes. Efficient recovery of different materials is possible when all the processes are properly aligned, although the specific focus on certain materials varies among companies based on their priorities. Some technologies primarily target gold, silver, and copper, while others concentrate on the recovery of lithium-ion batteries (LIBs) using specialized methods.

Other factors, such as the type, quality of the feed materials, and how e-waste is being pre-treated, also influence the effectiveness of the chosen pyro or hydro metallurgical approach. Literature suggests that the use of pyrometallurgy or hydrometallurgy proves efficient under specific circumstances. For instance, hydro metallurgy has shown success in recovering rare earth metals from depolluted printed circuit boards (PCBs), whereas the presence of mixed materials can disrupt the recovery process. The summarised key points are as below: -

1. **Technology-** The analysis of the BAT reflected that, pyrometallurgy is one of the preferred technologies to recover precious and base metals while battery recyclers prefer hydrometallurgical routes. It was also observed that, smelters were widely used and followed by various processes of chemical leaching. The purity of the metals is similar to a degree, 95-99% for various base and precious metals as claimed by several recyclers.
2. **Pre-treatment-** The review of BAT found that the most crucial step for all recyclers/ refiners to efficiently recover materials and purity of the metals depended highly on the pre-treatment processes. A lot of effort and importance is given to the pre-treatment stage of e-waste management at these facilities. The use of manual and mechanical process and majorly the use of mechanical separation technology was observed. Few of these separation technologies were:
   - Magnetic separation
   - Gravity separation
   - Air separation (for plastics)
   - Manual liberation only at initial level
3. **Diversity in feed-**The review of various companies' processes found that the diversity in feed is an important factor. There are few recycler/ refiners who accept various kinds of materials while a few handles only WEEE. The table below briefly explains the diversity of feed purchased or collected by different metal refiners.

Company	Feed / Input (Purchased and/or collected)
Umicore	PCB, Cell phones and other small IT devices without batteries, CPU, IC, connectors, Laptops without batteries & screen, Shredded fractions with PCBs. Sweeps of precious metals and bullions, spent industrial catalysts
Glencore	Circuit boards, electronic components (e.g., connectors, pins, integrated circuits), mobile phones, insulated copper wire, lithium-ion batteries. Metal-containing scrap materials, including brass, turnings and residues such as dross, sludge, hydroxide, dust, incinerator slag, and various copper bearing materials from end-of-life processing of automobiles.
Aurubis	Copper and copper alloy scrap, electronic scrap and industrial residues.
Boliden	Fixed Equipment, Mobile Equipment, Bulk Commodities, Tools and Consumables, Services, Logistics, Electrical, Indirect Materials and IT.
Cerebra	End-of-life and off-lease e-waste products
Sims	Computer and peripherals, data centre equipment, storage media, defence and aerospace equipment, office and telecom equipment, IoT (GPS devices, trackers, drones, security system), electronic manufacturing scrap

4. **By- product treatment-** The by-product released during various processes also contain highly value materials and with proper treatment these metals can be recovered. The review found that only a handful had any information regarding the by-products coming from their plants. For instance, the table given below briefly explains a few models.

Company	By-product treatment
Umicore	They store and process by-products coming from various processes. Industrial by-products include: dross, PM-containing slag, matte, flue dust, hydrometallurgical residue, filter cake, tank house slimes and copper cement.
Glencore	Stored in purpose-built tailings storage facilities (TSFs).
Boliden	large volumes of residual material from production that still contain valuable metals are stored at Boliden Rönnskärs's site. New technology developed- The leaching plant has been designed specifically to handle residual material from Rönnskär.22

5. **Plastic components–** Plastics are a major part of E-waste; it was observed that a few companies who dealt with different feed types, were not segregating their plastic component and rather used it as alternative fuel source or during smelting took advantage of the plastic components. A few companies used the plastics to generate heat for their plants and neighbouring areas. Those companies dealing with only e-waste, sent the plastic fraction to other plastic recyclers after pre-treatment. Being able to separate one type of plastic from another is the most challenging part of recycling electronics. At the same time, complete separation of different plastics is key to using recycled plastic to make new products

22 https://www.boliden.com/4a6fb9/globalassets/operations/smelters/ronnskar/leach-plant-2021/facts-sheet/fact-sheet-leaching-plant.pdf

5. TECHNOLOGIES IN INDIA TO HANDLE E-WASTE

5.1 Current technologies

As mentioned in the earlier section international e-waste recyclers/ refiners are processing e-waste, in case of India, similar technologies are being incorporated with few minor adjustments suiting the feed and Indian landscape.

