UNRAVELLING INDIA'S E-WASTE SUPPLY CHAIN: A COMPREHENSIVE ANALYSIS AND MAPPING OF THE KEY ACTORS INVOLVED

AMRITA GOLDAR
KARTIK NAIR
MD SARWAR ALI
RITIKA VERMA

NOVEMBER 2025

429
WORKING PAPER

Table of Contents

List of Figures

List of Tables

Abstract

India's rapid technological growth has significantly increased electronic consumption, resulting in a surge in electronic waste (e-waste) generation. This working paper examines the complexities of India's e-waste supply chain, focusing on key agents involved, such as collectors, dismantlers, refurbishers, and recyclers, with an emphasis on the dominant role of informal players. The analysis is grounded in field surveys conducted in Maharashtra and Karnataka, which were chosen for their high e-waste generation, industrial ecosystems, and green technology developments. The study highlights the environmental hazards of e-waste, including toxic material leakage, while underscoring its potential for resource recovery and contributions to a circular economy. Recycling e-waste can recover critical materials like copper and rare earth elements, aiding India's clean energy transition and reducing dependency on new mining activities.

This comprehensive analysis identifies supply chain challenges, proposes an incentive mechanism to improve e-waste management, and provides actionable policy recommendations to address inefficiencies. The study aims to create a more efficient, sustainable, and inclusive e-waste management framework for India by bridging the gap between informal and formal sectors.

Acknowledgment

We are grateful to our partners, the International Institute of Sustainable Development (IISD) and ClimateWorks Foundation, without whom this working paper would not have been possible.

We want to thank Dr. Deepak Mishra, former Director and CE, Indian Council for Research on International Economic Relations (ICRIER), who encouraged, inspired and motivated the team in the entirety of the project. We are thankful to the administrative and events team at ICRIER for their unfailing support with logistics, event management, organization, and other associated tasks.

We are also thankful to Dr. Vijai Singhal (Rtd. Chief Environmental Engineer, Rajasthan State Pollution Control Board), Dr. Parveen Kumar (Head Research and Development, Exigo Recycling) and Mr. Nirmal V (EHasiru Recycling) for their valuable inputs and guidance.

Lastly, the errors, if any, in this paper are the authors' responsibility alone.

Keywords: *Circular economy, E-waste management, Informal Economy*

JEL classification: *Q53, Q58, E20*

Author's email: *acharya.shankar@gmail.com*

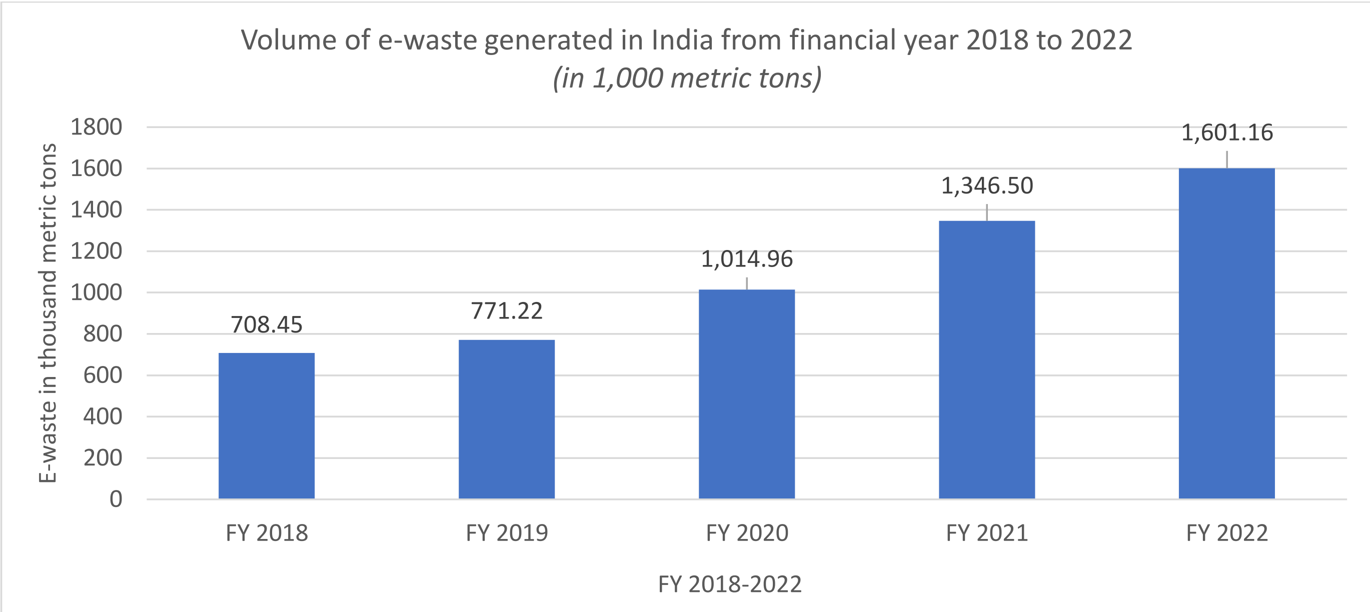
Unravelling India's E-Waste Supply Chain: A Comprehensive Analysis and Mapping of the Key Agents Involved

Amrita Goldar[1,2], Kartik Nair[3], Md Sarwar Ali[4] and Ritika Verma[5]

1. Introduction

In this technology-driven era, our dependency on electronic devices, home appliances, and other useful technological gadgets has been exponentially increasing, thus, resulting in the accumulation and generation of massive amounts of e-waste. E-waste generated by India is depicted in the chart below in Figure -1.

Figure 1: India's e-waste generation, by year



Source: Statista Market Insights, 2024

Consequently, the rising e-waste in the country has necessitated the immense need for a proper e-waste management system in India. E-waste has always been considered a threat to the environment, as it contains toxic materials such as lead, cadmium, etc. The leakage of these toxic chemicals is suspected to cause air, water, and land pollution, and they are also vulnerable to human health hazards. Majorly, the informal sector looks after the collection and processing of e-waste which contains hazardous chemicals like polycyclic aromatic hydrocarbons, heavy metals, inorganic acid, and other possible contaminants that pose major risks to occupational health (Annamalai, 2015)However, the recycling of e-waste can help in recovering some of the valuable materials like plastic, metals, etc. In addition, the efficient recycling of e-waste would further reduce the demand for new metals and minerals, thus reducing new mining activities and turning down pollution. In parallel, the recycling of e-waste is also anticipated to play a crucial role in the clean energy transition of the nation as the embedded critical minerals in electronic devices such as copper, nickel, etc., and some other rare earth elements are recyclable up to a significant percentage. This will help in building the e-waste circularity and further assisting the growth of a circular economy.

1 Corresponding author, agoldar@icrier.res.in
2 Senior Fellow, Indian Council for Research on International Economic Relations (ICRIER)
3 Research Associate, Indian Council for Research on International Economic Relations (ICRIER).
4 Research Associate, Indian Council for Research on International Economic Relations (ICRIER)
5 Research Associate, Indian Council for Research on International Economic Relations (ICRIER)

India's rapid technological advancement has led to a surge in electronic consumption, subsequently amplifying the generation of electronic waste (e-waste) across the nation. This paper delves into the intricate web of India's e-waste supply chain, aiming to provide a comprehensive analysis and mapping of the key agents involved in its management. This introduction sets the stage by elucidating the urgency and significance of studying India's e-waste supply chain. Subsequent chapters will delve into the components and actors involved in India's e-waste supply chain, the stages of e-waste recycling, global dynamics influencing the supply chain, various recycling technologies, state-specific case studies, and empirical analyses focused on Indian states. Through this exploration, we aim to unearth critical insights, identify challenges, and propose actionable recommendations for policymakers, industry stakeholders, and environmental advocates to navigate the complexities of India's e-waste landscape effectively.

Moreover, to further streamline the supply chain of e-waste management in India, the identification of critical agents or actors involved is a necessary ask. Incidentally, the e-waste management sector has been predominantly led by the informal players be it collectors, dismantlers, refurbishers, recyclers, etc.

To analyse the present scenario and choke points in the entire supply chain of e-waste in India, two states are selected i.e. Maharashtra and Karnataka. These states are chosen based on several parameters such as the quantum of e-waste generated, industrial and electric vehicle ecosystem, development of green technologies, the status of electric vehicle infrastructure, and the availability of workforce. The deep dive field survey has been conducted in these two states to analyse the informal and formal actors involved in the supply chain of e-waste management. Along with this, policy recommendations are developed based on the field research. In addition, the incentive mechanism is needed to leverage the e-waste management sector, as the treatment is less and this is further dealt with and discussed in the following sections. Table 1 below shows e-waste collected and processed in the two states.

Table 1: Selected states e-waste collected and processed during FY 2021-2022

S.No.	Name of the State	E-waste collected and processed (in Tonnes)
1.	Maharashtra	18559.30
2.	Karnataka	39150.63

Source: PIB,2022

2 India's E-waste Supply Chain Scenario – Components/ Actors involved.

India's e-waste supply chain is a complex ecosystem involving various components and actors. As one of the world's largest producers of electronic waste (e-waste), India faces significant challenges in managing the disposal and recycling of discarded electronic devices. The supply chain encompasses multiple stages, starting from the generation of e-waste to its collection, transportation, recycling, and disposal. Key components of the supply chain include consumers, manufacturers, retailers, recyclers, government agencies, and regulatory bodies. There are various intermediary players, such as collectors, PROs, and dismantlers, who act as small pieces of the larger jigsaw puzzle of e-waste management. However, the current regulatory approach does not consider these players, despite their critical role in maintaining the supply chain. Each actor plays a crucial role in shaping the dynamics of the e-waste management system, contributing to both its strengths and limitations. Comprehending the intricate interaction among these elements is imperative for formulating efficacious strategies to tackle the escalating e-waste dilemma in India. This study stresses on the informal sector in the e-waste supply chain of India. In addition, emphasis will also be on the key actors involved in the management of e-waste.

Informality in the e-waste supply chain

Informality in the e-waste supply chain refers to the involvement of unregulated or informal actors and practices in the collection, recycling, and disposal of electronic waste. This includes individuals or small-scale enterprises operating without adherence to formal regulations, often in unlicensed or makeshift facilities. Informal practices in the e-waste supply chain may involve unsafe handling of hazardous materials, inadequate environmental protection measures and exploitation of labour. Despite the challenges posed by informality, it remains a significant aspect of the e-waste management landscape, particularly in regions with limited formal infrastructure and enforcement mechanisms. Informal sector workers are often marginalized by society and may be referred to by unfavourable terms, including 'scavengers', 'rag pickers', and 'waste pickers' (US-EPA, 2020). While the formal sector consists of public service providers and private companies (US-EPA, 2020; Turuga et al., 2019). Addressing informality is crucial for promoting sustainable and safe e-waste management practices.

The informal segment within the e-waste value chain retains its significance owing to its capacity to create employment opportunities. There is a need to integrate the activities of the informal sector into the mainstream recycling of e-waste by dovetailing the activities of the informal and formal sectors. However, integrating the informal sector with the formal sector poses significant challenges.

Actors in e-waste supply chain

According to the various rules and regulations governing e-waste management in the country, numerous stakeholders are involved in the field of e-waste management. Through critical analysis, the identified key actors have been highlighted below:

- **Recyclers/Dismantlers:** It is unknown how many people are involved or how extensive the network of collectors and recyclers is in the Indian states. This is because gathering data on this industry is particularly challenging in the absence of a governing or monitoring structure, and comprehensive research focus on different players in the E-waste recycling market is sorely lacking (Rode et al., 2012, Turuga et al., 2019). Recyclers are responsible for collecting e-waste from various sources, such as consumers, businesses, and electronic manufacturers. Subsequently, they meticulously disassemble electronic devices to retrieve valuable components and materials, including metals, plastics, and precious metals such as gold and silver. In addition, as per the regulations, recyclers are permitted to collaborate with dismantlers for recycling purposes. Furthermore, recyclers assure the safe handling and proper disposal of hazardous materials and parts, such as batteries and mercury-containing lightbulbs in compliance with environmental laws. By employing suitable recycling methodologies, recyclers aid in diverting e-waste from landfills, preserving resources, and mitigating the environmental repercussions of recycling.

