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Creating an Effective E-Waste Management Framework for India: Insights from Germany and China Using Radar Chart

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Abstract:
The global e-waste crisis, with 53.6 million metric tons produced annually and only 17% properly recycled, poses significant environmental and health risks. Rapid technological advancements and consumer demand exacerbate this issue, particularly in India, where the unorganized sector manages 95% of e-waste without formal regulation or advanced technology, leading to substantial hazards. In contrast, Germany's stringent regulations and structured frameworks exemplify effective e-waste management. China, like India, faces challenges with a large informal sector handling 60% of e-waste. A proposed framework includes formalizing the unorganized sector, integrating local e-waste collectors through training and certification, and promoting public-private partnerships. Key strategies involve implementing stringent Extended Producer Responsibility (EPR) regulations, enhancing government oversight, and increasing public awareness. Additionally, investing in modular technologies, fostering international partnerships, and establishing widespread collection points are essential. These adaptive strategies can help India and China develop sustainable e-waste management systems, contributing to global mitigation efforts

Keywords: E-Waste, Unorganized Sector, Kabadiwalas, Germany, India, China, EPR, and Radar Chart

Introduction

In an article published by WEF, it is estimated that 53.6 million metric tons of e-waste are generated worldwide annually. Not surprisingly, but also alarmingly, only approximately 17 percent of that waste is collected, documented, and recycled each year across the globe. (*WEF*, 2023). Electrical and electronic waste are the fastest-growing waste stream in the world. The tremendous pace of technological innovation and the growth in consumer demand for new electronic devices also contribute significantly to this growth. From smartphones and laptops to household appliances and industrial machinery, the proliferation of electronic equipment has transformed our lives, making them more convenient and interconnected. Nevertheless, this rise in usage corresponds to a rise in electronic waste, which is both an environmental and health risk. Efforts to reduce the e-waste crisis are ongoing globally, where initiatives in improving recycling rates, promotion of designing product for better sustainable, and awareness of proper e-waste management are being initiated. It is a collective effort that involves the government, corporations, and consumers in addressing this issue. Through better rules and regulations and proper investments in recycling facilities and being mindful of one's electronics usage, people can really contribute to reversing of e-waste logistics.

India is one of the developing nations and very rapidly emerging as a global IT hub. The industry has become a significant pillar of India's economy with its contribution to GDP accounting for 7.5% in the fiscal year 2023 and it is estimated that this contribution would increase to 10% by 2025(*IBEF*, 2024). With this tremendous growth of the Indian IT sector, the consumption of electronic products has grown with a tremendous rate and is increasing day by day. In the fiscal year 2022 alone, India produced more than 1.6 million metric tons of e-waste (*Kajalben Patel*, 2021). The e-waste management currently is dominated by the unorganized sector in India, handling around 95% of the total produced e-waste. (*Kajalben Patel*, 2021). While very important to keeping large volumes of hazardous waste out of landfills, this industry operates unregulated and in many places is not exposed to cutting-edge processing technologies.

Countries such as Germany are leading the way toward proper e-waste management. The Electrical and Electronic Equipment Act (ElektroG) in Germany requires specific duties for relevant stakeholders, including manufacturers, trade, municipalities, owners, and disposers in managing e-waste (Nelles et al., 2016). Key stakeholders in this system include Public Waste Management Authorities (PuWaMA), e-waste producers, and the clearinghouse called the Elektro-Altgeräte Register (EAR). Interestingly, as of 2016, 14% of Germany's resources are sourced from recovered waste materials and the waste management industry(Nelles et al., 2016).

E-waste management in China is like India, dominated by an informal sector, as nearly 60% of e-waste in China is managed by this sector. (*Malika*, 2022). Among its regulatory measures, the country has also provided various guidelines where the country has defined responsibilities for manufacturers, retailers, consumers, and recycling enterprises.