1. C-MET – Hyderabad[23]

The front-firing rotary tilting furnace indigenously designed and fabricated technology at C-MET is capable of recycling PCB at the rate of 100 kg per day or approximately 1,200 tonnes per annum of e-waste. The technology is able to extract Silver 2N pure, copper approximately 90% pure and gold 99.9%. A demonstration plant is established at C-MET, Hyderabad, the facilities are being extended to recyclers for processing on chargeable basis. A brief explanation of the technology developed at C-MET is given below.

- Manual dismantling
- Depopulation: C-MET has indigenously designed a technique and optimized the parameters that can separate the solder from the components without igniting the PCB. Solder elimination before smelting can increase the purity of copper from 60 % to 90%.
- Shredding: To ease the feed for further processing, the PCBs are reduced to 40 to 50mm pieces.
- Calcination/pyrolysis: C-MET has indigenously designed, developed and optimized the parameters to calcine the organic content of PCB and treat the toxic gases evolved during calcination process and release them into atmosphere as per CPCB guidelines.
- Smelting: Removal of inorganic fillers and obtaining black copper. C-MET has optimized the parameters and flux ratios to enrich the precious metals concentrations in black-copper and remove the gangue[24] material through slag.
- Remelting/anode preparation: For the preparation for electrolysis, Anode has to be free from Sn, Pb and other impurities to eliminate the contamination of electrolyte which decrease the deposition rate. C-MET has adopted the standard procedure with indigenously developed furnace to eliminate impurities.

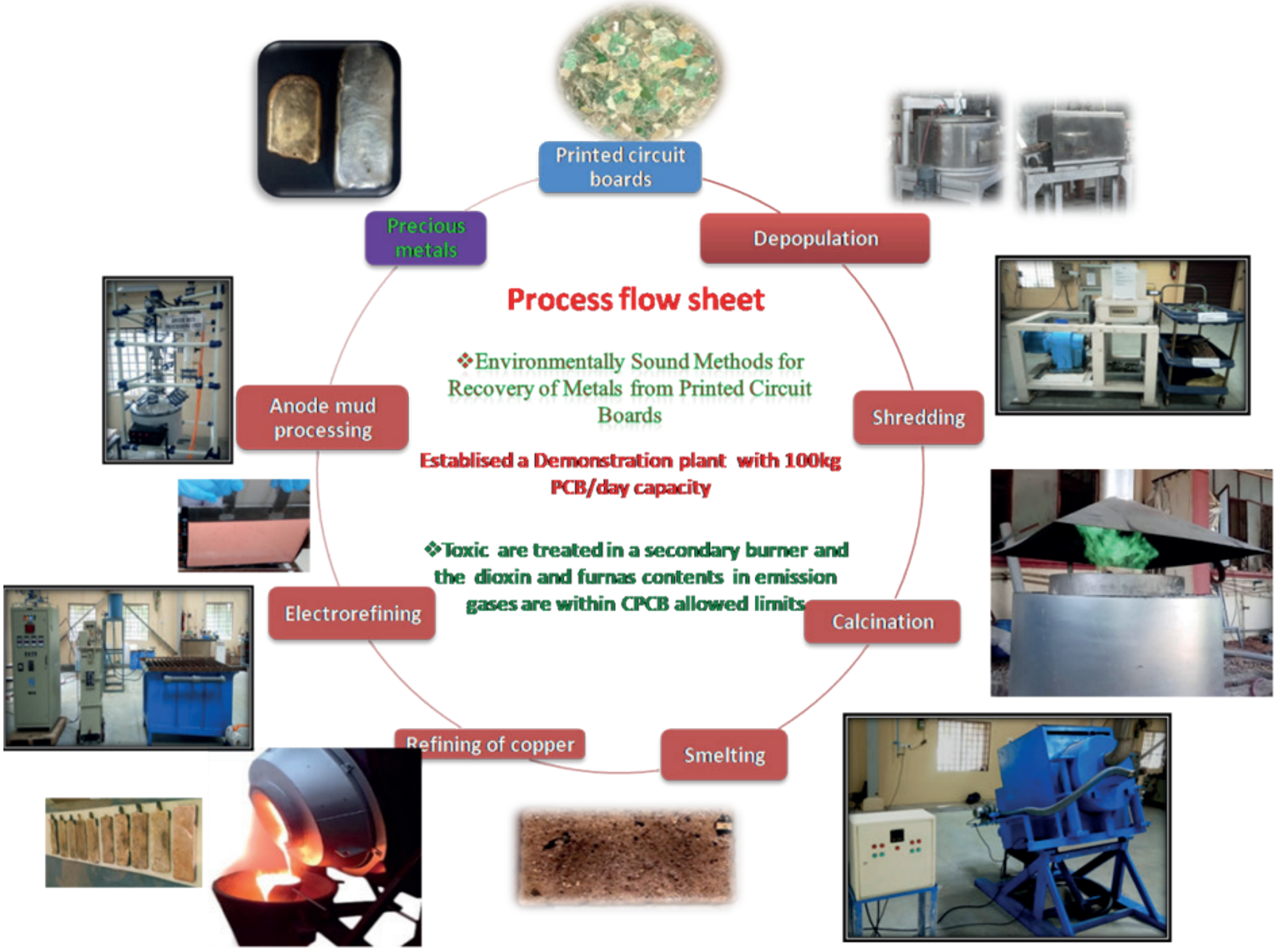
The technology is able to extract Silver 2N pure, copper approximately