- **Policymakers (Government):** The 'Hazardous Wastes (Management and Handling) Rules, 2023' and 'The E-waste (Management and Handling) Rules, 2022' by the Indian government have both addressed the issue of e-waste in our country. The application of these regulations is expected to continue to expand in the coming years. The collection, treatment, and disposal of e-waste must be carried out in an environmentally responsible manner, which underscores the need for effective governance (Turuga et al., 2019). Policymakers play crucial and distinct roles at the central, state, and local levels in establishing E-waste management hubs, placing significant emphasis on the involvement of authorized recyclers. They also seek to establish a framework for EPR (Extended Producer Responsibility), E-waste collection and recycling standards, and the enforcement of environmentally sound practices. There are various rules in place to regulate the e-waste supply chain in India. However, there is still room for improvement in harmonizing different aspects of e-waste management into a cohesive framework.

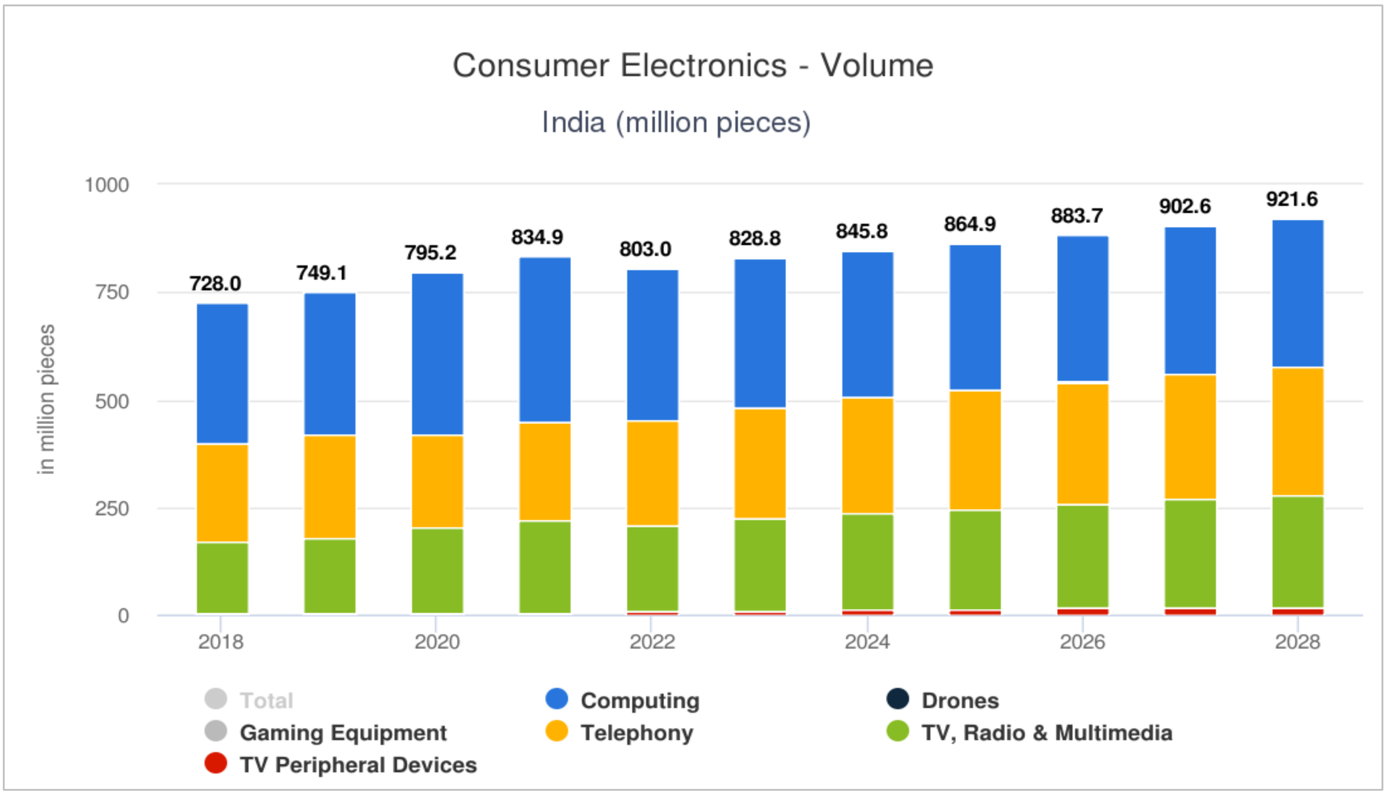
- **Battery Manufacturers:** The manufacturer and battery importer are in charge of gathering and recycling or renovating batteries that they have brought onto the market under the new regulations of the battery management rule of 2022. The fact that the new battery waste regulations are outcome-based and measurable is their strongest feature. It lays out required goals for recycling and collecting during a compliance period. Battery manufacturers have the potential to aid in e-waste reduction by instituting programs for reclaiming used batteries, advocating for battery recycling, and allocating resources towards the research and development of eco-friendly battery technologies. Overall, their actions significantly influence the lifecycle and environmental impact of batteries, thereby shaping the e-waste supply chain.

- **NGOs/Thinktanks/Academia:** Some NGOs/ Think-Tank and Academia actively promote and demand proper knowledge of the concerns surrounding e-waste. Different NGOs also place a lot of emphasis on the illegal import of E-waste. These NGOs/ Think tanks and academia conduct research on all significant facets of e-waste and make recommendations for national policy.
- **Producer Responsibility Organisations (PROs)/Aggregators:** The PROs and aggregators are professional organisations who are authorised and paid collectively or individually by the e-waste producers for taking the responsibility of collection of the wastes, and channelisation end-of-life of the products to appropriate recycling centres to ensure better management of the E-waste (Turuga et al., 2019).

3. Stages Involved in E-waste Recycling

The e-waste recycling has increasingly become important for the environment, and securing the critical minerals and metals embodied in electronic devices from recycling are also equally important to upscale the production of green and clean technologies. Securing critical minerals from these urban mines (referring to e-waste) would be imperative for India to achieve its net-zero commitments. The sales of consumer electronics in India have been astonishingly growing owing to multiple factors such as increasing disposable income, lifestyle changes, digitalization, etc. This, in turn, has been emanating a high amount of e-waste, hence, there is a large scope for recycling and recovering of critical minerals. Considering the increasing trend of buying and replacing of consumer electronics among individuals, the sales of consumer electronics are anticipated to grow in the forthcoming years as well. The e-waste recycling process involves several formal as well as informal players at different stages of e-waste recycling such as refurbishing, dismantling, segregation, etc. Figure 2 shows the India consumer electronics sales.

Figure 2: India consumer electronics sales



Source: Statista Market Insights, 2024

The process of e-waste management includes several stages to maintain the sustainable lifecycle of electrical and electronic equipment. This equipment are to be managed sustainably to reduce the usage of fresh materials in new products by recycling, expanding the life of products by refurbishing, etc. In addition, the recycling of e-waste involves steps such as collection, reuse and refurbishing, shredding, sorting, separation, and recycling.

Collection: The collection and transportation represent pivotal phases in the recycling process, encompassing the handling of e-waste as well. Recyclers strategically position collection bins or electronic take-back booths at designated sites, thereafter conveying the gathered e-waste to recycling plants and facilities. Following collection, the reusable electrical and electronic equipment are sent for refursbishing or reuse, if not these are recycled at the recycling facilities. Thereafter the recycled material can be used for the manufacturing of new products.

Dismantling: E-waste dismantling is a crucial step in the recycling process where electronic devices are taken apart to recover valuable components and materials for reuse or recycling. Dismantling of e-waste is done either manually or mechanically. This process involves skilled labour and specialized equipment to safely disassemble electronic items such as computers, smartphones, and televisions. The process includes the separation of hazardous and non-hazardous material from the e-waste as of the materials used in electronic devices are hazardous and cannot be dismantled further. The components such as Poly Chlorinated Biphenyl (PCBs) are recoverable from the e-waste and they are sent to Treatment, Storage, and Disposal Facilities (TSDFs) for further processing. Dismantling allows for the extraction of valuable metals like aluminium and copper, as well as other reusable components such as circuit boards and batteries.

Both types of dismantling processes, be it manual dismantling or mechanised dismantling, are popular among the e-waste management dealers in India. In India, a “dismantler” refers to an individual or organization involved in disassembling used electrical and electronic equipment into their constituent parts, possessing authorization from the respective State Pollution Control Board or Pollution Control Committee in accordance with the directives outlined by the Central Pollution Control Board.

Shredding, Sorting, and Separation: Segregation, shredding, and sorting are crucial processes in the management of electronic waste (e-waste) emanating from discarded electronic devices. These processes are essential for effective recycling and proper disposal of e-waste, aiming to mitigate environmental pollution and health risks associated with improper handling of electronic waste. Segregation involves the initial sorting of e-waste into different categories based on their type, material composition, and potential for recycling. This step helps in identifying components that can be reused, recycled, or disposed of separately. Segregation typically separates electronic devices such as computers, mobile phones, televisions, and other gadgets into distinct groups for further processing.

Shredding is the mechanical process of breaking down electronic devices into smaller pieces or fragments. This step is essential for several reasons:

- Data Security: Shredding ensures that sensitive data stored on electronic devices is irreversibly destroyed, preventing unauthorized access or data breaches.

- Volume Reduction: Breaking down e-waste into smaller pieces reduces its volume, making transportation and storage more manageable.

- Material Recovery: Shredding facilitates the extraction of valuable materials such as metals, plastics, and glass from electronic devices, which can be recycled and reused in various industries.

Sorting involves further categorization of shredded e-waste materials based on their composition and recyclability. Different types of materials, such as metals, plastics, glass, and hazardous components, are separated to optimize the recycling process. Advanced sorting technologies, including magnetic separators, eddy current separators, and optical sorting systems, are employed to efficiently separate and recover valuable materials from shredded e-waste.

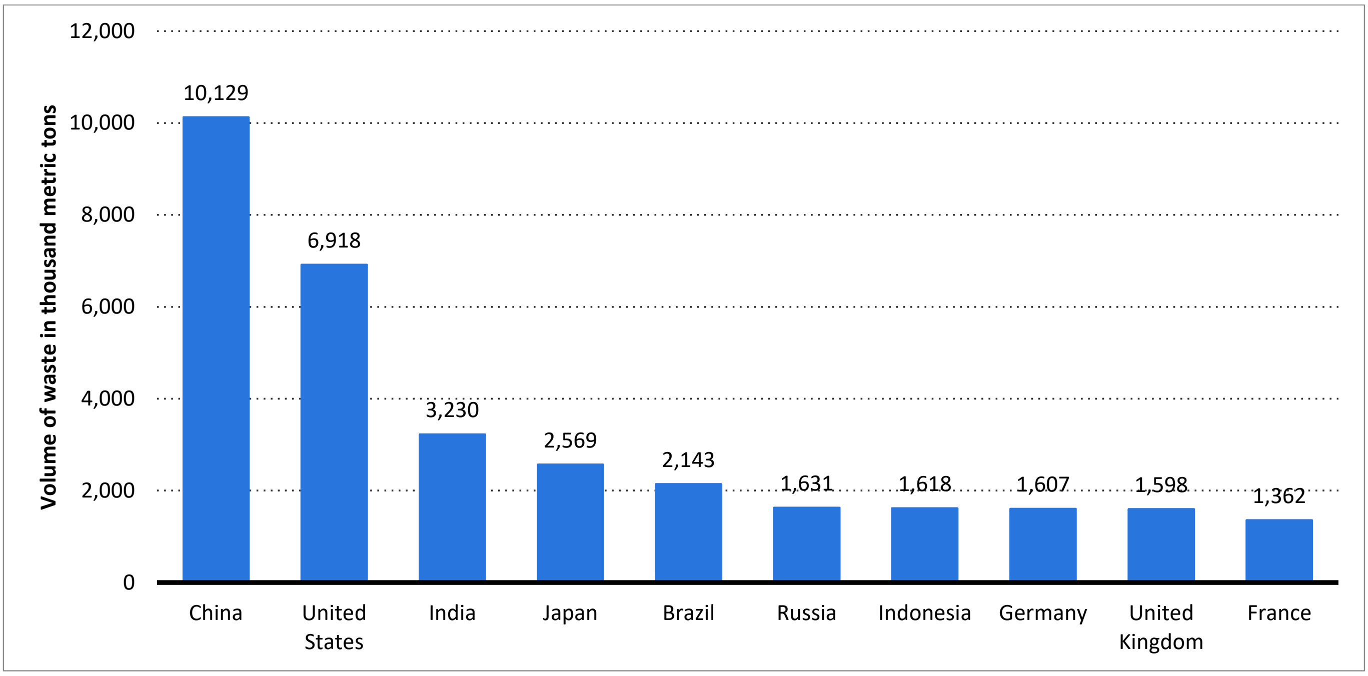
Overall, segregation, shredding, and sorting are integral steps in the e-waste management process, contributing to resource conservation, environmental protection, and sustainable development. Proper implementation of these processes ensures the safe and responsible handling of electronic waste, promoting a circular economy where valuable materials are recovered and reused, minimizing the negative impacts of e-waste on human health and the environment.