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E-Waste Management in Germany

Germany has a well-developed e-waste management structure, founded on strong legislation and backed by multiple stakeholders. At the heart of this framework is the Electrical and Electronic Equipment Act (ElektroG), which outlines clear responsibilities of manufacturers, trade entities, municipalities, owners, and disposers. The ElektroG requires producers to be responsible for the product lifecycle, from collection to recycling, ensuring that all stakeholders follow a structured process to manage electronic waste (UNU-ISP, 2011). This whole process is presented in Fig. 1.

In addition to ElektroG, the Closed Cycle Management Act (Kreislaufwirtschaftsgesetz, KrWG) is a central law for shifting the waste management approach towards being more resource-oriented in Germany. It focuses on closed-loop systems with responsibility for disposal at the hands of manufacturers and distributors. It has helped foster an increased awareness among the public in separating wastes, motivated new technologies in disposing, and increased capacities in recycling. Therefore, in 2016, recycled material accounted for 14% of Germany's resource supply, and the waste management industry produced €40 billion in revenue (Nelles et al, 2016).

Management of e-waste in Germany involves several key players. Public Waste Management Authorities, PuWaMA, have the role of setting up district stations for disposal of e-waste. These authorities can collect the e-waste directly from the public. Their role is critical in the early stages of waste management when the collected e-waste is transferred to producers for handling logistics, treatment, and final disposal. While EEE producers are responsible for takeback schemes of e-waste, the arrangement under which the schemes are to be implemented can be brand-selective, non-selective, or collective (Chaudhary & Vrat, 2018). A clearing house, the Elektro-Altgeräte Register (EAR), also monitors compliance by calculating market shares and ensuring that producers meet their collection targets.

Despite the sound regulatory environment and active participation of all relevant stakeholders, there are several problems in handling e-waste in Germany. The country is able to collect less than 50% of its e-waste, which, in turn, leads to illegal transboundary shipments of e-waste to developing countries and also, waste generation patterns highlight that the most waste generating sectors are the construction and demolition sectors and less are from mining rubble (UNU-ISP, 2011). These differences highlight that there must be continued improvement in recycling practices and waste management.

