Minerals Engineering 184 (2022) 107661

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Circular economy and household e-waste management in India: Integration of formal and informal sectors

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A R T I C L E I N F O

Keywords:
Circular economy transition
E-waste in India
Extended producer responsibility (EPR)
Household waste in India
Informal e-waste management
Sustainable human development

A B S T R A C T

E-waste is considered to be one of the fastest growing solid waste streams in the world. India, the second most populous country in the world, generated more than 3.23 million tonnes of e-waste in 2019 and thus, has become the world's third largest e-waste generating country. However, the documented formal e-waste recycling percentage in India is very low (less than 10%). The existing formal recyclers in India process approximately one-third of the total e-waste generated in the country, though they face e-waste supply chain constraints due to informal e-waste collectors. A significant e-waste fraction is handled by the informal e-waste collectors and value recovery operations. Approximately 1% of the country's population is expected to be currently engaged in informal waste management and value recovery activities and thus, the investigation of the informal e-waste sector in India is of paramount importance. Artisanal value recovery methods pose severe threats to human health and the environment due to toxic and hazardous chemicals in e-waste and their subsequent mobilisation. These drawbacks thus imply that improvements are required in both formal and informal e-waste collection and value recovery operations to establish a more sustainable e-waste industry in the country. Therefore, the aim of this study was to investigate the operational characteristics of both the sectors, including extended producer responsibility (EPR) schemes in India. A modified EPR model pertaining to e-waste was proposed to integrate the informal e-waste collectors to the existing formal industry. The results in this work could be useful to establish a sustainable e-waste industry in India.

1. Introduction

According to the Directive 2012/19/EU of the European Parliament and the Council, electrical and electronic equipment (EEE) is defined as any household or industrial equipment that depends on electric currents or electromagnetic fields for operation and is designed for the generation, transfer and measurement of these currents and fields (European WEEE Registers Network, 2017). These equipment items are designed to operate with a voltage rating of within 1,000 V for alternating current and 1500 V for direct current (European WEEE Registers Network, 2017). Waste electrical and electronic equipment (WEEE) or e-waste consists of EEE and their parts that have been discarded by users as waste without the intention of reuse (Jeyaraj, 2021), though these discarded items are not necessarily considered as waste EEE. Shorter replacement intervals are one of the crucial reasons for early replacements (Kang et al., 2020). E-waste includes all components, subassemblies (e.g. printed circuit boards – PCBs, cathode ray tubes - CRTs) and consumables that are parts of the equipment (Ilankoon et al., 2018). Under the Directive 2012/19/EU (WEEE Directive (recast), 2018), and from 15 August 2018 (Forti et al., 2018) e-waste is classified into 6 distinct categories, including (1) temperature exchange equipment, (2) screens, monitors, and equipment containing screens having a surface greater than 100 cm^2, (3) lamps, (4) large equipment, (5) small equipment, and (6) small IT and telecommunications equipment (no external dimension more than 50 cm).

E-waste generation has grown by 21% by weight in the last 5 years,

Abbreviations: BAT, Best available technologies; CEEW, Consumer electrical and electronics; CPCB, Central Pollution Control Board; CRTs, Cathode ray tubes; EEE, Electrical and Electronic Equipment; EPR, Extended Producer Responsibility; ITEW, Information, technology and communication; PAHs, Polycyclic aromatic hydrocarbons; PCBs, Printed circuit boards; PCCs, Pollution Control Committees; POPs, Persistent organic pollutants; PPE, Personal protective equipment; PROs, Producer Responsibility Organisations; PVC, Polyvinyl chloride; SPCBs, State Pollution Control Boards; TSDFs, Treatment, Storage, and Disposal Facilities; UNU, United Nations University; WEEE, Waste Electrical and Electronic Equipment.

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https://doi.org/10.1016/j.mineng.2022.107661
Received 8 March 2022; Received in revised form 26 May 2022; Accepted 27 May 2022
Available online 3 June 2022

making it one of the fastest growing solid waste streams worldwide (Forti, 2020). This significant growth is mainly due to the increase in consumption of EEE (Panda et al., 2020), rapid obsolescence (Tesfaye et al., 2017), shorter replacement intervals with limited options and higher costs for repair and, lack of reuse interests. According to the global e-waste monitor report 2020 published by the United Nations University (UNU), 53.6 million tonnes of e-waste were generated globally in 2019 out of which, only 17.4% were formally recycled (Forti et al., 2020).

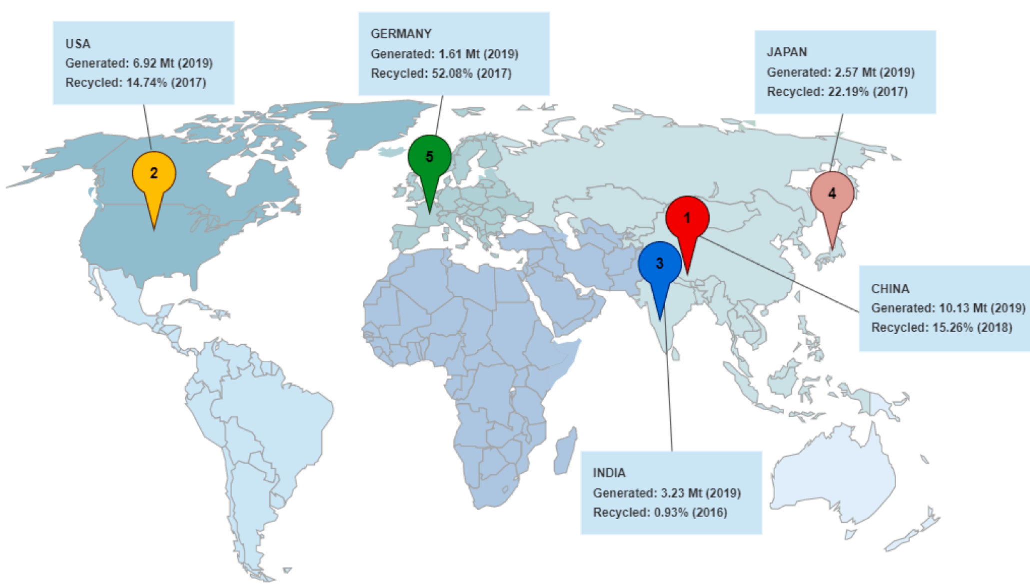
Toxic metals (e.g. lead, mercury) and chemical substances (e.g. polybrominated biphenyls, mercury, polybrominated diphenyl ethers and halogenated flame retardants) present in e-waste (Spalvins et al., 2008) pose severe health and environmental threats (Iqbal et al., 2020) if these substances are mobilised (Ilankoon et al., 2018). Additionally, the presence of valuable and recoverable elements in e-waste, including precious and base metals favour e-waste recycling (Kang et al., 2021), though the reuse of discarded EEE is found to be more sustainable than recycling (Yong et al., 2019). The lower recycling percentages also indicate that significantly large quantities of precious and base metals and other high-value recoverable critical raw materials contained in e-waste (e.g. rare earth elements), worth approximately US $57 billion (Forti et al., 2020), were either landfilled, incinerated or processed by employing artisanal recycling methods (Tabelin et al., 2021).