90%

pure and gold

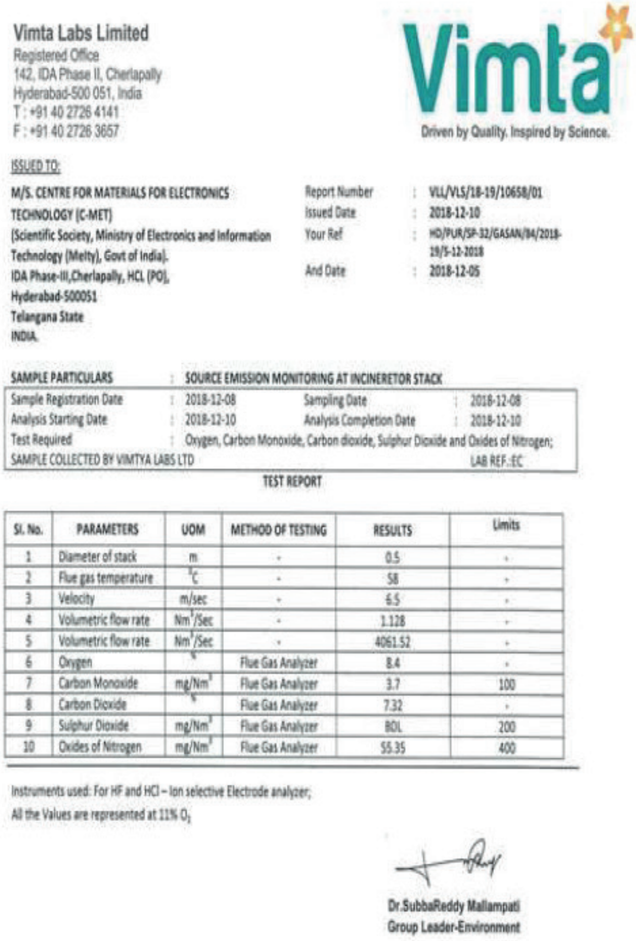
99.9%.

23 https://www.coeonewaste.com/pcb-recycling.html
24 Generally, an unwanted material or impurity



- Electro-refining: The process has been adapted from existing technology to obtain pure copper. The obtained anode copper is kept as anode keeping SS plate as cathode immersed in electrolyte ($CuSO_4$) in a PP electrolytic cell. The electrodeposition of copper takes place from anode to cathode and obtained 99.99% pure copper where the precious metals are concentrated in anode slime.
- Anode mud processing: Separation and purification of Au, Ag and Pd are extracted through a hydrometallurgical process by selective leaching and precipitation method.

Technology has been transferred to M/s Namo E-waste and training given as well by processing 300kg PCBs supplied by M/s Namo E-waste. As per reports, the technology has been tested for emission monitoring at incineration stack stage.



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ISSUED TO:

M/S. CENTRE FOR MATERIALS FOR ELECTRONICS TECHNOLOGY (C-MET)
(Scientific Society, Ministry of Electronics and Information Technology (Meity), Govt of India).
IDA Phase-III,Cherlapally, HCL (PO),
Hyderabad-500051
Telangana State
INDIA.