Recycling and Recovery: Generally, the composition of e-waste has been divided into several categories, as it contains different types of materials including hazardous and non-hazardous. The category of e-waste component includes usable metals such as iron, steel, and others whereas it also contains nonferrous metals like copper, aluminium, etc. E-waste also includes glass screens, plastic waste, and some other useful electronic components. The e-waste recycling plant operates effectively as it processes the electronic scrap while retaining the properties of many precious metals and minerals.

4. Global E-waste Supply Chain Dynamics

Globally, the unprecedented demand for electrical and electronic equipment (EEE) among consumers coupled with the proliferating discarding and replacement rate of EEE has resulted in the generation of e-waste in mass. Additionally, global e-waste has been massively generated by some of the leading economies such as the US, China, India, and others. These nations have saturated markets for electrical and electronic equipment. Exporting e-waste to developing countries, where regulations may be lax and labour costs lower, has been a common practice for some countries, leading to environmental and health hazards due to informal recycling methods lacking safety measures. Illegal cross-border exports of e-waste from developed countries to emerging economies also pose challenges in e-waste management (Evans et al., 2023). In response to these concerns, many countries are increasingly recognizing the importance of implementing effective e-waste management strategies, including recycling, proper disposal, and promoting sustainable product design to reduce the environmental impact of electronic devices. The increased cumulation of e-waste and its associated toxicity have been causing environmental concerns worldwide. As a consequence, the prior assessment and future predictions for the generation of e-waste are critical. Furthermore, the results of the preliminary assessment would help in formulating the strategies required for the recycling of e-waste, thereby encouraging the circular economy and decreasing landfill stress. Figure 3 depicts the global e-waste generation by countries.

Figure 3: Global E-waste Generation 2019, By Major Countries

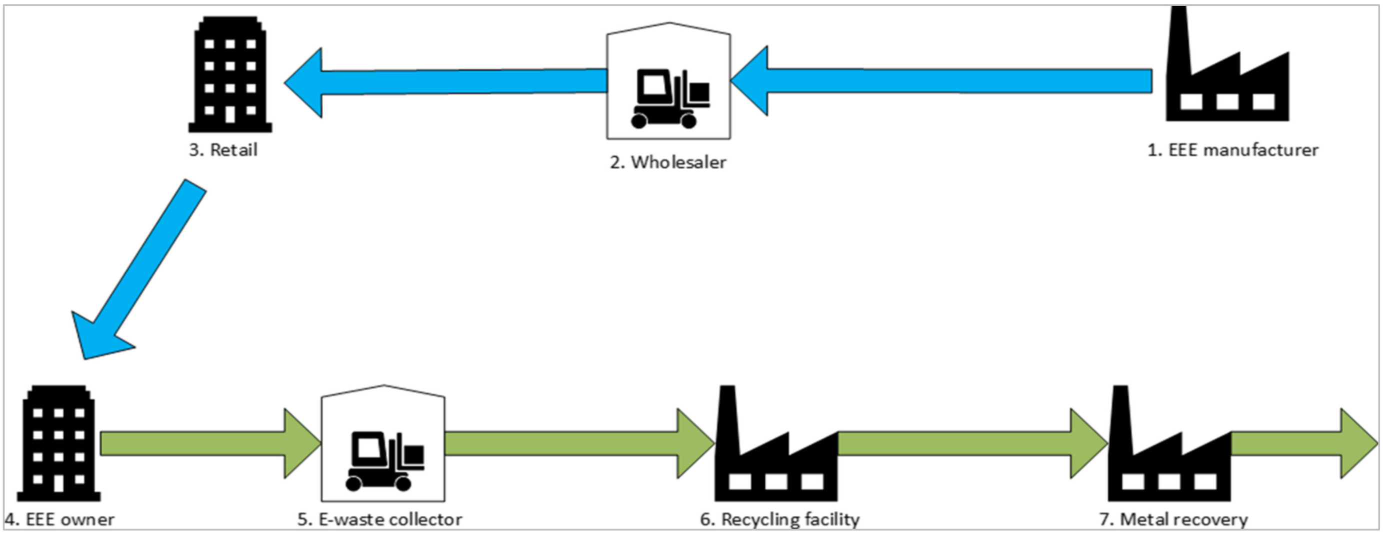


Source: Statista Market Insights, 2024

Similar to India's e-waste management scenario, global e-waste management is also highly informal, owing to the significant involvement of informal recyclers majorly in the regions like Middle East, Africa, Asia Pacific, etc. Around 53.6 million tonnes of e-waste were generated globally in 2019 but approximately 17.4% of the total amount was formally collected and recycled (Forti et al, 2020). Nevertheless, regions such as Europe and North America are way ahead in formalizing the supply chain of e-waste management to leverage their e-waste recycling capabilities. This is due to their stringent policy frameworks and norms associated with e-waste management. For instance, there are two directives for e-waste management in the European Union such as the Waste Electronic and Electrical Equipment (WEEE) directive and the Restriction of Hazardous Substances (RoHS) (Doan et al., 2019). In parallel, the objective of the WEEE directive has been to enhance the collection rate of e-waste, whereas the RoHS directive aims to reduce the usage of harmful materials such as mercury, cadmium, lead, etc. in electronic devices.

In the outlined WEEE directive, the role of each actor involved in the supply chain of e-waste is clearly stated such as for producers, EEE distributors, dismantlers, separate collectors for WEEE, recyclers, etc. In addition, the WEEE directive of the EU's e-waste management also includes measures to prohibit the illegal exports of e-waste. For instance, in 2021, the European Union achieved a collection rate of 46.2% for WEEE (Waste Electrical and Electronic Equipment), calculated as the weight of collected WEEE compared to the average weight of electronic equipment placed on the market during the three preceding years i.e 2018-2020 (Eurostat, 2023). The European WEEE Directive mandates that manufacturers of Electrical and Electronic Equipment (EEE) affix their products with a WEEE symbol, signifying the obligation to collect and transport the equipment to designated facilities for recovery and recycling (Doan et al., 2019). Additionally, the directive necessitates that all EEE manufacturers furnish information regarding the procedures for preparing products for reuse, maintenance, upgradation, refurbishment, and recycling. The WEEE Derivative also includes the role of Producer Responsibility Organizations (PROs), wherein the directive allows the producers to delegate their e-waste handling to the PROs. Figure 4 below represents the general supply chain associated with e-waste management in the EU.

Figure 4: Forward Supply Chain of EEE (blue) and the Reverse Supply Chain of E-waste (green)



Source: Andersen et al., 2023

The formal e-waste handling supply chain in the US includes several stages to ensure a sustainable approach of the electronics lifecycle. Effectively managing electronics involves minimizing materials usage, promoting reuse, refurbishment, and prolonging product lifespan, alongside efficient recycling practices. Such strategies are crucial for curbing waste on both local and global scales. Analysing a product's complete life cycle can unveil opportunities for lessening environmental footprints, conserving resources, and cutting expenses.

Figure 5 below illustrates each phase of the life cycle of electronic devices. Some electronics firms have embraced innovative strategies to ensure sustainable sourcing, design, and management of their products throughout their life cycles. These companies have been recognized through awards from the EPA's Sustainable Materials Management (SMM) Electronics Challenge for their commendable practices.

Figure 5: The US E-waste Handling Supply Chain

Source: US-EPA ,2020

In the United States, 25 states along with the District of Columbia have instituted laws to establish comprehensive e-waste recycling programs. Additionally, certain states have introduced legislation banning the landfilling and incineration of e-waste while mandating separate treatment methods. The Extended Producer Responsibility (EPR) principle stands as the predominant policy approach, adopted by most states. Typically, state policies on EPR align with international practices, although California notably implements an advance recycling fee system. The lack of a consistent federal law has resulted in a varied regulatory landscape across different states, presenting compliance challenges for producers regarding Extended Producer Responsibility (EPR). A considerable portion of used Electrical and Electronic Equipment (EEE) is either stored in households or disposed of in landfills and incinerators. Another issue pertains to the export of collected e-waste from the United States to low-income countries with inexpensive labour, where informal dismantling poses health hazards due to exposure to toxic materials. However, recycling standards and certifications such as R2 (Responsible Recycling) and e-Stewards have been established to mitigate improper handling and illegal export of e-waste containing hazardous chemicals (The Global E-waste Monitor, 2024).

Apart from the US and EU, China has been also one of the largest e-waste generators globally. As China remains a center stage for the electronics supply chain globally, manufacturing nearly 70% of the global mobile phones. Regarding the uprising e-waste in China, the Chinese government announced the circular economy-driven targets of e-waste recycling up to 50% by 2025 and to include 20% of recycled materials in the new products. Being one of the largest e-waste producers, there has been a noticeable involvement of informal players in the entire supply chain of e-waste management in China. Numerous informal clusters for e-waste processing have emerged in China. Notably, Guiyu in China and the Agbogbloshie community of Accra in Ghana stand out as the two largest informal e-waste recycling centres globally, attracting millions of tons of e-waste from developed nations (Wang et al., 2020). China hosts a significant informal sector specializing in the import, trade, collection, and recycling of e-waste. More recently, China has surpassed the U.S. to become the world's largest e-waste-generating nation. Consequently, a substantial portion of the escalating domestic e-waste is redirected to Guiyu for processing. China recently imposed tight regulations for e-waste, otherwise, China has been one of the largest e-waste importers from the developed nations. Nonetheless, to strengthen the formal channel of e-waste recycling in China, the Chinese government announced the subsidy policy framework in 2021 for waste electrical and electronic equipment including television sets, computers, washing machines, electric refrigerators, and air conditioners.

China E-waste Import Restrictions:

In 2018, China announced the ban on the import of all 24 grades of solid waste along with e-waste. Further, in 2020, the country also declared the ban on the imports of all types of solid waste. Lack of e-waste processing capabilities coupled with the growing e-waste accumulation in the country had led the government to announce the e-waste import restrictions.

This move was part of the country's broader efforts to address environmental concerns and promote sustainable waste management practices. China had been a major destination for the world's electronic waste, but concerns over pollution and health hazards prompted the government to impose stricter regulations, including outright bans on certain types of e-waste imports.

The ban on e-waste imports has significant implications for global waste management practices and has prompted other countries to reassess their own approaches to handling electronic waste. Some nations have increased domestic recycling efforts, while others have sought alternative export destinations for their e-waste. Following China's decision to limit waste imports, countries in Southeast Asia like Vietnam, Malaysia, and the Philippines experienced a comparable increase in the influx of plastic waste and electronic waste. Consequently, these nations implemented their own import bans or restrictions in response to the heightened environmental concerns (Sasaki, 2020).