According to the global e-waste monitor report 2020, India has become the world's third largest e-waste generating country after China and the USA, producing more than 3.23 million tonnes of e-waste annually (Fig. 1).

India's e-waste generation has grown by almost 43% between 2018 and 2020 (Rao, 2021). It is predicted that by 2050, the country will be generating over 161 million tonnes of e-waste (Biswas and Singh, 2020). Apart from the large quantities of e-waste being generated within the country, significant amounts of e-waste are also known to be imported from developed countries (i.e. transboundary movement of e-waste – Ilankoon et al., 2018). However, this aspect has not been investigated in India in detail.

Even though India generates significantly high quantities of e-waste, the collection and recycling rate in the country remains low (0.93% in 2016 – Forti et al., 2020) as compared to other e-waste producing countries in the world (e.g. 52% in Germany in 2017). This indicates that e-waste management is still at its infancy in this developing country (Mohan, 2020).

According to the latest reports, however, about 5 (Dutta and Goel, 2021) – 10% (Biswas and Singh, 2020) of the total e-waste generated in India were sustainably recycled by the formal sector (managed by the legislative frameworks of the government – section 2) using advanced technology, while the remaining fraction is processed by the informal sector which remains unaccounted for. As per the E-waste (Management) Rules, 2016 in India, the responsibility of effective e-waste management lies on the Central Pollution Control Board (CPCB), State Pollution Control Boards (SPCBs) and the Pollution Control Committees



Country	Categorisation criteria	Types of WEEE included	References
China	Type	1st batch: Televisions, refrigerators, computers etc. 2nd batch: Printers, copy machines, phones etc.	Tan, 2019
USA	-	No federal legislation that mandates e-waste recycling in the country. Types of WEEE collected/recycled depends on each state's legislation.	Schumacher and Agbemabiese, 2021
India	Type	Information, technology & communication (ITEW): Computers, printers, phones etc. Consumer electrical & electronics (CEEW): Televisions, refrigerators, lamps etc.	Biswas and Singh, 2020
Japan	Size	Home appliances: Televisions, refrigerators, air conditioners etc. Small home appliances: Laptops, digital cameras, mobile devices etc.	Ministry of the Environment of Japan, 2014
Germany	Size, type and use	6 categories of WEEE based on Directive 2012/19/EU (mentioned in Section 1). Each category is further divided into subcategories based on usage. b2c equipment: EEE used in private households. b2b equipment: EEE used in other than private households.	Stiflung EAR, 2022

Fig. 1. Top 5 e-waste generating countries in the world, their recycling rates according to the global e-waste monitor report 2020 (Forti et al., 2020) and their e-waste categorisation. Note: the generation data are from 2019 while the recycling data are from the years they were last reported by the countries. (See above-mentioned references for further information.)

(PCCs) of the Union Territories (Ministry of Environment, Forest and Climate Change, 2016).

The E-waste (Management) Rules, 2016 heavily emphasise on the concept of extended producer responsibility (EPR) and mandate the producers to establish proper collection and disposal of WEEE generated in India (section 2 and Table 1). Due to the ever-rising quantities of e-waste and the implementation of such new regulations for e-waste management in the country, several formal recyclers and other stakeholders are entering the e-waste recycling industry (Raghupathy et al., 2018). These government authorised organisations collect, recycle and dispose of the e-waste using the best available technologies (BAT) and environmentally safe methods (Panwar et al., 2018). However, at present these formal recyclers are limited in number and their processing capacities are insufficient, due to which the formal sector is incapable of handling the total e-waste generated in the country. Moreover, there is limited information regarding the final waste management strategies implemented by these authorised recyclers to dispose of the waste generated (e.g. solid waste residues and acidic liquid effluents after recycling e-waste).

In India, the major challenge faced by the formal e-waste recyclers is their limited access to the e-waste generated due to the prevalence of the informal sector in the country (Borthakur and Sinha, 2013). E-waste management and value recovery in India is still dominated by the informal sector (2 sides here: informal e-waste collection and informal value recovery operations), where they collect and process the majority of the e-waste generated within the country as well as the e-waste that is imported from other countries (Nivedha and Sutha, 2020). They typically fail to abide by the aforementioned regulations and legislations laid out by the Government of India. Informal value recovery operations are carried out using artisanal recycling methods without taking into account appropriate safety measures. A recent study by Toxics Link, New Delhi reported the establishment of illegal e-waste recycling facilities in residential colonies where e-waste value recovery operations are performed using informal and rudimentary methods (Mahesh and Mukherjee, 2018). This often poses severe threats to human health and the environment (Lee and Mishra, 2018) due to the presence and mobilisation of toxic and hazardous metals and chemicals in e-waste (Manish and Chakraborty, 2019).

Table 1
Summary of the e-waste management regulations in India in chronological order.