Report Number : VLL/VLS/18-19/10658/01
Issued Date : 2018-12-10
Your Ref : HO/PUR/SP-32/GASAN/94/2018-19/5-12-2018
And Date : 2018-12-05

SAMPLE PARTICULARS : SOURCE EMISSION MONITORING AT INCINERETOR STACK

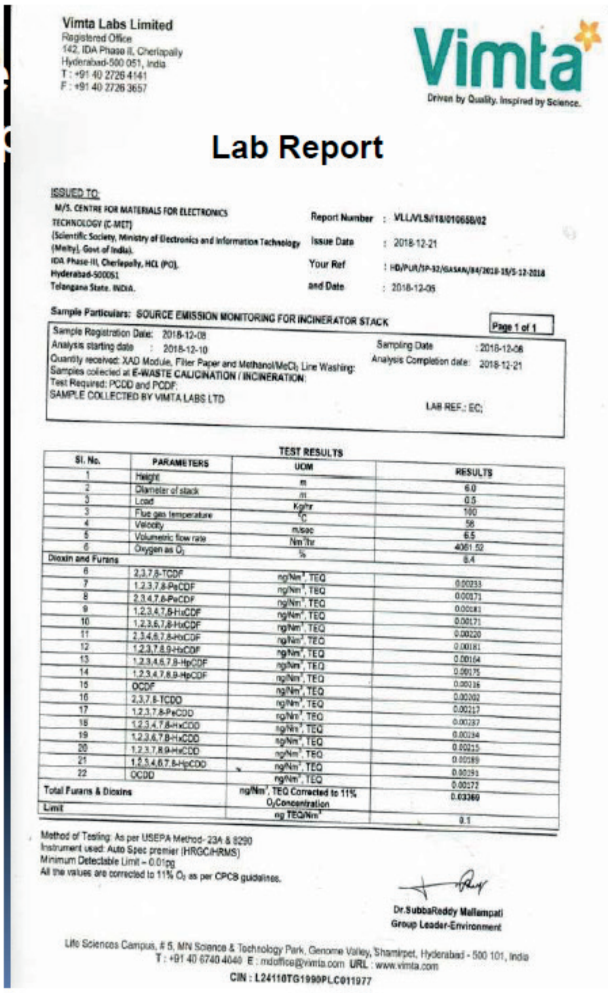
Sample Registration Date : 2018-12-08 Sampling Date : 2018-12-08
Analysis Starting Date : 2018-12-10 Analysis Completion Date : 2018-12-10
Test Required : Oxygen, Carbon Monoxide, Carbon dioxide, Sulphur Dioxide and Oxides of Nitrogen;
SAMPLE COLLECTED BY VIMTYA LABS LTD LAB REF.:EC

TEST REPORT

Sl. No.	PARAMETERS	UOM	METHOD OF TESTING	RESULTS	Limits
1	Diameter of stack	m	-	0.5	-
2	Flue gas temperature	°C	-	58	-
3	Velocity	m/sec	-	6.5	-
4	Volumetric flow rate	Nm^3/Sec	-	1.128	-
5	Volumetric flow rate	Nm^3/Sec	-	4061.52	-
6	Oxygen	%	Flue Gas Analyzer	8.4	-
7	Carbon Monoxide	mg/Nm^3	Flue Gas Analyzer	3.7	100
8	Carbon Dioxide	%	Flue Gas Analyzer	7.32	-
9	Sulphur Dioxide	mg/Nm^3	Flue Gas Analyzer	BDL	200
10	Oxides of Nitrogen	mg/Nm^3	Flue Gas Analyzer	55.35	400

Instruments used: For HF and HCl – Ion selective Electrode analyzer;
All the Values are represented at 11% O_2

Dr.SubbaReddy Mallampati
Group Leader-Environment



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Lab Report

ISSUED TO:
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(Scientific Society, Ministry of Electronics and Information Technology (Meity), Govt of India).
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Report Number : VLL/VLS/18/010658/02
Issue Date : 2018-12-21
Your Ref : HO/PUR/SP-32/GASAN/94/2018-19/5-12-2018
and Date : 2018-12-05

Sample Particulars: SOURCE EMISSION MONITORING FOR INCINERATOR STACK — Page 1 of 1