5. Recycling Technologies

E-waste recycling technologies encompass various methods for recovering valuable materials from discarded electronic devices. These methods can be broadly categorized into two main approaches: hydrometallurgy and pyrometallurgy. Additionally, there are other emerging and complementary techniques aimed at improving efficiency and sustainability in e-waste recycling. Below are explanations of these types of e-waste recycling technologies:

- Hydrometallurgy: Hydrometallurgy involves the use of aqueous solutions (usually acids or alkaline solutions) to extract metals from e-waste materials. In hydrometallurgical processes, crushed or shredded e-waste is subjected to leaching, where metals are dissolved into the solution. The solution containing metal ions is then purified and subjected to further processing steps such as precipitation, solvent extraction, or electroplating to isolate and recover specific metals (Saleem et al., 2023).

- Pyrometallurgy: Pyrometallurgy involves the use of high temperatures to extract metals from e-waste materials. In pyrometallurgical processes, shredded e-waste is subjected to high temperatures in furnaces or smelters. During this process, metals are melted and separated from other components of the e-waste based on their physical properties such as melting points. The molten metals are then collected and further refined to obtain high-purity materials (Evans et al., 2023).

- Biometallurgy: It also known as bioleaching or biohydrometallurgy, involves the use of microorganisms to extract metals from e-waste materials. In this process, specially selected microorganisms are used to catalyze the leaching of metals from e-waste. These microorganisms produce organic acids or enzymes that dissolve metals into solution. The metal-rich solution is then processed further to recover the metals (Evans et al., 2023).

- Electrochemical Recycling: This process involves using electrochemical processes to recover metals from e-waste. The e-waste materials are dissolved or leached in an electrolyte solution, and metals are selectively deposited onto electrodes through electroplating or electrowinning processes. The deposited metals can then be recovered and purified (Evans et al., 2023).

- Plasma Technology: Plasma technology for e-waste recycling is an innovative approach that involves using high-temperature plasma to break down and separate electronic waste materials into their constituent components. Plasma, often referred to as the fourth state of matter, is an ionized gas consisting of charged particles. In e-waste recycling, plasma technology offers several advantages such as high efficiency, selective metal recovery, etc (Sanito et al., 2021).

These e-waste recycling technologies play a crucial role in recovering valuable resources from electronic devices, reducing environmental pollution, and promoting sustainable practices in waste management. The choice of technology depends on factors such as the composition of e-waste materials, desired metal recovery rates, environmental considerations, and economic viability.

6. India State-Specific Case Studies

In the realm of electronic waste (e-waste) management, India presents a unique and complex landscape marked by a multitude of challenges and opportunities. With its burgeoning population, rapid urbanization, and an escalating consumer electronics market, India stands at the forefront of the global e-waste dilemma. Moreover, there is an observable trend seen in the e-waste generation rate across various states of India. To understand this intricate dynamic, examining India-specific case studies becomes imperative. Various critical aspects were considered when selecting the study area. These included understanding the industrial and Electrical Vehicle (EV) ecosystem, logistics, green technologies, the status of EV infrastructure, hazardous waste generation and recycling capacities and the availability of a skilled workforce.

The selection of sites to identify the critical agents (collectors, dismantlers, refurbishers, recyclers, etc.) involved in the recycling supply chain of e-waste is a crucial step for the analysis process. This would further help in estimating the contribution of the agents involved in the supply chain from the base of the pyramid (involved in collection) to the top (involved in material recovery) in terms of value addition, employment, and other factors. Preliminary analysis done by the team used the following criteria to narrow down sample states for further engagement and research investigation:

a) Understanding the Industrial and Electrical Vehicle (EV) ecosystem: Industrial Electric vehicle (EV) policies can significantly impact recycling within a state.

b) Logistics: Logistics impact the recycling operations by optimizing collection, transportation, processing methods and distribution of recyclable materials. Recycling logistics contributes to the overall success and viability of recycling as a sustainable practice.

c) Green technologies: The renewable energy sector often relies on materials like aluminium, copper etc for infrastructure. This increased demand for materials can drive the recycling industry as it encourages the collection and recycling of these materials to meet the renewable energy sector's needs.

d) Status of EV infrastructure: For the circular economy model, recycling is a key component which emphasizes minimizing waste and extending the life of products. In the context of EVs, this means reusing and recycling components like batteries, electric motors, and even entire vehicles to reduce waste and resource consumption.

e) Hazardous waste generation and recycling capacities: The generation of hazardous waste is influenced by a range of factors, including industrial processes, population density, and economic activities. Recycling capacities, on the other hand, depend on the availability of technology, infrastructure, and regulatory frameworks that promote recycling.

f) Availability of workforce: Employment opportunities in the recycling sector can vary widely and encompass a range of roles, from collection and sorting to management and research.

The main objective of the study is to delve into the Indian states to understand the actors involved in the circularity of e-waste management at the state level. Based on the above-mentioned criteria the following states were found suitable for the study at the early phase: Tamil Nadu, Maharashtra, Gujarat, Karnataka, Uttar Pradesh, and Andhra Pradesh. Later, on critically analysing the mentioned factors. The study seeps into Maharashtra and Karnataka states to delve into the diverse facets of e-waste management within the Indian context. Through a comprehensive exploration within these states, we attempted to unravel the complexities inherent in India's journey towards sustainable e-waste management, shedding light on both successes and shortcomings in the pursuit of a greener, more responsible future. Indeed, both the selected states are Tier one states in India. Tier one states, commonly denoting the most progressed and economically prosperous areas, frequently produce significant volumes of e-waste as a result of heightened levels of industrialization, urbanization, and consumption habits.

To conduct the fieldwork, both stratified and snowballing sampling were employed. While engaging with government agencies, stratified sampling was utilized meticulously to gather essential information. A structured set of questionnaires was presented, and a majority of government officials readily cooperated in furnishing their responses. Stratified sampling was also conducted as part of the team's dialogue with previously identified large recycling companies in each state. Snowballing technique, on the other hand, was also applied in the interactions with informal recyclers and dismantlers.

Exploring these case studies on e-waste management in India sheds light on the diverse approaches and challenges faced in tackling this pressing environmental issue. Below are the state-specific case studies:

Maharashtra

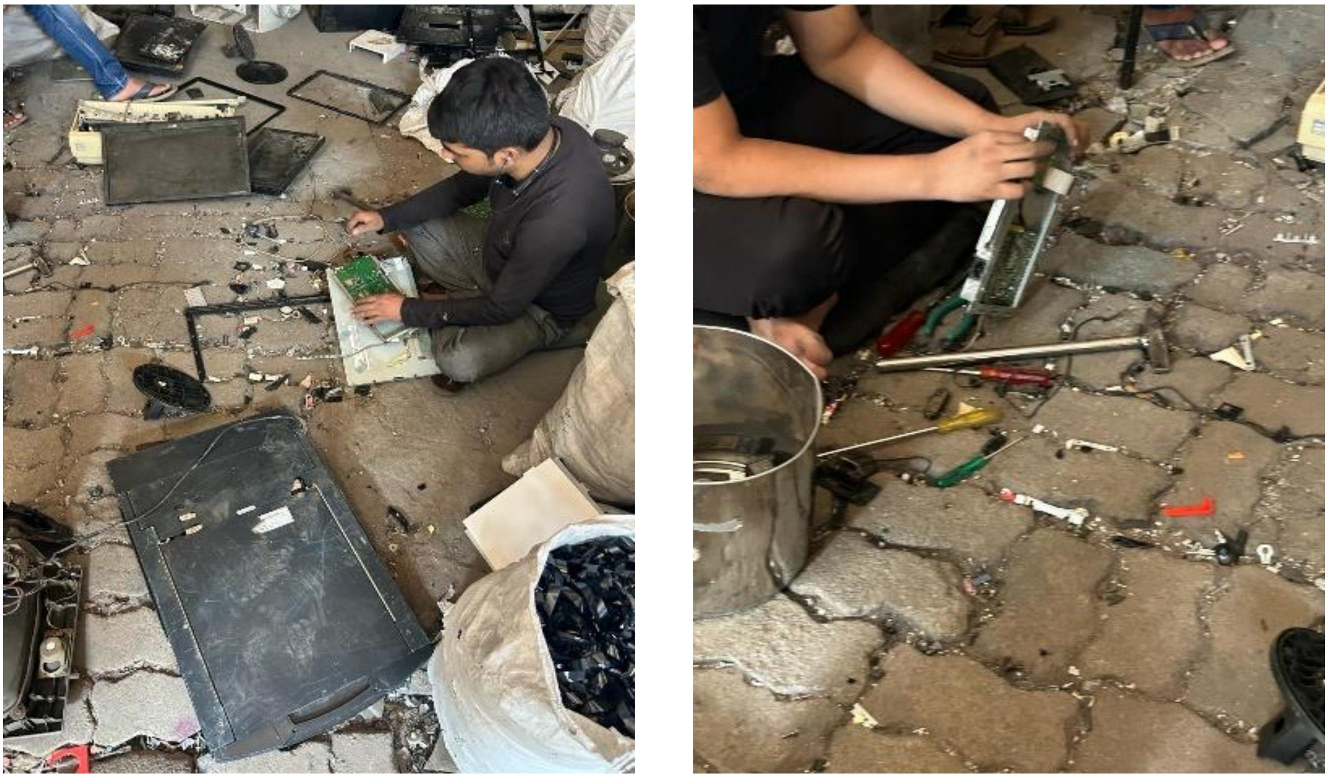
Maharashtra, an Indian state that is home to prosperous cities like Mumbai and Pune, is a microcosm of the nation's rapid economic and technical progress. Maharashtra is leading India's electronic revolution with a growing population and booming economy, but managing e-waste is becoming more and more of a challenge. The state-generated e-waste, collected and processed, during FY 2021-22 was 18559.30 Tonnes (PIB, 2023). In this case study, the complex e-waste management landscape of Maharashtra was explored. Both formal and informal recyclers were visited to understand the on-ground e-waste management situation.

Consultations were also held with the government as well as non-government stakeholders. The government bodies, such as the Maharashtra Pollution Control Board (MPCB) and the Transport Department office were visited to gather insights into current e-waste generation statistics in the state. Moreover, discussions revealed that currently there are no preferred recycling technologies and the choice depends on individual industry facilities. Regarding EV policy implementation, officers stated that industry players began submitting EPR on time as directedWith the EPR schemata in their mind, the board is looking forward to formalise this informal sector.

There were extensive engagements with key players in the e-waste recycling sector in Maharashtra, including category II recyclers. They are actively participating in recycling with sufficient capacity. In addition, the companies mostly handle everything, including refurbishing, segregation, dismantling, and recycling of all types of e-waste. Furthermore, a comprehensive land area concerning the capacity of the plant is established for the facility and most of the recycling facilities are functioning as per the guidelines of CPCB. Surveys showed that most recycling plants are located on the outskirts of the main city. However, due to organisation rules and security reasons, visiting the premises of the recycling facility was not allowed.

One of the recyclers provided some valuable insights on the investment. It was told that a total investment of INR 2 to 3 Crore is required for the establishment of the e-waste recycling plant. It was elucidated that a land area of 10,000 sq ft.is required to handle the capacity of the 500 MT plant. Furthermore, a total land area of approximately 15,000 square feet is required to effectively manage an annual influx of nearly 1,000 metric tons of electronic waste, with around 800 metric tons handled on a regular basis. Interestingly, they are developing a battery recycling unit, and it would cost around INR 2 Crore. The informal recycling network within the state forms an extensive and intricately interconnected system. An anonymous source disclosed that the e-waste recycling sector comprises 10% formal and 90% informal workforce. Upon visiting some of the informal recyclers, it was observed that within the recycling area, they initially segregate all types of waste, followed by the extraction of valuable metals such as copper, aluminium, etc. Much of the operational work is carried out manually by either skilled or unskilled labour. In the later stages, to recover precious metals from the separated components of e-waste during the dismantling process. Figure 6 depicts one of the informal workers dismantling the collected e-waste in one of the recycling facilities in Mumbai.