Regulation	Changes/Impacts
The Environment (Protection) Act, 1986	India's first comprehensive environmental law to delegate the responsibility of implementing management plans for hazardous waste.
The Hazardous Wastes (Management and Handling) Rules, 1989	Classification of hazardous waste into 18 categories (e-waste was not specified) based on their constituents and the quantities of generation.
The Hazardous Wastes (Management and Handling) Rules, 2003	Classification of hazardous waste by process of waste generation (Schedule-1), waste characteristics (Schedule-2) and imports/exports (Schedule-3).
The Hazardous Wastes (Management, Handling and Transboundary Movement) Rules, 2008	Prohibition of transboundary movement of hazardous waste. Registration of all entities involved in recycling or reprocessing hazardous waste (including e-waste) under the CPCB.
E-waste (Management and Handling) Rules, 2011	India's first legislation specifically designed for e-waste management, highlighting the significance of recovery and/or reuse of useful material from e-waste. Introduction of EPR schemes in India.
E-waste (Management) Rules, 2016	Expansion of the EPR concept to ensure its effective enactment by EEE producers. Introduction of manufacturers, dealers, refurbishers and PROs as additional stakeholders.
E-waste (Management) Amendment Rules, 2018	To ensure the majority of the generated e-waste is channelised towards formal dismantlers and recyclers. Revised collection targets along with new targets for EEE producers.

The current situation of e-waste management in India clearly indicates that both the formal and informal sectors need to be developed in order to establish a more sustainable e-waste industry in the country. That development fosters the transition to circular economy in India, including sustainable human capital development. This article discusses relevant legislative frameworks for e-waste management in India, including existing EPR schemes and operational characteristics of both formal and informal e-waste management sectors. In addition, a modified EPR scheme will be formulated based on the analysis by integrating informal e-waste collectors to the formal e-waste management and value recovery businesses. The recommendations of this paper could be helpful to enhance the lifestyle of the large number of people currently engaged in the informal waste management sector and improve the existing e-waste management and recycling industry in India, making it more extensive and effective.

2. Current status of e-waste management in India

2.1. Legislative frameworks

The Environment (Protection) Act, 1986 was India's first comprehensive environmental law. It delegated the responsibility of implementing management plans for hazardous waste to the Central Government. The Hazardous Wastes (Management and Handling) Rules, 1989 were enacted which helped in the classification of hazardous waste into 18 categories (e-waste was not specified) based on their constituents and the quantities of generation (Rajya Sabha Secretariat, 2011).

Basel Convention was entered into force in 1992 to control the transboundary movement of hazardous waste for their disposal, especially from developed countries to developing countries (Basel Convention, 2018a). India is one of the parties that ratified the Basel Convention, and the regulations were implemented in India since 22nd September 1992 (Basel Convention, 2018b).

In 2000, amendments were made to the Hazardous Waste (Management and Handling) Rules, 1989 to ensure compliance with the Basel Convention wherein the waste was mainly classified by process of waste generation (Schedule-1) and as per their characteristics (Schedule-2) (Rajya Sabha Secretariat, 2011). Although there was no direct reference to e-waste in the above regulations, the disposal process of e-waste and its constituents were deemed hazardous in nature and therefore considered to be covered under both Schedules-1 and 2. E-waste was also considered to be a part of Schedule-3 which represents a list of hazardous waste applicable for imports and exports. These amendments were then notified as the Hazardous Wastes (Management and Handling) Rules, 2003 (Rajya Sabha Secretariat, 2011).

Even though India ratified the Basel Convention in 1992 and was one of the first countries to call for a ban on hazardous waste exports to developing countries (Ipen, 2020), it is supposed that considerably large quantities of e-waste are still imported (quantities are not reported) to India from developed nations (Ilankoon et al., 2018). This is often done illegally (Sepúlveda et al., 2010) due to lack of understanding of the nature and quantity of these imported e-waste (Turaga et al., 2019).

The Hazardous Wastes (Management, Handling and Transboundary Movement) Rules, 2008 was enacted and it was the first legislation accounting for e-waste in India. Under these rules, the CPCB along with SPCBs were given the responsibility of identifying various sources of e-waste and devising environmentally safe methods for its handling. All entities involved in recycling or reprocessing hazardous waste (including e-waste) would be required to register themselves under the CPCB. In 2010, the E-waste (Management and Handling) Rules were drafted after understanding the significance of recovery and/or reuse of useful material from e-waste. This was notified as the E-waste (Management and Handling) Rules, 2011 and was the first regulation passed in India focusing solely on e-waste management (Rajya Sabha Secretariat, 2011). It introduced the EPR concept in India. Later, E-waste (Management) Rules, 2016 was implemented to expand the concept of EPR and ensure its effective enactment by producers of EEE (Borthakur, 2020). This rule introduced manufacturers, dealers, refurbishers and producer responsibility organisations (PROs) (section 2.2) as additional stakeholders (Ministry of Environment, Forest and Climate Change, 2016). In 2018, amendments (revised targets) were made to the existing rules and titled as E-waste (Management) Amendment Rules, 2018 (Ministry of Environment, Forest and Climate Change, 2018). E-waste (Management) Rules, 2016 and E-waste (Management) Amendment Rules, 2018 are the most recent e-waste management regulations in India (Central Pollution Control Board, 2018).

As per the Schedule I of the E-waste (Management) Rules, 2016, various EEE have been divided into 2 categories: Information, technology and communication (ITEW) and consumer electrical and electronics (CEEW). Each of the categories is further divided into 16 (ITEW) and 5 (CEEW) subcategories respectively (Ministry of Environment, Forest and Climate Change, 2016). The major sources of e-waste in India originate from households, bulk consumers like government offices and commercial establishments, manufacturers and retailers.

At present, the responsibility of implementing an effective e-waste management system in India lies jointly on the CPCB along with the 30 SPCBs and 5 PCCs (Verma, 2020) under the Ministry of Environment, Forest, and Climate Change of the Government of India. The main responsibilities of these bodies include providing authorisation/licence to e-waste recyclers, checking for compliance with EPR schemes, maintaining inventories of e-waste and conducting random inspection of recyclers. Local municipalities are responsible for ensuring that any e-waste found in the other solid waste streams are separated and sent to formal recyclers for further processing.