Sample Registration Date: 2018-12-08
Analysis starting date : 2018-12-10
Sampling Date : 2018-12-08
Analysis Completion date: 2018-12-21
Quantity received: XAD Module, Filter Paper and Methanol/$MeCl_2$ Line Washing;
Samples collected at E-WASTE CALICINATION / INCINERATION;
Test Required: PCDD and PCDF;
SAMPLE COLLECTED BY VIMTA LABS LTD
LAB REF.: EC;

TEST RESULTS

Sl. No.	PARAMETERS	UOM	RESULTS
1	Height	m	6.0
2	Diameter of stack	m	0.5
3	Load	Kg/hr	100
3	Flue gas temperature	°C	58
4	Velocity	m/sec	6.5
5	Volumetric flow rate	Nm^3/hr	4061.52
6	Oxygen as O_2	%	8.4
Dioxin and Furans			
6	2,3,7,8-TCDF	ng/Nm^3, TEQ	0.00233
7	1,2,3,7,8-PeCDF	ng/Nm^3, TEQ	0.00171
8	2,3,4,7,8-PeCDF	ng/Nm^3, TEQ	0.00181
9	1,2,3,4,7,8-HxCDF	ng/Nm^3, TEQ	0.00171
10	1,2,3,6,7,8-HxCDF	ng/Nm^3, TEQ	0.00220
11	2,3,4,6,7,8-HxCDF	ng/Nm^3, TEQ	0.00181
12	1,2,3,7,8,9-HxCDF	ng/Nm^3, TEQ	0.00164
13	1,2,3,4,6,7,8-HpCDF	ng/Nm^3, TEQ	0.00175
14	1,2,3,4,7,8,9-HpCDF	ng/Nm^3, TEQ	0.00336
15	OCDF	ng/Nm^3, TEQ	0.00202
16	2,3,7,8-TCDD	ng/Nm^3, TEQ	0.00217
17	1,2,3,7,8-PeCDD	ng/Nm^3, TEQ	0.00287
18	1,2,3,4,7,8-HxCDD	ng/Nm^3, TEQ	0.00194
19	1,2,3,6,7,8-HxCDD	ng/Nm^3, TEQ	0.00215
20	1,2,3,7,8,9-HxCDD	ng/Nm^3, TEQ	0.00189
21	1,2,3,4,6,7,8-HpCDD	ng/Nm^3, TEQ	0.00191
22	OCDD	ng/Nm^3, TEQ	0.00172
Total Furans & Dioxins		ng/Nm^3, TEQ Corrected to 11% O_2 Concentration	0.03360
Limit		ng TEQ/Nm^3	0.1

Method of Testing: As per USEPA Method- 23A & 8290
Instrument used: Auto Spec premier (HRGC/HRMS)
Minimum Detectable Limit – 0.01pg
All the values are corrected to 11% O_2 as per CPCB guidelines.

Dr.SubbaReddy Mallampati
Group Leader-Environment

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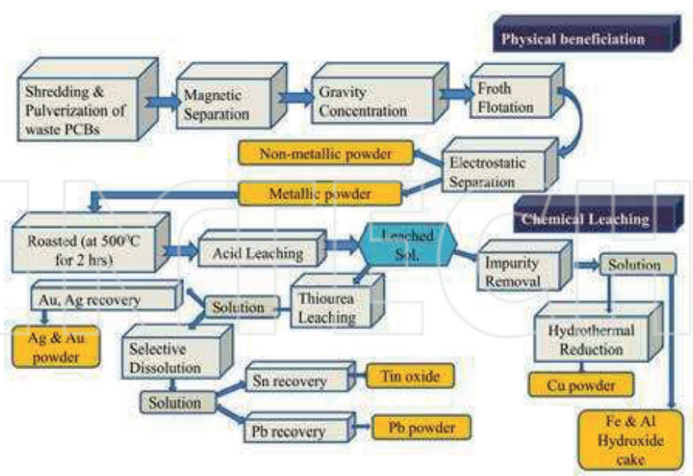
CIN : L24110TG1990PLC011977

Source- Presentation on Low-cost E-waste Recycling Technologies by Dr. Sandip Chatterjee[25]

2 CSIR-NML, Jamshedpur

The technology developed at CSIR- NML functions in a manner in which metal-bearing e-waste components are shredded and pulverized at the initial operation stage. Subsequently, the metals are separated from the plastics in the particulate mass, adopting a series of physical separation processes. The natural hydrophobicity of non-metallic constituents is effectively exploited by a flotation process and a continuous operation at plant level can reasonably be expected to minimize the loss of ultrafine metal values to a negligible level. The operation is simple and the overall processing cost is low, taking into account the comparatively inexpensive physical separation processes deployed. The techniques used are purely physical in nature and thus generate no additional harmful effluents. The process enables the recovery of both metallic and non-metallic constituents separately.