Figure 6: Dismantling of e-waste



Source: Authors' compilation

Currently, in an informal recycling facility, the number of employees may range from at least 2-3 to around 20 employees depending on the working capacity at the facility. In addition, it also depends on the inflow of e-waste being collected from within the state as well as from pan India based on the connection of the individual. Interestingly an unidentified informant hinted that it's also plausible that they either do not receive any e-waste or occasionally receive a substantial volume. In the informal sector, the functioning of the site is entirely dependent on the availability of e-waste. There can be times when a large amount of waste is available, while at other times, there might not be a single unit of waste available. Upon further investigation, it was observed that in the informal sector, everything depends on contacts and trust in the dealer.

In Mumbai, informal e-waste recyclers, dismantlers, and refurbishers are based in different regions. However, while using the snowball survey technique, some key areas for e-waste handling are identified for the state. The prevalence of e-waste in the state is elevated due to the large population, numerous shops, hospitals, malls, educational institutions, and small industrial units in the city. Additionally, the presence of numerous software and IT industrial units contributes to the generation of e-waste in the city. It was identified that the majorly e-waste recyclers/dismantlers are situated in areas such as Saki Naka, Jogeshwari West, Andheri East, Dharavi, Malad, and Govandi. These regions are known for hosting informal recycling operations due to factors such as accessibility, affordability of land, and proximity to sources of e-waste generation.

Four circular economy parks will be established in Nagpur, Ratnagiri, near Pune, and Aurangabad. The recycling of scrap and other wastes will be the main emphasis of these circular economy parks . In addition, Maharashtra Industrial Development Corporation (MIDC) occupied land banks for the proposed parks. The Material Recycling Association of India (MRAI) serves as a strategic collaborator with the government, providing expertise in formulating policies and facilitating their effective implementation.

Karnataka

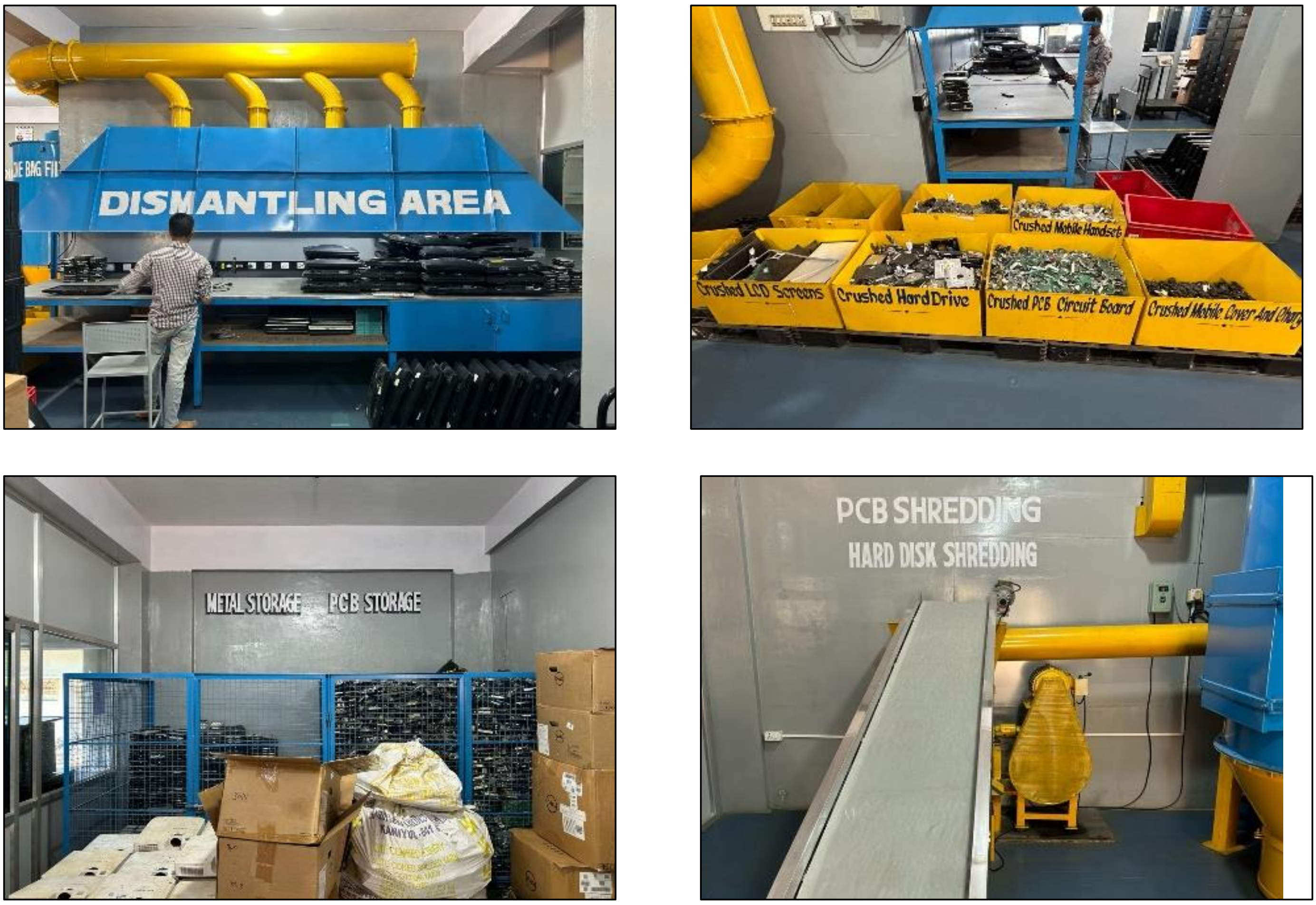
Karnataka is one of the major states with a maximum number of Information Technology (IT) and Information Technology Enabled Services (ITeS) units in the country. The state-generated e-waste, collected and processed, during FY 2021-22 was 39150.63 tonnes (PIB, 2023). With such a high collection and processing rate of e-waste, this state is crucial to study from the aspect of management of e-waste in the country.

To understand the state scenario government entities have been visited. It was perceived that the e-waste recycling sector has been majorly informal, around 90% to 95%. Moreover, a high volume of e-waste is produced at present but there is a lack of associated data regarding the quantum of e-waste generated, One of the major reasons is also the lack of a collection system for e-waste from industrial and commercial establishments due to which waste accumulates with the generators. Perhaps, over time with stringent rules, things might shape up. Furthermore, concerning the battery waste in Karnataka, accurate data for lithium and cobalt recycled or collected from the e-waste or battery waste is not present. To overcome all these data issues, proper consent for operation as well as detailed documentation is required. An experienced person working in the e-waste recycling sector informed that land of around 300 m2 is required to refurbish around 100 tons of e-waste and nearly 500 m2 is needed to refurbish about 150 tons of e-waste per month. In Karnataka, the Mysore area also needs attention for the development of an e-waste recycling zone, as the area also generates a significant amount of e-waste.

Interestingly, the formal recyclers in the Bangalore region are operating efficiently, adhering to the CPCB guidelines for e-waste recycling. The major functioning of recyclers is involved in the collection, transportation, and recycling of Waste Electrical and Electronic Equipment (WEEE), battery waste, metal waste and plastic waste in environmentally sound and safe facilities. The collected e-waste is sourced locally from adjacent districts as well as from interconnected states such as Maharashtra and the northern part of India.

It was observed that the e-waste recyclers of the state are strictly operating as per the guidelines of KSPCB. One of the recyclers mentioned that recycled waste is primarily recovered for the extraction of precious metals, which are obtained in nearly pure form. The process involves applying basic technologies at the initial stages, such as conventional dismantling, followed by recycling through methods like wire recycling, electronic hammers, and mechanized shredders. Figure 7 illustrates the different areas within a visited recycling facility where various steps involved in recycling are performed.

Figure 7: E-waste recycling plant



Source: Authors' compilation

Regarding the technological aspect of recycling e-waste, one of the anonymous entities from the recycling plant visited explained the process which is being adopted by most of the recyclers. The collected waste is being manually segregated and dismantled through semi-automatic processes. After that, the material is moved to the furnace, through which different materials are obtained based on their chemical characteristics. In the end, the leftover waste is converted to powder in a pressing machine. Moreover, skilled labour is required to perform these steps and their number can vary based on the capacity of the recycling plant. However, unskilled labour is also engaged in dismantling in the facility. The collected hazardous waste is then transported to hazardous waste treatment facility. The investment involved in setting up the plant may vary from INR 50 lakh to 1 crore.

Summary results from the survey

In conclusion, a total of 24 interviews were undertaken in Karnataka, while 35 interviews were conducted in Maharashtra for the analysis of the two states. One integral observation regarding the movement of e-waste was made from the surveys. The collected e-waste sent to various hotspots of the country are majorly being sent to three major locations in Delhi including Shastri Park, Mustafabad, and Seelampur. Apart from these locations, in Uttar Pradesh, there are also some of the hotspots for e-waste like Meerut, Hapur, and Moradabad. Many women workers are involved in the separation process of metals from different components in these respective areas of the states. These informal recyclers use traditional crushing techniques for metal. In Bangalore, Gori Palya has been considered an informal hotspot for e-waste recycling.

One of the important findings may include the impact of COVID-19 on the recycling of e-waste. One informal recycler informed us that before COVID-19, he had a turnover of over INR 1 crore, but currently, business is very slow. The findings from the various visits have indicated that although other higher-order recycling operations might be centered in the formal sector, the collection, segregation, and first dismantling of non-hazardous e-waste fractions is handled by the informal sector.

Some of the issues and challenges in the e-waste management are:

- E-waste should be looked at with a social concern. Producers of e-waste are looking at revenue-generation aspects instead of disposal in compliance with environmental regulations.

- The involvement of the informal sector is still increasing in the collection of e-waste from consumers. Certain recyclers are sharing their certificates with the owners of informal businesses for collecting electronic waste on their behalf.

- SEZ plays a major role in e-waste recycling, where a recycler, although it has an agreement with the producer, still faces SEZ authorities asking for three quotes for creating more revenue for the government which is forfeiting the real agenda of recycling. Formal recycling can contribute revenue to the government directly through taxes and indirectly through the broader way of circular economy as well. Chances are more that this kind of material would go into the grey market if proper compliance is not followed.

- The recycler price is based on the recovery of the metal and non-metal raw material commodities after recycling. However, the producers are expecting more than the market value which may pave the way again for the grey market. Additionally, e-waste rules do not particularize any collection targets for producers, leading to a lack of oversight on the movement of e-waste. Presently, producers are only obligated to meet recycling targets, not collection goals.

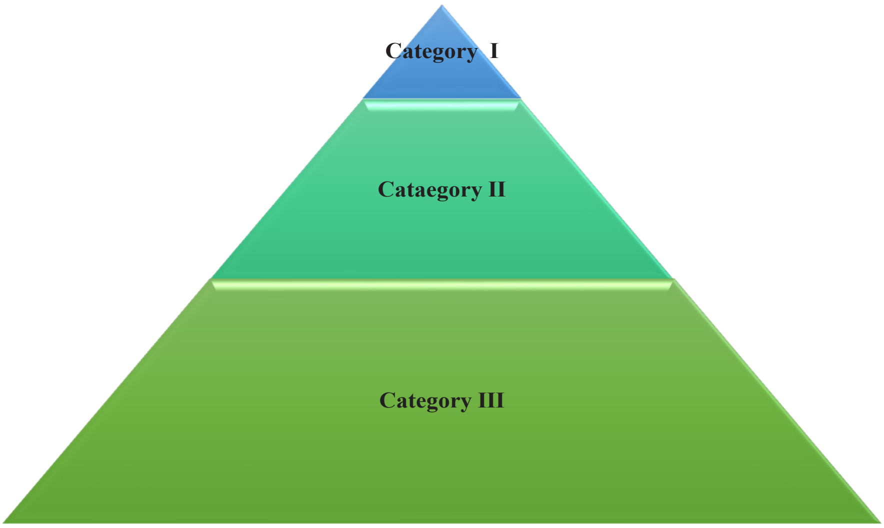
- Material being collected from other states where the recycler does not have a facility are being sold locally to the informal sector. This may cause a revenue loss to the state government as well as it creates environmental damage by improper handling.