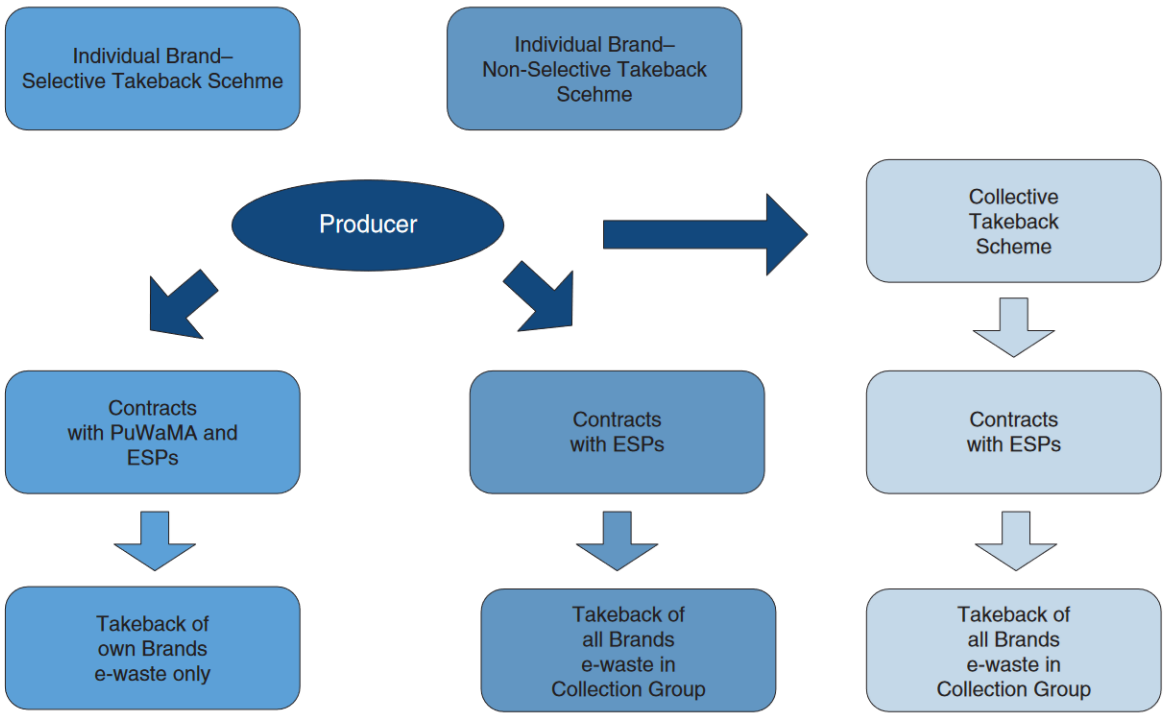

Fig 1: E-Waste Management in Germany. (Source: Adapted from UNU-ISP (2011))

E-Waste in India

E-waste management in India is a very complex issue that has been characterized by a fragmented value chain involving the organized, unorganized, and semi-formal sectors. This sector, involving scrap dealers and kabadiwalas or rag pickers of informal waste collectors as depicted in Fig. 2, generally handles e-waste using very primitive methods, thereby resulting in grave environmental and health hazards (Skinner et al., 2010). Conversely, the organized sector, represented by formal players, is involved in regulated e-waste management processes.

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There are three stages in the e-waste lifecycle in India: preliminary, secondary, and tertiary. Preliminary stakeholders such as scrap dealers source the e-waste from the formal sectors through bidding and pass it to the secondary stakeholders and the secondary players have limited financial capacity and transfer the e-waste to the tertiary stakeholders who manage the dismantling, segregation, and extraction of valuable components using less advanced techniques. (Sinha et al., 2011). It is clearly noticed that the formal sector does not provide comprehensive processing as most of the formal recyclers work on segregation and dismantling up to the size reduction of printed circuit boards. The pre-processed PCBs are then sent out to developed countries for further recovery of precious metals and slag treatment (Sinha et al., 2011).

Formal sector in India finds it hard to execute their e-waste management programs due to dominance of informal sector. Informal sector players can operate at lower costs and circumvent regulations, challenging formal recyclers who bear high costs for collection, transport, and disposal alongside a shortage of facilities for precious metal extraction (Skinner et al., 2010). Formal sector processes are limited to PCB size reduction with advanced technologies used only for efficient recovery of metals in a protected environment. The technologies that include zero-landfill approaches are economically viable as the high capital costs are spread over large volumes of processed e-waste. However, the end-to-end recycling solution is not available in India, which leads to inefficient metal recovery and environmental management.

Another major issue is the low level of awareness among consumers and producers on e-waste management. Effective consumer participation in successful recycling programs is critical, but little effort from the producers in educating consumers has led to inefficient product usage and a low involvement in recycling practices (Sinha et al., 2011). The absence of indigenous e-waste processing centres limits the ability to handle e-waste domestically and recover valuable materials effectively.