25 https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/SiteAssets/Pages/Events/2019/Policy-awareness-workshop-on-E-waste/Presentation%201.pdf

3. Central Institute of Petrochemicals Engineering & Technology (CIPET)26

The key steps in the CIPET technology for recycling plastics are mentioned below.

The use of various separation technologies such as:-

- Magnetic separation
- Electrostatic Technique
- Density separation,
- Sink and Float Separation
- Air Table Technique
- Froth Flotation
- Air Classification and elemental analysis are used.

Further, the key function of elemental analysis is used to identify the presence and concentration of various metals, plastics in E-waste, following methods are used for elemental analysis:

- Fourier-transform infrared spectroscopy (FTIR)
- Differential scanning calorimeter (DSC)
- Thermogravimetric analysis (TGA)
- Melt flow index tester (MFI)

These processes are used and may take 1-2 days to separate(100Kg) depending on the plant. Capacity. The entire 100kg of ground E-waste shall be used for separation, whereas elemental analysis can be carried out by using a few of materials from each segment. The process was tested and as per CIPET, the recovery and cost of those materials are given below.

Feed	Recovered materials	Total cost of material (Considering that the 100 kg batch consisted of mixed plastics from WEEE items)
100 Kg	Plastics: 30-35kg Metals: 45-50kg Glass, ceramics and others: 10-15 kg	Plastics: Rs. 65-75/kg Metals: Rs. 15-150/kg (depending upon various metals) Glass, ceramics and others: Rs. 5-10/kg

*For the technologies mentioned above there have been limited to no auditing of the efficiency or emission monitoring hence inferences made as per data reported.

26 https://www.niti.gov.in/sites/default/files/2019-03/E-WasteStrategy.pdf

5.2 Novel technologies

There are numerous institutes that have dedicated research to develop new and efficient technologies that might improve the recovery of precious material and metals present in e-waste. And more importantly, help enterprises, government, and non-profits upgrade capability and competitiveness in India. The table below briefly summarizes indigenous technologies developed in India as of April 31st, 2023. (*Data represented as reported by various agencies)

Technology developed & organization	Stage of Development	Applications/ purity achieved	Advantages/ feature worth mentioning
Recycling of mixed/ any chemistry of spent lithium-based batteries for extraction of lithium, nickel. CSIR National Metallurgical Laboratory (NML) Jamshedpur[27]	Prototype	**Purity:** 96-99% pure Individual Element (Li, Co, Mn, Ni, Cu, Al)	Complete separation among Li, Ni, Co and Mn Batteries Tested: LCO, LCA, LMO, NMC, LFP Total recycling of reagents with 85% recovery of acid residual carbon is converted to high pure flake graphite.
Development of sustainable technology for recycling of e-waste. Indian Institute of Technology (IIT) Delhi28	Technology Readiness Level- 4 A pilot plant with a capacity of 10 kg per hour has been installed at IIT Delhi campus for recycling electronic waste. The facility pyrolyzes the polymeric fraction of the electronic waste into oil and combustible gases in an environment friendly manner.	Reduction of electronic waste. Extraction of metals from electronic waste. Thermal conversion of plastics into oil and combustible gases.	Pyrolysis efficiently converts the organic parts of e-waste into valuable products. Pyrolysis also helps in enhancing the separation of the metallic fraction. High amounts of metals can be recovered using this technique with high selectivity, low energy consumption, and low cost. The amount of generation of toxic and corrosive effluent is also minimal in low-temperature roasting technique.
Extraction of mixed rare earth oxides from spent compact fluorescent lamps (cfls)& fluorescent lamp. Centre for Materials for Electronics Technology (C-MET) Hyderabad 29	Prototype Level	**Application:** The recovered rare earths have applications in the production of phosphors for display applications, solid state lighting, WLEDs, fibre optics communications, IT products, automobile industry, etc.	Cost-effective, easily scalable, environment friendly, resource efficiency and circular economy.