Most of these legislative frameworks are mostly applicable to the formal e-waste recycling sector. After the implementation of the E-waste (Management) Rules in 2016, it was expected that the inflow of e-waste to the informal recycling sector would reduce thereby establishing control of the formal sector. The formal e-waste management system was also expected to be inclusive which would utilise the resources and skills of the workers engaged in the informal sector. However, to date, the informal sector remains the key player in the e-waste management system of the country, and its operations are still crude, primarily manual and without any consideration of environmental or occupational health and safety measures (Borthakur and Singh, 2012).

2.2. Existing EPR schemes and characteristics

In India, EPR refers to the "responsibility of any producer of electrical or electronic equipment, for channelisation of e-waste to ensure environmentally sound management of such waste" according to the Ministry of Environment, Forest and Climate Change (2016). The responsibility of e-waste collection lies on the producers (i.e. manufacturers, retailers and importers) of EEE and the formal dismantlers, recyclers and refurbishers of WEEE according to the E-waste (Management) Rules, 2016. As a part of the formal e-waste management system, each of the 4 above-mentioned stakeholders is required to obtain an authorisation from the CPCB (Ministry of Environment, Forest and Climate Change, 2016).

Since the EPR schemes deem the producer of EEE responsible for the end-of-life treatment of the products distributed and retailed by them, they are required to establish a system for the collection and recycling of WEEE. They can also employ authorised dealers who collect the waste on their behalf. The formal institutions that engage in the dismantling, refurbishing and value recovery operations have also been considered responsible for the collection of the e-waste by setting up their own e-waste collection centres. No separate authorisation is required for these collection centres as the authorisation is already granted to the establishment of e-waste recycling facilities (Ministry of Environment, Forest and Climate Change, 2016).

Each formal institution (collection centre, dealer, dismantler, refurbisher, recyclers) must operate in accordance with the standards and guidelines issued by the CPCB. It is essential that the waste collected and recycled by them are stored, transported and processed in a secure and environmentally safe manner. They are required to maintain strict documentation recording all the handled e-waste fractions and this documentation will be checked by the CPCB/SPCB when required (Ministry of Environment, Forest and Climate Change, 2016).

The EPR schemes established the concept of deposit refund scheme wherein the producer of EEE can charge an additional amount as a deposit at the time of sale of the EEE (not implemented yet) and return it to the consumer along with interest when the end-of-life EEE or WEEE is returned to the producer through their 'take back' scheme (Ministry of Environment, Forest and Climate Change, 2016). The EPR schemes have also established the concept of the PROs (Ministry of Environment, Forest and Climate Change, 2016), which is financed by the producers to meet the EPR requirements. The PRO helps producers by taking over the responsibility of collecting and processing the e-waste. A licence is required from the CPCB for PRO operation and there are 68 registered PROs in India as of 2021 (Central Pollution Control Board, 2021a).

3. Formal sector and operational characteristics

The formal e-waste management sector in India comprises government authorised companies or agencies who are responsible for collecting, recycling and disposing e-waste in an environmentally safe manner. These e-waste recycling units are registered under the SPCB of the State they are located in. They use modern equipment and provide a safe and healthy environment for workers in order to ensure safe and sound recycling and disposal of e-waste (Panwar et al., 2018).

As of December 2021, there are 468 authorised e-waste dismantlers/recyclers in India (Fig. 2) with an operating capacity of approximately 1.38 million tonnes/annum (Central Pollution Control Board, 2021b) which is just slightly over one-third of the e-waste generated in India in 2019. However, it has often been found (through anecdotal evidence) that the processing capacities of these recyclers do not match the reported figures (Radulovic, 2017).

Bhardwaj (2016) claimed that one of the major challenges faced by the registered dismantlers and recyclers in India is not receiving sufficient supply of e-waste to perform their value recovery operations continuously. Additionally, strict occupational health and safety, and environmental standards and high capital costs (e.g. machinery) make formal value recovery operations cost-intensive and these aspects further result in e-waste supply chain and economic constraints, respectively, for the formal e-waste sector (Raghupathy et al., 2018).

The lack of awareness regarding harmful impacts of unregulated e-waste recycling and costs of returning WEEE to formal collection centres have been found to reduce the willingness of household and institutional consumers to dispose of their waste to the formal sector (Turaga et al., 2019). In addition, data security could also be a concern (Ilankoon et al., 2018). The door-to-door collection service provided by informal waste collectors (section 4), coupled with certain monetary incentives provided by them to disposers, which is fairly nominal, is making e-waste disposal to them preferable as compared to the formal e-waste collection mechanisms in India (Borthakur and Govind, 2018).

3.1. Operational characteristics

The main steps involved in formal e-waste recycling include collection, pre-treatment, processing and value recovery, and final waste disposal. Most of these recyclers in India use the concept of reverse logistics to collect WEEE. They set up their own collection centers and use

State	Number of formal recyclers	Capacity (tonnes per annum)
Andhra Pradesh	8	32123
Assam	1	120
Chattisgarh	2	6750
Delhi	2	120
Gujarat	33	84302
Goa	1	103
Haryana	42	124282
Himachal Pradesh	2	1500
Jammu & Kashmir	3	705
Jharkhand	2	660
Karnataka	71	52842
Kerala	1	1200
Maharashtra	116	106281
Madhya Pradesh	2	9600
Orissa	5	5690
Punjab	7	9492
Rajasthan	23	83254
Tamil Nadu	32	132049
Telangana	16	91563
Uttar Pradesh	89	494043
Uttarakhand	6	147305
West Bengal	4	1950
Total	**468**	**1385932**

Fig. 2. Number of formal e-waste dismantlers/recyclers and their processing capacities in India as of December 2021 (Central Pollution Control Board, 2021b).

logistic partners to provide door-to-door collection services. They also provide efficient data destruction services such as bulk hard drive shredding, data wiping, tape destruction, hard drive crushing/drilling, hard drive degaussing, and secure hard drive transportation, and these steps are very crucial to alleviate data security concerns among e-waste disposers.