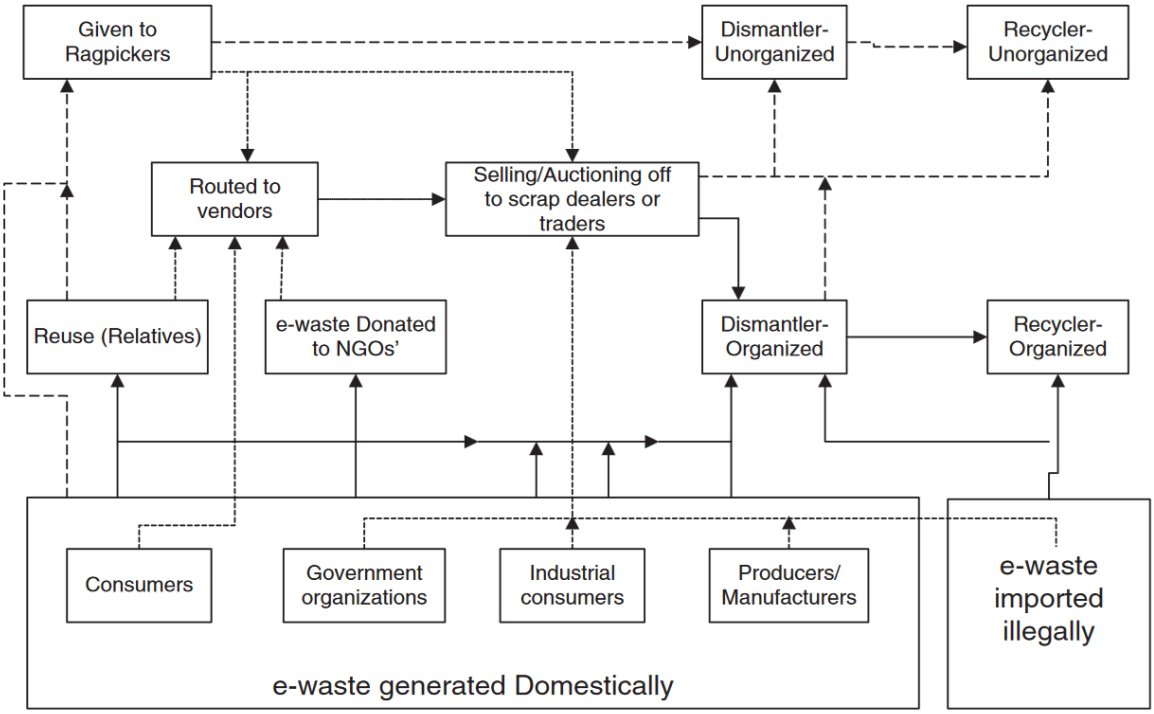

Fig 2: Source: E-Waste Flow in India (skinner et al 2010)

E-Waste Management in China

In China, e-waste management has multiple stakeholders and diverse economic reasons interacting with each other in an informal and formal interplay. The informal sector constitutes waste pickers or 'pedlars', traders, retailers, collectors specialized on certain materials, and second-hand markets. (Lines et al., 2016). This industry flourishes as a result of income differences between the rural and urban centres and also due to the electronic equipment high turnover rates in urban areas. The demand for electronics in rural areas, where the prices for the devices are relatively lower, has led to second-hand electronic devices being repaired and resold.

Informal waste pickers and recyclers in China are more interested in reusing devices or components than in extracting metals, which generally has a higher economic payback. The sector encompasses a wide range of activities and income levels, from the most marginalized groups that are only able to survive through waste picking to more complex networks

involving collectors, brokers, and recycling facilities (Bo & Yamamoto, 2010). Despite its size and economic significance, informal recycling is often carried out using primitive methods that present significant environmental and health hazards. Besides the informal sector, China has also instituted formal collection systems for e-waste as we have in Fig. 3. These include collection by specialized recycling plants and trade-in programs offered by home appliance stores. However, these formal methods pose challenges such as low participation rates due to the hassle and cost associated with collection from recycling plants, the relatively recent adoption of trade-in schemes that offer reductions on new appliances in return for old ones. While these initiatives have been carried out, formal collection methods have not increased e-waste recovery rates by much (Bo & Yamamoto, 2010).