27 https://www.istem.gov.in/digitalcatalogue-report/technology-product/info/TP19768338247
28 https://www.istem.gov.in/digitalcatalogue-report/technology-product/info/TP19769495192
29 https://www.istem.gov.in/digitalcatalogue-report/technology-product/info/TP19769401615

Technology developed & organization	Stage of Development	Applications/ purity achieved	Advantages/ feature worth mentioning
Extraction of rare earth oxides from spent permanent magnets. Centre for Materials for Electronics Technology (C-MET) Hyderabad30		**Application:** The recovered materials find applications in manufacture of IT-products, photonics, solid state lighting and fibre optic communications, etc.	Recovery of rare earths elements like Neodymium, Dysprosium and Praseodymium from spent permanent magnets using a simple and commercially viable hydrometallurgical route.
Solvent extraction process for the selective extractions of various metal contents from black mass. (C-MET) Hyderabad31	Prototype Level	**Application:** Li-Ion batteries manufacturing in the country. **Purity:** Cobalt (99.9 %), Manganese (99.9 %), Lithium (99.9 %), and Nickel (99.9 %).	Selective extraction of materials, scalable hydrometallurgical route, environment friendly, resource efficiency, circular economy, indigenous technology.
Extraction of cobalt-nickel alloy from discarded lithium -ion batteries using pyrometallurgical route (C-MET) Hyderabad	Prototype Level	**Application:** Co-Ni alloy find potential applications in jet engines, gas turbines, chemical processing, petroleum refining, marine, electronics and other applications where common stainless steels may not provide adequate performance.	An effective way to recover metals from waste lithium-ion batteries (LIBs), wherein pure cobalt-nickel (Co-Ni) metal alloy is extracted in a single smelting step. Indigenous technologies, Cost-effective, easily scalable, environment friendly, resource efficiency, circular economy.
Production of high purity copper oxide nanoparticles from depopulated printed circuit boards MP&CED, BARC.		**Purity**: >99.9% from printed circuit boards (PCBs)/powder concentrate **Scope:** The process offers fully scalable technology for production of CuO nano particles, SnO and PbS from e-waste.	Empowers metal recyclers to start production of high purity copper oxide nanoparticles whose current market rate is about Rs 18,000/- per kg.

30 https://www.istem.gov.in/digitalcatalogue-report/technology-product/info/TP19765949050
31 https://www.istem.gov.in/digitalcatalogue-report/technology-product/info/TP19766511672

6. DISCUSSION & RECOMMENDATION

Extensive research has explored various recycling technologies, with pyrometallurgy or combined hydro and pyrometallurgical techniques emerging as the most viable and widely used options. Implementing global Best Available Technology (BAT) for e-waste recycling can be challenging due to various factors that need careful consideration. It is important to address these factors in order to successfully adapt and implement BAT in the e-waste recycling industry. However, one of the challenges is the lack of clear guidance on what constitutes BAT and how it is defined specifically in the context of e-waste. Currently, there are no universally accepted benchmarks or standards for BAT[32] in the global or Indian context for E-waste recycling technology, making it difficult to establish a clear framework for implementing BAT in e-waste recycling practices.

Involving key stakeholders' views is crucial in overcoming these obstacles and adapting the BAT to the Indian context. By incorporating their insights and perspectives, strategies can be developed to address the challenges and effectively implement recycling technologies.

E-waste
recycling technology, making it difficult to establish a clear framework for implementing BAT in e-waste recycling practices.

6.1 Stakeholder discussion

The successful adaptation of any technology necessitates thorough research and evaluation of parameters both at the source location (where the technology originates) and at the destination location (where the technology is being adapted). Based on our extensive discussions with stakeholders, including industry players involved in e-waste recycling and academicians, it has become evident that there is a need to address numerous parameters when discussing the adaptability of best available techniques (BAT).

One of the key points highlighted by most of the stakeholders was regarding the feeds (Quality, Type, and Continuous inflow). The current BAT globally in operation has diversity in the feed from metal scraps, automotive scrap, etc, the feed is not confined to just E-waste. However, in the case of Indian recyclers, this emerges as a limiting factor.

32 There are BAT reference documents for various other industries which can be consulted to frame a similar document for E-waste recycling technology. https://eippcb.jrc.ec.europa.eu/reference

Another key point raised was regarding the pre-treatment processes used globally. Pre-treatment is one of the most important steps in e-waste recycling and recovery. Global BAT incorporates both manual and mechanical processes, and is more focused on mechanical. The feed preparation at these facilities is manner that recovery of materials becomes easier and efficient. While in the case of India, the pre-treatment mostly involves manual and in some cases a mix of both manual and mechanical. It emerged from the discussion that the current pretreatment processes are efficient and more appropriate conditions.