The pre-treatment step mostly comprises segregation (based on type of e-waste and working condition) and manual/semi-manual dismantling. Repairable items undergo repair and refurbishment in an environmentally safe manner. These refurbished electronic items are either sold by the recyclers directly at lower prices or sold to respective dealers. The non-repairable items undergo dismantling to retrieve components that can be reused or dismantled further. The formal recyclers employ certain mechanical methods such as shredding, magnetic separation, eddy-current separation, ball milling and gravity separation to separate the metallic and non-metallic fractions from waste PCBs (Rautela et al., 2021). Valuable materials (base and precious metals) are extracted from the dismantled components using various metallurgical methods (e.g. hydrometallurgy, pyrometallurgy and electrometallurgy), or a combination of two or more of these processes (Arya and Kumar, 2020a). Metal extraction from PCBs is often the primary objective of e-waste recyclers in India (Arya and Kumar, 2020a). All of these operations are carried out in an environmentally safe manner using advanced technologies.

There is limited information on the strategies used by the formal recyclers to handle the solid and liquid waste generated during the recycling operations. This has been identified as a major problem by several researchers in developing countries (e.g. In Malaysia - Yong et al., 2019). Some of the formal recyclers are known to dispose of their solid and liquid waste to treatment, storage, and disposal facilities (TSDFs). TSDFs are government authorised bodies that receive hazardous wastes for treatment, safe storage and disposal (ENVIS Centre, 2020). However, limited information regarding their operations is currently available.

4. Informal sector and operational characteristics

Door-to-door e-waste collection is typically employed followed by crude recycling methods in the informal sector. However, the latter is heavily criticised for causing severe environmental and occupational health hazards (Ravindra and Mor, 2019). Despite that, these operations continue to be the most prominent aspects in the e-waste management and value recovery industry of India. Large workforce, cheap labour, inexpensive e-waste collection methods, artisanal e-waste value recovery operations, and cheaper workshops (e.g. use their own residential area) and operating costs (e.g. use residential electricity) are considered to be the crucial factors that favour informal e-waste supply chains and value recovery operations in India.

4.1. *Material flow of e-waste*

'Kabadiwalas' (informal waste collectors) is the local term used in India to describe those people who informally collect end-of-use and end-of-life items, such as newspapers, cardboards, scrap metal pieces, plastic bottles, tires, and e-waste (Radulovic, 2017). In India, a significant number of people still dispose of their waste to kabadiwalas and it causes them to operate at very large scales all over the country (though the exact number is not reported). They also perform initial e-waste sorting and dismantling operations using inexpensive, rudimentary and often unsafe methods to separate and extract the different parts of e-waste (e.g. copper cables, PCBs). The majority of the e-waste disposed of by households, shops, and small industries are effectively collected by the kabadiwalas due to their large workforce (Fig. 3).

In the informal waste collection systems in India, a middleman (Fig. 4) is responsible for the recruitment of the kabadiwalas to collect the waste items, including e-waste. The middleman usually assigns the waste collection area to the kabadiwalas to collect the relevant waste items from nearby households and small businesses.

They employ modified manual or motorised rickshaws (i.e. three-wheeler vehicle with an attached cart at the rear end (Fig. 5a) to

a) b) c)

Fig. 3. E-waste collected by the kabadiwalas: (a) refrigerators, (b) fluorescent lamps and (c) printers collected by the kabadiwalas.

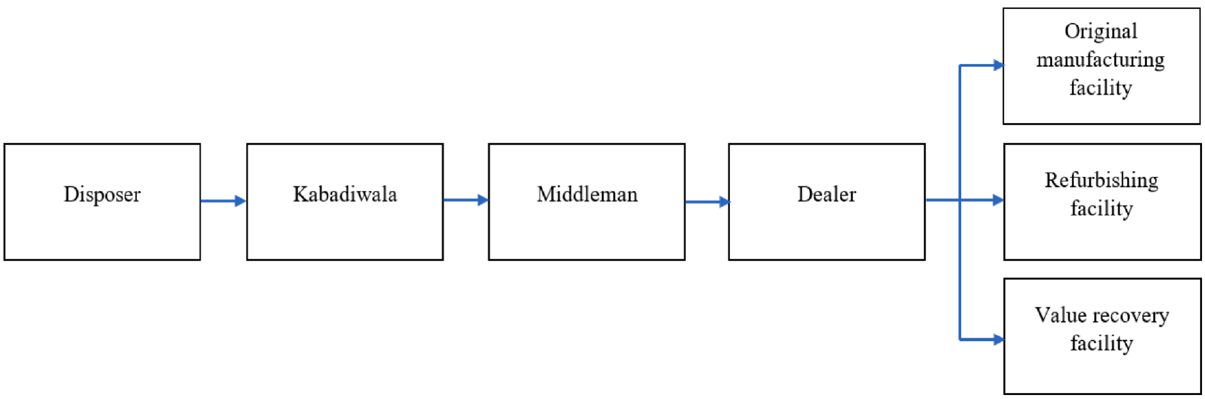


Fig. 4. Material flow of e-waste in the informal sector in India.

a) b) c)

Fig. 5. (a) Modified 3-wheeler vehicles used by kabadiwalas (b) storage of waste collected by kabadiwalas (c) segregated waste after preliminary sorting and dismantling.

travel around residential and commercial areas to collect waste, including e-waste. Kabadiwalas in India award small monetary incentives to disposers to encourage them to discard their waste. This is mainly due to the inevitably large competition that exists among kabadiwalas. They do not provide data destruction services for consumer electronic devices.

4.2. Operational characteristics

E-waste processing in the informal sector mainly comprises 5 operations: door-to-door collection, sorting/segregation, dismantling, refurbishing/repairing and artisanal recycling (informal value recovery operations) (Kumar, 2021) or formal recycling operations.

The different kinds of waste collected (Fig. 5b) are segregated by the kabadiwalas in terms of plastic waste, scrap metal waste, e-waste and stored at the middleman's site. The e-waste fraction is further segregated in terms of their working condition. Preliminary segregation is done to separate functional WEEE from the non-functional ones (Mahesh and Mukherjee, 2018). WEEE that can be potentially refurbished and reused are sold to the dealers or repair shops directly. The fraction of e-waste that is considered unrepairable, undergoes preliminary dismantling. The kabadiwalas or the informal collectors perform this dismantling manually using small tools wherein they break open such WEEE to separate the plastic chassis and the different electronic components such as the PCBs, wires, and motors (Dutta and Goel, 2021). This preliminary dismantling is performed mainly to maximise their earnings as they then get paid separately for the sorted components (i.e. preliminary sorting increases the value). However, any waste generated during these preliminary sorting and dismantling operations are disposed of in open land or drains (Mahesh and Mukherjee, 2018).