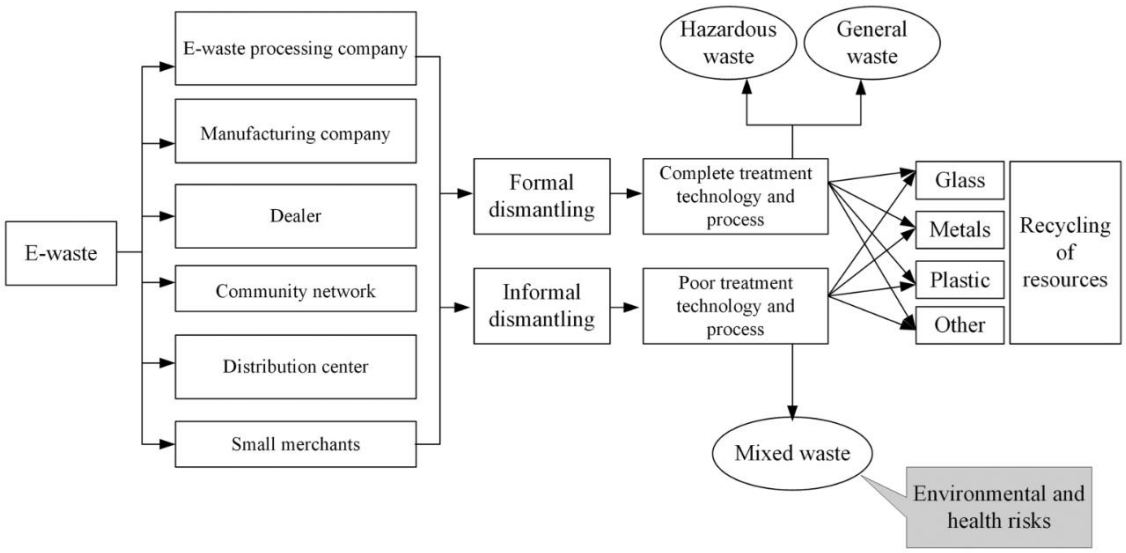

Fig 3: China's E-Waste Management Flowchart (Yang and Zhang, 2022)

Literature Review

Brebbia et al., 2014, publishes the proceedings of the seventh International Conference on Waste Management and the Environment, from the success gained in past conferences since the year 2002. The scope of the topic's ranges over the broad coverage of the areas related to waste management and environmental protection, namely the environmental implications of waste, strategies toward the 4Rs reducing, reusing, recycling and recovering energy recovery from wastes, managing e-waste, optimising landfill, and mining as well as relevant legislation concerning environmental remediation. The proceedings reflect the latest research and developments in these areas, aiming to address contemporary challenges and advance effective waste management practices globally.

According to UNU-ISP, 2011, estimates that European Union member states produce around 10 million tonnes of e-waste every year, which is roughly the same as the annual growth in electrical and electronic equipment (EEE) sales, at 2.5% to 2.7% (UNU-ISP, 2011). In this regard, the WEEE Directive of 2003 has made it mandatory to use environmentally friendly collection and treatment methods for e-waste. Each member state then enacts this directive in its national legislation, hence differing in approach. For example, in Germany, responsibility for handling e-waste was moved to producers through the ElektroG 2005.

Chaudhary & Vrat, 2018 has presented an e-waste management system in Germany. Under the Electrical and Electronic Equipment Act (ElektroG), each stakeholder such as the manufacturer, trade entity, municipality, owner, and disposer of e-waste is specified with their specific responsibilities of managing e-waste and the major stakeholders in the system are the public waste management authorities (PuWaMA) that set district stations for e-waste disposal and collect e-waste directly from the people where EEE producers (private organizations) manage e-waste through three different methods: Individual brand-selective take back schemes, individual non-selective take back schemes and collective take back schemes (Chaudhary & Vrat, 2018).

According to Nelles et al., 2016 e-waste management in Germany follows the principles of closed cycles where the responsibility of disposing the waste is assigned to manufacturers and distributors, thus raising public awareness about the separation of waste, bringing about new technologies for disposal, and increasing recycling capacities. As of 2016, 14% of Germany's resources were acquired from recovered waste materials, and the waste management industry

generated €40 billion. In 2013, mining rubble produced the least waste, while construction and demolition activities generated the most waste.

In a research paper by Chatterjee, 2011, in India, 95% of e-waste is processed by the informal sector and only 5% is handled by formal units. The informal e-waste recyclers are spread all over the country. In most cases, such treatment releases hazardous substances in the air, soil, and water because of inappropriate safety measures and not to mention that the recycling efficiency is low, focusing mainly on recovering valuable metals like gold, silver, aluminium, and copper, while others such as tantalum, cadmium, zinc, and palladium are not recovered (Chatterjee, 2011).