- E-waste should not be disbursed by calling of tenders. This could also create unethical competition among the formal and informal sectors. Strict instructions may be provided to all government departments to implement the producers' request to dispose the e-waste through authorized recyclers only and not through tenders to any unknown players. Even if a tender is called, only authorized recyclers should be allowed to take part in the tender. In that way, e-waste generator may realize a good value of the waste from the recyclers and also ensure that the waste is recycled at the authorized facility.

- To formalize the informal e-waste sector, the government is required to provide land to the recyclers, and technologies for recycling as well as take up the plan for incentivizing the overall recycling of e-waste.

- The 18% GST on ferrous waste and scrap has also been causing a challenge to the e-waste sector.

Figure 8: Categories of state capacities for recycling/dismantling e-waste



Source Author's Compilation

Nature of e-waste recycling plants in India

To analyse the state capacities of recycling/ dismantling of e-waste based on the authorization issued by SPCBs/PCCs under E-Waste (Management) Rules, 2016 (As of 08-06-2023), the Figure 8 below is classified into 3 categories (Table in annexure). The table categorizes states based on their capacities. The table presents data on the capacity of e-waste recycling plants categorized by their annual processing capacity in metric tons (MTA) and the number of recycling plants falling within each capacity range. The majority of recycling plants, totalling 470, have a capacity between 1000 to 5000 (Category III) metric tons annually. A smaller number, 89 plants, have a capacity ranging from 5000 to 25000 (Category II) metric tons per year. Furthermore, there are 10 recycling plants with significantly larger capacities, falling within the range of 25001 to 150000 (Category I) metric tons annually. It can be observed that the number of Category I plants is less compared to the Category II and Category III capacity plants in India. Overall, the table provides insights into the distribution of e-waste recycling plants based on their processing capacities, highlighting both the prevalence of smaller-scale facilities and the presence of a few larger-capacity plants in the industry. Table 2 given below describes the number of recycling/dismantling plants in India as per the capacity in MTA.

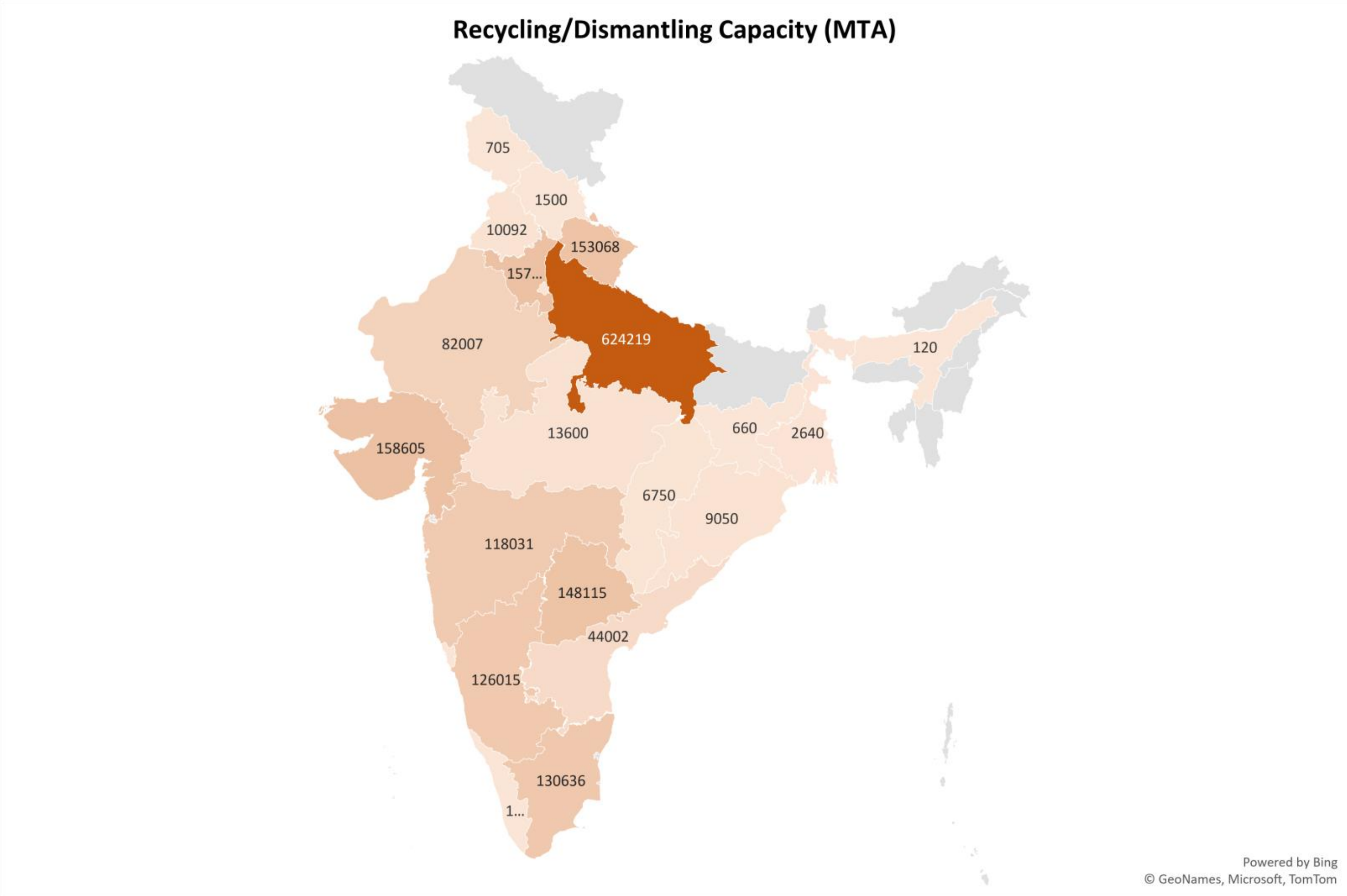
Table 2: Recycling/dismantling plants in India

Category	Capacity (MTA)	Recycling Plants
Category I	More than 25001	10
Category II	5001-25000	89
Category III	Less than 5000	470

Source: PIB,2022

The map below depicts the state-wise capacity for e-waste recyclers/dismantlers in India, Figure 9. As per the data, Uttar Pradesh has the highest capacity to treat e-waste across the country. However, e-waste is generated in higher numbers by Maharashtra and Karnataka as per CPCB. The survey analysis also indicates that the majority of the collected e-waste is transported to regions in Uttar Pradesh and Delhi.

Figure 9: State-wise recycling/dismantling capacity (MTA)



Source: Authors' Compilation

7. Case Studies Focused on Indian States: Integrating Empirical Analysis

The study attempts to provide a detailed cost analysis to ascertain the economic viability of e-management systems. In the analysis, the technologies for e-waste management were considered which will be used to build Sampada 2.0. The cost of treating e-waste plays a crucial role across electronic waste management systems. The management of e-waste predominantly relies on two distinct technological approaches: pyrometallurgy and hydrometallurgy. Yet, empirical analysis underscores the prevalent utilization of pyrometallurgy in the extraction of precious metals from electronic waste.

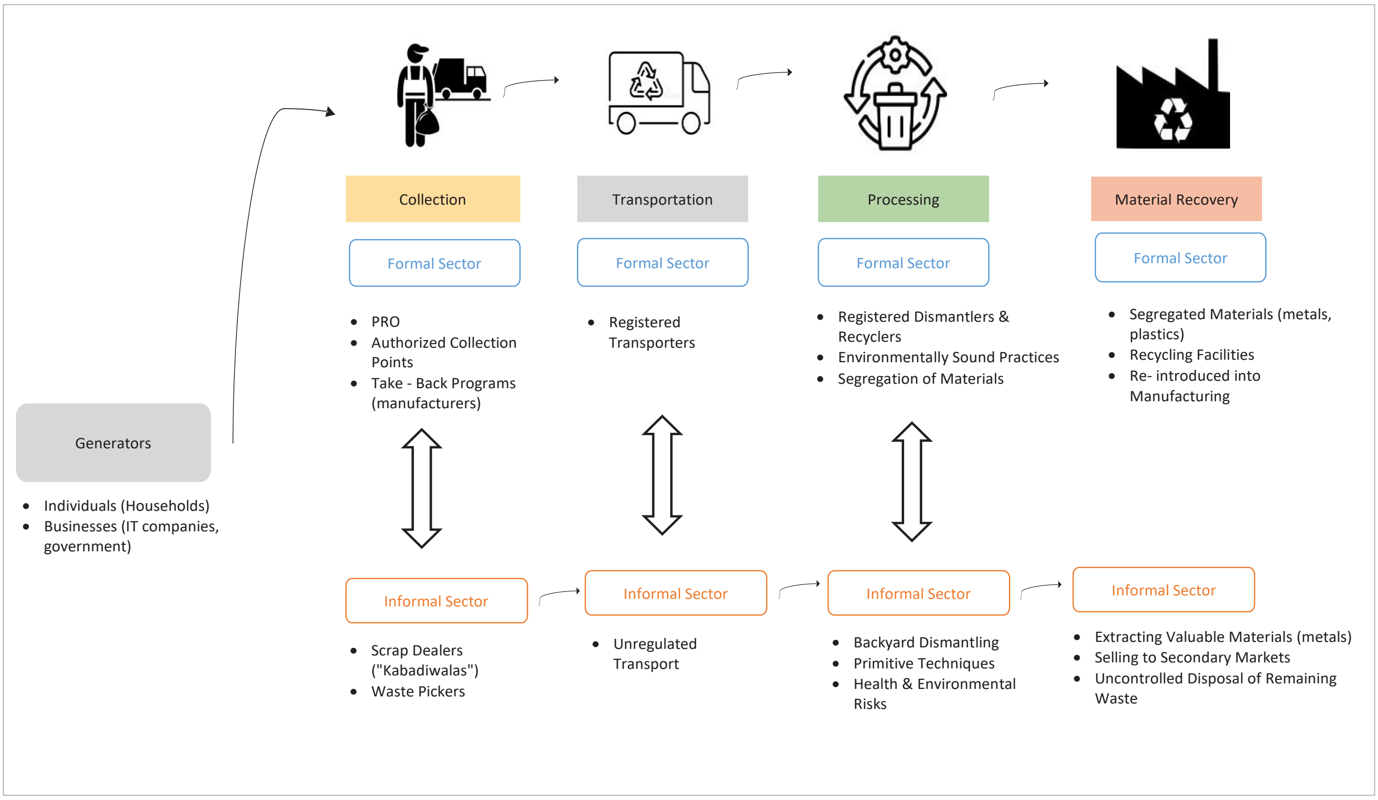
During our analysis, one of the anonymous entities enlightened us with critical details on cost analysis. For instance, the laptop is purchased from the e-waste provider at the rate between INR 2,500 to INR 3,500, then the recycled metals are sold to the downstream vendors at the price of about INR 35 per kg, and plastics at the rate of INR 3 per kg. For dismantled glass, the company itself pays some amount to the downstream partners. The company has a license for refurbishment and non-repairable devices are dismantled and segregated. In addition, setting up a pyrometallurgy plant with a treatment capacity of 1080 MTA would require an investment of around INR 5 crore.