Once all the waste is segregated, all the extracted components and materials are stored until they reach a minimum quantity (Fig. 5c) and then sold to respective dealers. Different items are purchased by different dealers. For example, one dealer might be responsible for picking up all the segregated functional WEEE while another dealer might be responsible for purchasing the segregated PCBs. The dealers then deliver the collected waste to their respective repair facilities and recyclers, mainly informal refurbishing/repairing and value recovery facilities in India. Sometimes the dealers also engage in dismantling of the purchased items before selling further.

Upon reaching the informal/formal refurbishing facility, functional WEEE undergo manual repairing and the products are then sold directly to consumers or dealers and sellers of refurbished EEE at low prices.

The last stage of informal e-waste handling involves value recovery operations and the majority of the collected e-waste by kabadiwalas is processed by the informal sector. The informal e-waste value recovery facilities predominantly engage in two kinds of recycling activities: plastic recycling (obtained during dismantling) and PCB recycling mainly to obtain copper, lead (Mahesh and Mukherjee, 2018) and other valuable metals (e.g. copper from motors and cables). Plastic parts are sold (mixed or segregated based on resin type) to plastic recyclers who segregate, grind and melt the plastic to make pellets. These pellets are sold directly to plastic product manufacturers or in the market. Informal value recovery facilities employ open air incineration or acid leaching to recover valuables from PCBs (Jeyaraj, 2021). These recovered metals are sold to respective manufacturers or in the market. All solid and liquid wastes generated during these recycling activities are disposed of in open or in community bins located close to drains with risk of contaminating soil, surface, sub-surface and groundwater (Panwar and Ahmed, 2018).

4.3. Impact on the environment due to informal e-waste value recovery operations

Toxic substances present in e-waste such as mercury, cadmium, brominated flame retardants, polycyclic aromatic hydrocarbons (PAHs) and plastics pose severe threat to the environment (Cobbing, 2008) when disposed irresponsibly, especially in artisanal e-waste value recovery operations (i.e. mobilisation happens during informal value recovery operations).

Unregulated dumping of e-waste in landfills can have adverse impacts on soil fertility. It can further render surface and groundwater unfit for consumption as heavy metals leach into the soil and water (Ilankoon et al., 2018). High concentrations of heavy metals and other toxins have negative impacts on soil microbial population thereby reducing its fertility. A study conducted by Zhang et al. (2019) found high concentrations of heavy metals in crops that grew near water pools located in e-waste recycling sites.

Open incineration of e-waste to recover valuable substances causes emissions of the hazardous substances present in e-waste as smoke, oils, and charcoal (Sivaramanan, 2013). Incineration of e-waste plastics and polyvinyl chloride (PVC) leads to the emission of polychlorinated dibenzofurans (PCDFs)/polybrominated dibenzofurans (PBDFs), and polychlorinated dibenzo-p-dioxins (PCDDs)/polybrominated dibenzo-p-dioxins (PBDDs). The World Health Organisation classifies these toxic dioxins as persistent organic pollutants (POPs) that can cause long-term health risks associated with numerous genetic disorders (Rautela et al., 2021). Polychlorinated biphenyls, which are commonly used as plasticisers, lubricants, and coolants in transformers and condensers, pose severe environmental threats as their open-air combustion can cause acid rain and depletion of the ozone layer (Rautela et al., 2021). Absence of proper gas cleaning equipment in informal value recovery operations leads to the release of harmful gases directly into the atmosphere (Deng et al., 2007).

Developing countries like India face serious problems due to economic challenges and lack of infrastructure for proactive management of hazardous waste (Shamim et al., 2015). A study conducted by Pradhan and Kumar (2014) in the Mandoli industrial area in Delhi, India (a major hot spot for informal e-waste storage and recycling) indicated that uncontrolled informal value recovery operations and final waste disposal in the area caused significantly elevated levels of heavy metal contamination in surface soil, plants and groundwater. Panwar and Ahmed (2018) found similar soil and water contamination in the Krishna Vihar industrial area, Delhi due to leaching of heavy metals.

4.4. Social, occupational health and safety concerns of informal recyclers

In India, many workers engaged in the informal e-waste management and value recovery sectors and their families are often found residing in close quarters to the recycling facilities. Most informal recycling units operate in residential or commercial areas as many of these unit owners tend to use part of their residential space as their working units in order to save costs. The workers employed in these recycling units most of the time do not use any personal protective equipment (PPE). They are not paid minimum wages and sometimes the whole family (even minors) is engaged in e-waste collection and value recovery activities to reduce labour costs (Mahesh and Mukherjee, 2018). These workers along with others residing in proximity to such facilities get exposed to heavy metals and other toxins through several pathways including inhalation, ingestion, and dermal and *trans*-placental contact (Grant et al., 2013). Direct inhalation of toxic components released from open incineration of e-waste can cause thyroid abnormalities, cell proliferation, changes in mood and behaviour, adverse neonatal effects, and impaired lung function (Rautela et al., 2021). Exposure to elevated levels of mercury, lead and cadmium present in e-waste can impair intellectual and neurobehavioral development in children. At the same time, it can damage nervous, blood and reproductive systems in adults. It can also lead to anaemia, kidney damage, lung emphysema and chronic neurotoxicity (Ilankoon et al., 2018).

According to the Associated Chambers of Commerce and Industry of India (ASSOCHAM), approximately 80% of the informal e-waste workers in India suffer from respiratory ailments like breathing difficulties, irritation, coughing and choking due to insufficient or negligible health and safety measures (Garg and Adhana, 2020). It is supposed that the lifestyle, and health and safety of the informal e-waste collectors and value recovery operators in India can be improved by incorporating them into formal e-waste management and value recovery operations coupled with EPR schemes (section 5).