A few of the stakeholders also pointed out the necessity for extensive data-driven research and evaluation as one of the key factors in understanding efficiency of these technologies. One of the stakeholders mentioned the need for Economic v/s Environmental evaluation of the technologies. According to them, there are times when focussing on the environmental efficiency the commercial aspect gets compromised, and vice versa, an environmentally compromised technology can be efficient in terms of recovery and commercial value. For instance, cyanide-based methods which are easier and more economical to recover metals may not be desirable on environmental parameters.

One of the stakeholders highlighted a possible reason why global companies/ organisation might be hesitant to coming to India. According to them, these international organisations might be taking a cautious approach in investing in India. At the same time, there are larger Indian refineries who are trying to join the bandwagon of Circular Economy when it comes to secondary material reliance. There is a lot of competition internally which makes them cautious. There are other gaps which might make these foreign companies hesitant to come to India with their technology such as: -

- Material traceability
- Procuring high grade materials
- Ambiguity in the regulatory compliance requirements and there are long delays that make it difficult to get consent and permits.

Based on our stakeholder interactions, it became clear that the feed holds paramount importance for any recycler. We observed that technology, infrastructure, and knowledge were not the primary concerns; rather, the continuous supply of feed was the key issue identified by every stakeholder. Also the lack of incentives to recyclers makes it challenging to have a robust recycling system. However, as per the discussion it was also evident that there are technologies present in India but appropriate measures, schemes and regulatory frameworks are required.

Addressing these challenges necessitates a comprehensive approach that takes into account the local context, regulatory framework, available infrastructure, and engagement with relevant stakeholders. By developing and implementing effective and sustainable e-waste recycling solutions tailored to the Indian context, these challenges can be effectively overcome.

6.2 Recommendations

In light of the growing global concern over the management of e-waste, it is imperative to identify effective strategies and recommendations that can pave the way for a sustainable and efficient e-waste recycling. The previous chapters have provided the current state of e-waste, its environmental and economic implications, as well as the existing practices and technologies employed in its treatment and disposal. Building upon this knowledge, the following recommendations aim to address the challenges and gaps identified, with the ultimate goal of achieving a circular economy approach to e-waste management.

Benchmarking: There is an absence of a clear definition of Best Available Technologies for handling e-waste at different stages of treatment. Setting up a guidance document for BAT that considers various parameters such as:

- **Environmental norms:** The technology should comply with environmental norms and cause least harm to environment. It should result in least amount of toxics or hazardous residues or emissions.
- **Energy & resources requirements:** All technologies have an energy foot print and this also can shift the cost structures of metal recovery. All such technologies need to be tried on energy parameters.
- **Recovery efficiency:** This is another important parameter of recover efficiency, and can be one determining factor to define a technology. This also entails the extraction volume achieved by the technology.
- **Cost:** Technology also comes at a cost and it can be a defining factor for a country or a situation. Scale of operation also is to be considered while making choices. Lower volumes of feed has been a critical concern for suitability of technology. Technology with lower volumes of continuous feed would be an important factor for judging best technology for Indian context.

Manual Pre-treatment processes: Setting up of guidance document for manual pre-treatment processes as BAT at the pre-treatment stage keeping in mind several parameters:

- Occupational safety
- Appropriate measures (appropriate lighting, workstation requirements)

A best of 2 worlds study, which will make it is possible to identify at which point and for which processes, materials and devices is preferred. This study can be for pre-treatment (manual and mechanical processes), end processing (Pyro, Hydro or other metallurgical methods).

Pilot plant testing facility: Encourage and facilitate testing of pilot / lab scale models for commercial viability. Making data available to recyclers or institutes to understand and adopt such technologies. This will help in making informed decisions by interested recyclers or entrepreneurs.

Research & Development: Invest in research & development to explore innovative recycling technologies and processes that can maximize resource recovery from e-waste; Regular updating and publishing of these novel technologies for scalability and adaptation.

Encourage collaboration between ministry, industry, academia, and research institutions to drive technological advancements in e-waste recycling by providing scholarships and incentives.

Regular documentation: Updating of website (Istem) for all data regarding commercially available recycling technologies.

It is recommended that a **compendium is prepared** of technologies and companies that manufacture these machines, including some typical specs that are useful for recyclers to decide on what is needed such as processing capacity/day, energy consumption/tonne.

ANNEXURE

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