The role of e-waste recycling plant volume and treatment cost is pivotal in shaping sustainable waste management practices. The volume of e-waste processed by recycling plants directly correlates with their capacity to alleviate environmental burdens associated with electronic waste disposal. Furthermore, the treatment cost associated with these facilities influences the feasibility and efficiency of e-waste recycling initiatives. High treatment costs may deter investment in recycling infrastructure, hindering progress toward sustainable waste management goals. Therefore, striking a balance between plant volume and treatment cost is imperative to foster the widespread adoption of e-waste recycling practices, ensuring the effective utilization of resources while mitigating environmental impacts.

As discussed above, the e-waste supply chain involves a variety of actors playing different roles at various stages of the process. Figure 10 describes the different sectors of the e-waste supply chain in India. It shows two main paths that e-waste can take: formal and informal. The diagram shows that the informal sector handles a much larger portion of e-waste in India than the formal sector. This is a problem because it can lead to pollution and health hazards. However, it can be inferred that these two sectors largely work hand in hand and are interconnected in their operations. For a more sustainable system, there needs to be a stronger integration between the two sectors.

Through in-depth interactions with various actors in the selected states, a few key points emerged for consideration. Firstly, formalizing the chain would facilitate tracking activities across the sector. Secondly, training unskilled workers in the informal sector would enhance efficiency and productivity. Thirdly, formalizing the sector would increase transparency in the e-waste management ecosystem.

Figure 10: E-waste supply chain in India



Source: Authors' Construction

8. Incentive Mechanism for Actors involved in the supply chain

India's e-waste supply chain is a multifaceted ecosystem, encompassing various stages spanning from collection, transportation, dismantling, segregation, recycling, and recovery. The E-waste Management Rules 2022, recognized stakeholders as producers, dealers, refurbishers, consumers or bulk consumers, dismantlers, and recyclers except informal recyclers. As discussed in Section 2, the informal sector in India manages a significantly larger share of e-waste compared to the formal sector. A target-based Extended Producer Responsibility (EPR) has started showing positive results in formalising e-waste collection and material recovery but still, due to the dominance of the informal sector, the formal sector is facing intense competition and a severe lack of input feedstock (e-waste). Furthermore, the collected e-waste is facing disposal challenges because of inadequate recycling facilities.

In India, the informal sector currently serves as the mainstay for recycling and resource recovery. However, due to limited economic capital and technological access, the methods employed often rely on rudimentary practices, resulting in low efficiency and wastage of valuable resources. Moreover, the extraction processes utilised are hazardous to both human health and the environment. This issue is exacerbated by the lack of capacity development in the recycling sector, resulting in decreased efficiency in e-waste recycling and secondary raw material recovery. It is noted that the informal sector benefits from easier access to materials due to its extensive network. Besides this, informal sector is also able to offer a better value for the e-waste which incentivises the diversion of large quantity towards the informal sector.

Efficient and sustainable recycling systems involving various actors like producers, dealers recyclers etc can significantly impact e-waste recycling. Collaboration and coordination among these actors are crucial for India's success. Understanding the complex interplay among these actors is important to devise effective strategies that would address India's e-waste management challenge.

Policies when formulated and implemented well would encourage investments in recycling infrastructure, support research and development in recycling technologies, and promote public-private partnerships for recycling thereby creating an overall supportive ecosystem for recycling.

Designing the incentive mechanism

The inadequate recycling capacity within the formal recycling sector coupled with the e-waste leakage towards the informal sector is defeating the objectives of the E-waste Management Rules, 2022. The Production Linked Incentive (PLI) scheme is a government initiative which aims to bolster manufacturing in key sectors, attract investment, enhance global competitiveness, foster innovation, and generate employment. By incentivising production, the PLI scheme aims to strengthen India's industrial base and propel economic growth.

To encourage investments, innovation, and growth within the recycling sector, a Production Linked Incentive (PLI) scheme is the need of the hour. This would also foster a circular economy and domestic critical mineral supply chain within the country. The PLI scheme is to create a circular domestic supply of secondary materials and provide a stable supply of raw materials. The scheme proposed is to focus on both the formal and informal recyclers within the e-waste supply chain.

Firstly, the scheme is to incentivise the formal recyclers operating with near-global best practices. As per CPCB data on the list of registered e-waste recyclers, India has 569 recycling plants installed with a combined capacity of 1.78 million tonnes per annum. As discussed in Section 6, the recycling plants were categorised based on their annual processing capacities. Figure 8 indicates three categories. Category III are recycling plants with a capacity between 1000 to 5000 metric tonnes per annum. Category II are recycling plants with a capacity between 5001 to 25000 metric tonnes per annum. The top on the hierarchy are 10 plants with a recycling capacity between 25001 to 150000 per annum. Incentivising apex recyclers would encourage other recyclers to augment their recycling capacities and adhere to global best practices in the recycling sector.

Secondly, the scheme would support the informal sector availing indigenously developed technologies to recycle e-waste and strengthen the recovery of secondary materials.

To establish a more sustainable recycling system, there is a necessity for close collaboration and integration between the formal and informal sectors. Adding to the discussion from Section 5, transforming the informal sector would enable better tracking of activities, lead to skill development and also enhance transparency within the recycling sector. Informal e-waste collectors should be registered with the Pollution Control Boards (PCBs) or relevant government agencies, with social and health incentive packages integrated into the registration process to encourage participation. Once the collection system is formalized, the influx of material from the informal sector will reduce significantly, prompting other stakeholders in the value chain to align accordingly. This will not only improve efficiency but also create a more accountable and sustainable recycling ecosystem.

This calls for the government to take initiatives such as the PLI scheme with which the e-waste can be managed efficiently and effectively. This will not only benefit the ecosystem but will aid the country's economy through the recovered metals. Recent policy signals suggest an indicative INR 1,500 crore outlay over three years to catalyse compliant e-waste recycling and critical-mineral recovery; operationally, this would blend capex support for new/expanded compliant capacity and process upgrades (~40%) with performance-linked opex incentives (~55%) that pay per verified tonne meeting the Table 4 recovery thresholds, plus a small technical-assistance window (~5%) for third-party verification and integration pilots with high-efficiency informal collection. This keeps the scheme outcome-oriented (pay for actual recovery), complements rather than dilutes EPR, prioritises capacity augmentation among compliant recyclers, and channels informal collection into formal, environmentally sound processing.

There are certain moving parts to the PLI design for each sector. Some suggestions on each facet of PLI design are given below:

Eligibility Criteria

For participating in the PLI scheme, it is suggested that the following be the criteria:

- The recycler should be a registered entity with the Central/State Pollution Control Board (henceforth called registered recycler).
- The recycler should have a threshold capacity greater than 25,000 metric tonnes per annum. This is as per category I criteria of recycling capacity as mentioned in the previous section. This is necessary to indicate the ability of the recycler to process a minimum volume of e-waste materials within a specified timeframe.
- The recycler should be involved in the recovery processes of one or more of the following metals from the e-waste:Iron (Fe), Copper (Cu), Aluminium (Al), Lead (Pb), Nickel (Ni), Silver (Ag), Gold (Au), Palladium (Pd) etc. some of these are identified as critical minerals as per the Ministry of Mines.
- The recycler would be eligible for an incentive based on the percentage of recovery of the metal from the e-waste. The metals that could be extracted from the e-waste are shown in Table 3. Owing to the heterogeneity of e-waste it becomes challenging to determine the precise amount of metals in the e-waste and the ongoing market rates for extracting metals might influence the recovery and recycling of metals. This can be streamlined further post-industry consultation.

Table 3: Recovery values of metals from 1 tonne of e-waste

S.no	Material	Percentage	Quantity (kg)
1	Copper	20	181.44
2	Iron	8	72.58
3	Nickel	2	18.15
4	Tin	4	36.29
5	Lead	2	18.15
6	Aluminium	2	18.15
7	Zinc	1	9.08
8	Gold	0.1	0.90
9	Silver	0.2	1.81
10	Palladium`	0.005	0.04

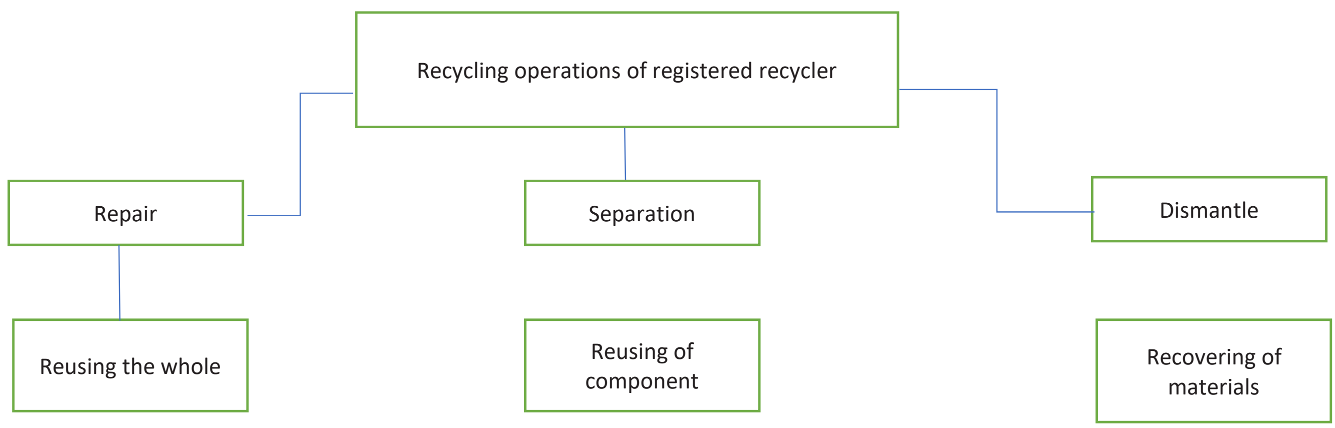
Source: (Tipre et al., 2022)

Incentive Structure

To encourage investment and innovation in the e-waste recycling sector, incentives are to be provided.

The operations at the recycling plants of the registered recyclers are as shown in the below flowchart in Figure 11.

Figure 11: Operations at the recycling plants



Source: Authors' Construction

The incentives will be given only for recovering the metals after achieving the following targets as given in Table 4 below:

Table 4: Recovery Targets for Metals found in the e-waste

Metal	Critical Raw Mineral	Target Recovery in 1st Financial Year Post 3 years of implementation of the scheme
Cu	Yes	>20% of wt. of e-waste collected (in tonne) in the preceding year
Fe	No	>8% of wt. of e-waste collected (in tonne) in the preceding year
Ni	Yes	>2% of wt. of e-waste collected (in tonne) in the preceding year
Sn	No	>4% of wt. of e-waste collected (in tonne) in the preceding year
Pb	No	>2% of wt. of e-waste collected (in tonne) in the preceding year
Al	No	>2% of wt. of e-waste collected (in tonne) in the preceding year
Zn	No	>1% of wt. of e-waste collected (in tonne) in the preceding year
Ag	No	>0.1% of wt. of e-waste collected (in tonne) in the preceding year
Au	No	>0.2% of wt. of e-waste collected (in tonne) in the preceding year
Pd	Yes	>0.005% of wt. of e-waste collected (in tonne) in the preceding year

Source: Author's construction

The recovery targets are to be reviewed and increased each year. The incentives would enable and encourage formal recyclers to collect more e-waste. The scheme should be effective in aiding the huge recovery of the critical raw minerals from the e-waste and also give a push towards the formation of a new recycling system within the country.

It is also essential to monitor and evaluate the impact of the PLI scheme, the performance metrics that can be used to measure the impact are waste collection volume and recovery rates. Regular audits are needed during the operation of processes, this ensures a strict and efficient investigation. Examination of the recycling targets being achieved by the recycler is vital. The auditing system would ensure the registered recyclers availing the benefits of the scheme to improve upon themselves, otherwise, they may be withdrawn if they fail to meet the requirements.