5. Moving forward: EPR schemes and a sustainable e-waste management industry in India

Arya and Kumar (2020a) stated that 1% of the total population is engaged in the informal waste management sector in developing countries like India. Several similar findings have indicated that many people are currently involved in India's informal e-waste recycling sector. Even though they handle a substantial fraction of the e-waste generated in the country, their income is often low. They are also exposed to potential occupational health and safety hazards. The authors believe that both the formal and informal sectors need to be developed and integrated to function as one system (rather than virtually eliminating the current informal waste recycling sector and its practices) through EPR schemes to establish a sustainable e-waste management system in India. It is believed that this integration will ensure that the existing formal recycling institutions operate at their total capacity and provide healthier working conditions (improved lifestyle) to the informal e-waste recyclers. The e-waste management system in India is expected to benefit from the synergistic functioning of the formal and informal sectors.

Here, the regulatory protocols followed by the formal sector and the large workforce of the informal sector would help establish a more effective e-waste management industry in the country, including efficient e-waste supply chains. Several researchers (e.g. Ikhayel, 2018; Raghupathy et al., 2018; Turaga et al., 2019; Arya and Kumar, 2020b) have also emphasised integrating the informal and formal e-waste management sectors in developing countries like India.

The integration process of informal e-waste collectors (kabadiwalas) and recyclers and formal e-waste recyclers can be potentially achieved with modified EPR schemes in India.

5.1. Current status of EPR schemes in India and challenges

Introduction of EPR schemes in India resulted in the expansion of the formal e-waste management sector. Additionally, manufacturers of EEE have started to integrate the design for environment (DfE) aspect into their products (Turaga et al., 2019).

Bhardwaj (2016) claimed that one of the major challenges faced by the registered dismantlers and recyclers in India is not receiving sufficient supply of e-waste to perform their value recovery operations continuously. Additionally, strict occupational health and safety, and environmental standards and high capital costs (e.g. machinery) make formal value recovery operations cost-intensive and these aspect further result in e-waste supply chain challenges for the formal e-waste sector (Raghupathy et al., 2018).

Even though a substantial amount of work is done to enhance the formal e-waste management sector in the country via existing EPR schemes, the majority of the e-waste supply chains and informal recycling operations are still handled by the informal sector (Tiwari et al., 2019 and section 4).

5.2. Modified EPR model

A modified EPR model is proposed in this work to integrate informal e-waste collectors and recyclers into the formal e-waste supply chains, and value recovery operations and the simplified form is presented in Fig. 6.

With most e-waste in India being handled by the informal sector, kabadiwalas are the starting point of the e-waste management supply chains. They, therefore, play a very significant role in the e-waste management and recycling industry in India. The authors believe that integrating the informal sector into the formal sector will have to start with the formalisation of these informal waste collectors.

Considering the synergistic effect provided by the kabadiwalas on the existing e-waste supply chains in India, the kabadiwala clusters must first be identified and registered under respective SPCBs to incorporate in the modified EPR model (Fig. 6). As most of the kabadiwalas in India are employed by a middleman, each of these clusters comprising the middleman and his employed kabadiwalas will function as one institutional setup. The government can initiate these registration schemes with the local SPCB. Once these clusters are registered, they need to abide by the operational guidelines and regulations of the Ministry of Environment, Forest and Climate Change (e.g. prohibition of e-waste supply to informal recyclers). These preventive measures will ensure a safe working environment.

In the proposed e-waste management system (Fig. 6), the kabadiwalas are responsible for the collecting, segregating and dismantling operations of e-waste with proper PPE. These e-waste dismantling