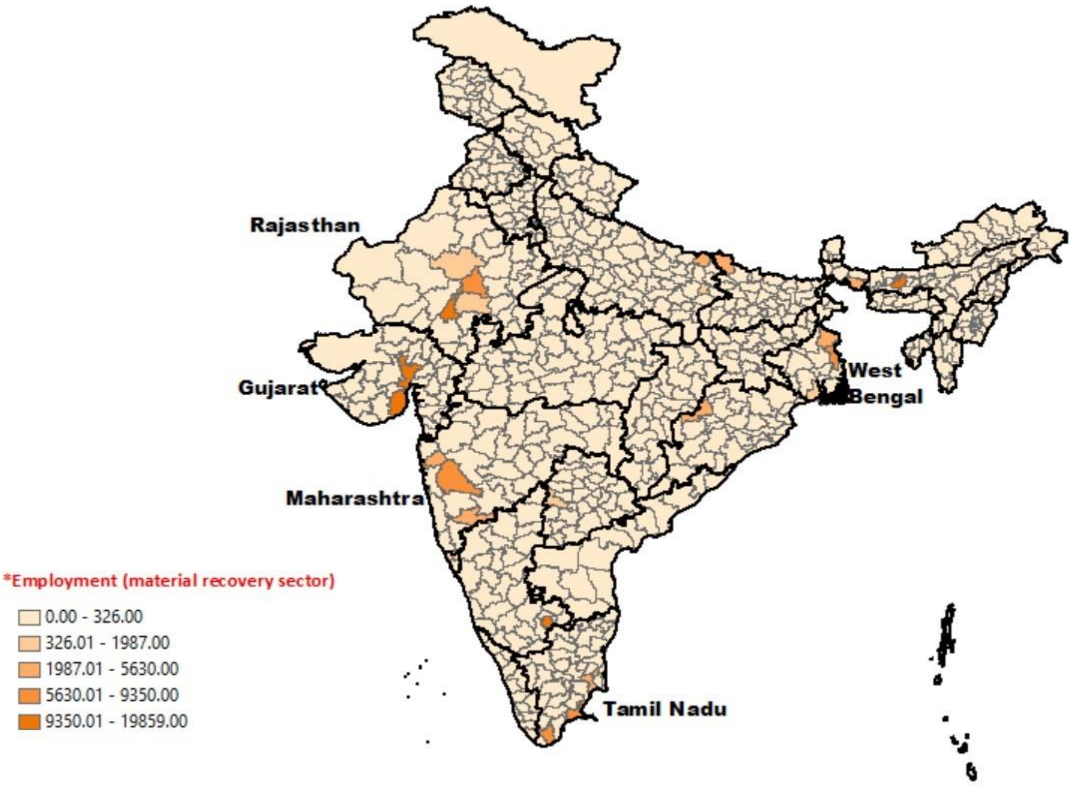
As discussed above, the scheme should also focus on the informal sector. There is a need to acknowledge the informal sector and aid their transformation. Bridging the gap between the formal and informal sectors would help the informal players adopt legal channels and undertake business transactions. Tapping on the collection strength of the informal sector would help the formal recycling sector facilitate larger volumes of e-waste. This is done through the Recycling Development Programme (RDP) which may include concessional funding and technological handholding.

- For the development and uptake of recycling, the informal sector is an invaluable resource. Its collection efficiency is much higher than the formal sources and if leveraged well, it can provide the critical mass needed for efficient recycling technology deployments through RDP. Formation of local collection points or drop points and managing collection centres of formal recyclers would increase the effectiveness and efficiency of the recycling sector.

- The integration of the informal sector into the mainstream can be facilitated through the RDP by enhancing their skills and aligning institutes that could provide research and support to the informal sector to adopt locally developed technologies for e-waste recycling. This would be beneficial to the informal sector and contribute towards establishing a sustainable e-waste management system.

- Drawing parallels from the material recovery sector, employment in the e-waste recycling sector can be established. The material recovery sector includes the recovery of materials such as paper, plastics, used beverage cans, and metals into distinct categories, from garbage. This also includes the processing of metals and non-metal waste and scrap and other articles into secondary raw material. As seen in the figure, the map shows district-wise existing e-waste recycling clusters within India. While this may be an overestimate, this information could be used further to identify the cluster that merits the development programme. However, a subsequently done e-waste recycler census would be suggested as well. The material recovery sector is operational in 13 states within India and the highest employment in this sector has been observed in the State of Gujarat followed by Maharashtra, Rajasthan, and Tamil Nadu. These are organically developed recycling clusters formed within the state.

Figure 12: Employment in Material Recovery sector (District wise)



Source Authors' construction based on PLFS 2022-23

RDP can be a crucial step in facilitating market linkages for informal recyclers by engaging them with manufacturers, dealers, etc thus ensuring a steady supply of e-waste to recyclers within the cluster. Formal recyclers can provide training and capacity-building programs to informal recyclers, thereby fostering collaboration and knowledge sharing among e-waste recyclers. Also documenting best practices can facilitate the replication of successful cluster development in other regions as well. The RDP would help in transforming the informal sector, improving their livelihoods, mitigating environmental pollution, and contributing towards a sustainable management of e-waste.

References

Annamalai, J. (2015). Occupational health hazards related to informal recycling of E-waste in India: An overview.

Doan, L. T. T., Amer, Y., Lee, S. H., Phuc, P. N. K., & Dat, L. Q. (2019). E-Waste reverse supply chain: A review and future perspectives. In Applied Sciences (Switzerland) (Vol. 9, Issue 23). MDPI AG. https://doi.org/10.3390/app9235195

Evans, M., Brooks, C., & Johnson, M. K. (2023). United States Energy Association: Critical Material Recovery from E-waste.

Saleem, U., Joshi, B., & Bandyopadhyay, S. (2023). Hydrometallurgical Routes to Close the Loop of Electric Vehicle (EV) Lithium-Ion Batteries (LIBs) Value Chain: A Review. In Journal of Sustainable Metallurgy (Vol. 9, Issue 3, pp. 950–971). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s40831-023-00718-w

Sanito, R. C., You, S. J., & Wang, Y. F. (2021). Application of plasma technology for treating e-waste: A review. In Journal of Environmental Management (Vol. 288). Academic Press. https://doi.org/10.1016/j.jenvman.2021.112380

Tipre, D. R., Khatri, B. R., Thacker, S. C., & Dave, S. R. (2022). The brighter side of e-waste-a rich secondary source of metal. https://doi.org/10.1007/s11356-020-12022-1/Published

Wang, K., Qian, J., & Liu, L. (2020). Understanding environmental pollutions of informal e-waste clustering in global south via multi-scalar regulatory frameworks: A case study of Guiyu Town, China. International Journal of Environmental Research and Public Health, 17(8). https://doi.org/10.3390/ijerph17082802

Annexure 1 Recycling/dismantling facilities in India

The table shows the number of recycling/dismantling facilities within each state of India.

States	Number of Plants
Andhra Pradesh	10
Assam	1
Chhattisgarh	2
Delhi	6
Goa	2
Gujarat	41
Haryana	43
Himachal Pradesh	2
Jammu & Kashmir	3
Jharkhand	2
Karnataka	72
Kerala	1
Madhya Pradesh	3
Maharashtra	140
Orissa	7
Punjab	8
Rajasthan	27
Tamil Nadu	42
Telangana	23
Uttar Pradesh	121
Uttarakhand	8
West Bengal	5
Grand Total	**569**

LATEST ICRIER'S WORKING PAPERS

NO.	TITLE	AUTHOR	YEAR
428	MACROECONOMIC DEVELOPMENTS AND POLICIES SINCE 2000	SHANKAR ACHARYA	MAY 2025
427	INSPECTING THE IMPACT OF FINANCIAL INCLUSION ON EMISSIONS IN INDIA: THE BANKING CHANNEL	SAON RAY VASUNDHARA THAKUR	MARCH 2025
426	E-COMMERCE IN TRADE AGREEMENTS: INDIA'S STRATEGIES AND OPTIONS	ARPITA MUKHERJEE PRITAM BANERJEE, AAHANA SRISHTI	JANUARY 2025
425	TOWARDS GREATER REGULATORY CO-OPERATION IN THE ASIA-PACIFIC FOR BOOSTING E-COMMERCE TRADE	ARPITA MUKHERJEE, KETAKI GAIKWAD, AAHANA SRISHTI	OCTOBER 2024
424	MAKING STATE CIRCULAR ECONOMY PARKS WORK FOR INDIAN STATES (PART 2): AN ECONOMIC ANALYSIS USING THE ICRIER'S SAMPADA WSUT MODEL	AMRITA GOLDAR, SAJAL JAIN RITIKA VERMA, KARTIK NAIR	JUNE 2024
423	MAKING STATE CIRCULAR ECONOMY PARKS WORK FOR THE INDIAN STATES (PART 1): AN EMERGING STORY OF RAJASTHAN	AMRITA GOLDAR, RITIKA VERMA, TARUN MALAY KOTAL	JUNE 2024
422	ESTIMATING LOSS AND DAMAGE FROM CLIMATE-INDUCED DISASTERS: AN EVALUATION USING ICRIER 'PRAKRITI' MODEL	AMRITA GOLDAR, SAJAL JAIN, DIYA DASGUPTA	MAY 2024
421	DECOMMISSIONING OF COAL-BASED PLANTS IN INDIA AND ITS RAMIFICATIONS	SOMIT DASGUPTA	MAY 2024
420	REGIONAL VALUE CHAINS: OPPORTUNITIES FOR INDIA AND ASEAN?	SAON RAY VASUNDHARA THAKUR	APRIL 2024
419	BENEFITS OF BBIN MOTOR VEHICLE AGREEMENT TO THE NORTHEAST REGION: A SUPPLY CHAIN ANALYSIS	NISHA TANEJA, BISWAJIT NAG, SANJANA JOSHI, RASHMI RASTOGI, SANYA DUA	FEBRUARY 2024
418	WTO REFORM – IMPROVING TRANSPARENCY AND NOTIFICATIONS IN THE WTO	ANWARUL HODA	NOVEMBER 2023
417	UNIVERSAL COVERAGE, ENHANCING SPACECOM SECTOR GROWTH, AND SUPPORTING DEMOCRATIC ETHOS: THE ROLE OF SATELLITE SPECTRUM ASSIGNMENT	REKHA JAIN	JULY 2023
416	BENCHMARKING ADOPTION OF E-COMMERCE ACROSS THE G20 MEMBERS	TANU M. GOYAL PETER MORGAN	MARCH 2023
415	SUPPORTING OPEN PLURILATERAL NEGOTIATIONS FOR MULTILATERAL LIBERALISATION OF TRADE	ANWARUL HODA	JANUARY 2023

About ICRIER

Indian Council for Research on International Economic Relations (ICRIER) is an independent public policy organization known for providing informative and insightful ideas to accelerate India's inclusive development. Established in 1981 with the motto of "linking India with the world," it has grown to become one of India's most well-known policy research think tanks in the areas of Agriculture, Climate Change, Digital Economy, Economic Growth, Jobs and Gender, and Trade, Industry and Investment. While serving as a trusted advisor to the governments, corporates, multilaterals and foundations, ICRIER continues to function as a bridge between the academic world and the policy arena.

ICRIER has two office locations in Delhi; in the institutional complex of India Habitat Centre and a new office at the Institutional Area, Sector 6, Pushp Vihar, New Delhi.

ICRIER's Board of Governors include leading academicians, policymakers, and representatives from the private sector. Mr. Pramod Bhasin is ICRIER's chairperson and Dr. Shekhar Aiyar is Director & Chief Executive.

ICRIER conducts thematic research in the following five thrust areas:

1. Growth, Employment and Macroeconomics (GEM)
2. Trade, Investment and External Relations (TIER)
3. Agriculture Policy, Sustainability and Innovation (APSI)
4. Digital Economy, Start-ups and Innovation (DESI)
5. Climate Change, Urbanization and Sustainability (CCUS)

To effectively disseminate research findings, ICRIER organises workshops, seminars and conferences to bring together academicians, policymakers, representatives from industry and media to create a more informed understanding on issues of major policy interest. ICRIER routinely invites distinguished scholars and policymakers from around the world to deliver public lectures and give seminars on economic themes of interest to contemporary India.