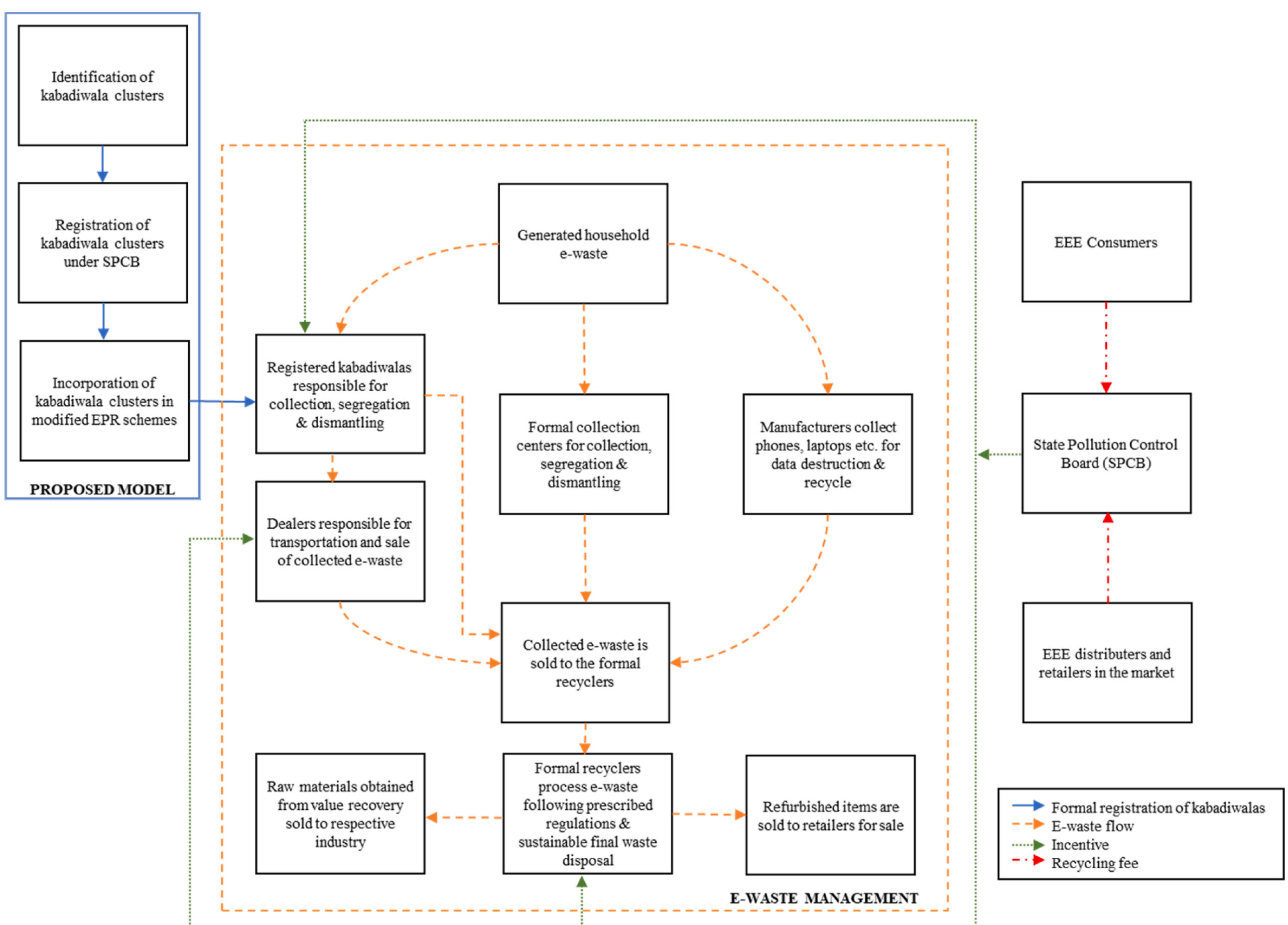


Fig. 6. The modified EPR proposal to integrate informal e-waste collectors into the formal e-waste supply chains and value recovery operations.

activities must be appropriately documented, and the records must be stored efficiently. Alternatively, similar e-waste collection activities can be carried out by a formal collection centre. Consumers concerned about data security issues relating to the disposal of personal consumer electronics (e.g. phones, tablets, laptops and hard disks) can choose to send those back to the manufacturer/distributor. The manufacturer/distributor needs to provide proper documentation to ensure that data is completely wiped from the discarded devices, which helps to establish appropriate data destruction processes.

The collected e-waste (by informal collectors and manufacturers) should only be sold to the formal e-waste recycling facilities. Delivery of e-waste to the formal recyclers is expected to provide an adequate supply of e-waste required to run their operations smoothly, thereby eradicating a significant challenge currently faced by the formal recyclers in the country. Ideally, kabadiwalas should sell their collected e-waste directly to the formal recycling facilities. However, they can choose to sell the waste through the registered dealers (Fig. 6). Existing informal dealers are encouraged to operate according to the established legislative frameworks and get themselves registered under their respective SPCB.

The formal recyclers will process the e-waste according to the prescribed regulations. The extracted materials are then sold to downstream industries, whereas the refurbished items are sold to retailers as second-hand products. To benefit from the proposed model, the informal e-waste based value recovery operations (the scale is not reported in detail) are encouraged to register themselves under the respective SPCB by upgrading their e-waste handling systems according to the prescribed regulations (Note: informal e-waste value recovery operations are not embedded in the proposed EPR model in Fig. 6).

Kaushal and Nema (2013) and Garg (2021) previously proposed the use of specific front-end economic tools, such as the advanced recycling fee (ARF) or advanced disposal fee (ADF) in India, which could be instrumental in improving the e-waste management scenario. Similarly, recycling fees will be charged from the consumers and the distributors and retailers of EEE. In the modified EPR model (Fig. 6), it is proposed that CPCB collects this revenue and then allocates it to the SPCB of each state. The funds can be used to pay the incentives for kabadiwalas and formal e-waste value recovery operations monthly.

Suppose a formal recycler issues a receipt to the kabadiwalas during the delivery of collected e-waste. The kabadiwalas can use the same receipt to claim the incentive for e-waste collection and transportation from the SPCB at the end of each month.

When kabadiwalas sell their e-waste through a registered dealer, the formal recycler issues a similar receipt to the dealer. The receipt can be used to claim the relevant incentives for e-waste transportation. The dealer should share the receipt with the kabadiwalas, and they can use it to claim the incentive for e-waste collection activities.

These incentives can be calculated based on the type and quantity of waste collected and delivered by kabadiwalas/dealers throughout the month. The formal recycling facilities engaged in refurbishing and value recovery operations will also be eligible to receive an incentive from the SPCB based on the adopted value recovery operations, including final solid and liquid waste disposal strategies.

Considering the significant number of people involved in India's informal e-waste supply chains and value recovery operations, integrating them into the proposed model would be challenging. However, the authors believe that the integration and more formal e-waste supply chains and value recovery plants will help in developing a sustainable e-waste business in India, fostering the United Nations sustainable development goals (SDGs), such as sustainable cities and communities (SDG 11) and responsible consumption and production (SDG 12).

6. Limitations and future recommendations

Though integrating informal and formal e-waste management sectors appears to be one of the most effective methods for designing a more efficient e-waste management system in India, the integration task is expected to be considerably complicated and time-consuming. Due to the large number of kabadiwalas currently working in India (could be as high as 1% of the population), identification and registration of these informal waste collectors will be an elaborate process. Designing and implementing a functional e-waste management system integrating both sectors will require more detailed and large-scale studies and perhaps some legislative changes to the country's existing e-waste management laws and regulations. In addition, informal e-waste value recovery operations need to be managed by the legislative frameworks before integrating into the proposed EPR model (i.e. operation of informal value recovery operations are much more complex than informal e-waste collectors/kabadiwalas).

7. Conclusions

Despite being the third-largest e-waste generating country globally, the collection and recycling rates of e-waste in India remain very low, implying inefficient e-waste management and value recovery. Using advanced technology, a small fraction of the total e-waste generated is sustainably recycled by the formal sector. At the same time, the rest of the generated e-waste is processed by the informal sector using artisanal value recovery operations that often pose severe threats to human health and the environment. In India, kabadiwalas, as informal solid waste collectors, play a very significant role in e-waste supply chains. Thus their engagement is crucial when handling household e-waste collection economically in India.

Considering the more significant number of workers engaged in the informal e-waste management and value recovery sector and the challenges faced by the formal sector (e.g. inefficient e-waste supply chains), the integration of both the sectors is crucial when establishing a sustainable e-waste management and value recovery operations in India. Modified EPR schemes in India can potentially achieve this, but government support and relevant legislative frameworks are paramount.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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