Adhana, 2020 in shows how e-waste recycling remains a barely existent concept in India, in which cases electronic waste often makes its ways into rivers and dump yards without proper treatment or recycling. This scenario poses several hazards to environment and health. The existing paper develops the e-waste situation in India that is of comparison interest with other aspects of the world. It is disclosed that computer equipment and mobile phones are the biggest e-waste producers in India, accounting for computers to contribute to 70% of the total e-waste and telecommunication equipment constituting 12% (Adhana, 2020).

Wang et al., 2022 discussed the importance of informal recycling practices reduction for sustainable electronics end-of-life management. It emphasizes recent studies that show how the informal and formal sectors can collaborate to create greener recycling solutions. Using Guiyu, China, as a case study, it examines efforts to integrate the informal e-waste recycling sector into a formalized industry. The study analyzes policy, technology development, and market establishment in Guiyu's formal sector to improve local e-waste management. Key findings include the success of advanced centralized treatment alongside traditional informal practices such as manual dismantling and private collection networks that preserved reuse value and ensured a stable supply of e-waste.

Chenyu Lu et al, 2014 China is a leading manufacturer and consumer of electronic products. A great amount of e-waste is, therefore, generated in this country. There are critical environmental and health impacts, which have been noticed globally, hence making central and local governments strengthen efforts in this area. During the past years, there have been new regulations established and the cooperation between the enterprises enhanced. This study examines the rapid growth in the collection and dismantling of e-waste from 2000 to 2012 across five major types of electronic equipment in China. It identifies barriers and proposes solutions to address e-waste challenges, emphasizing the need for policies to enhance eco-efficiency in e-waste management.

Vrat et al., 2017 present India as the fifth largest producer of electronic waste (e-waste) globally, yet 95% of its e-waste is processed by the unorganized sector using unscientific methods, causing significant environmental and health issues. Leveraging the reverse supply chain (RSC) for e-waste can offer numerous social, economic, and environmental advantages. This paper identifies and analyzes the barriers to effective RSC implementation in India through extensive literature review and expert consultation. Through interpretive structural modeling, the study discovered that the primary barriers include legal issues, lack of awareness, and inadequate infrastructure.

Federal Ministry for the Environment et al, 2023 show that the circular economy intends to reduce resource consumption through the efficient use and recycling of raw materials throughout the whole lifecycle of a product-from extraction to disposal The 2018 Circular Economy Act incorporates the polluter pays principle as well as the five-step waste hierarchy. Germany's circular economy sector, encompassing 11,000 companies and generating 80 billion euros annually, provides a model for other countries seeking to close their material cycles ecologically.

R. Wang et al., 2021 demonstrate how waste electrical and electronic equipment, e-waste, is an essential constituent of "urban mining" and is gaining attention for pollution control and circular recycling potential. In China, there is significant progress in WEEE reutilization and pollution control. WEEE recycling involves four levels: repair, reuse, and remanufacture, waste-to-materials, waste-to-products, and waste-to-energy. Future WEEE management will be intelligent handling of hazardous waste and pollution, while technologies will shift towards value-added and automated reutilization rather than simple dismantling.

Malika, 2022 e-waste is increasing globally, with an annual increase of 3-5%. China faces an increased volume of e-waste both from its domestic sources and from illegal imports. It is handled through both formal and informal sectors. The author claims in the paper that China is the largest producer and importer of electronic devices and the largest e-waste market. Over 60% of China's e-waste is recycled informally, while about 40% goes through formal channels. The major challenge for China is to create incentives for formal recyclers to curb informal recycling activities.
Sengupta et al., 2023 2023 present a structured expository presentation about the rapid advancements of electronics and telecommunications technologies, which significantly contributed to the e-waste becoming one of the largest and fast-

growing solid waste streams. India annually generates over 3.23 million tons of e-waste with more than 90% being treated by the informal sector. According to the author, informal waste collectors, commonly referred to as 'kabadiwalas,' handle most of this e-waste, though no percentage is known. The study concludes that kabadiwalas' large workforce and low operating costs enable effective nationwide e-waste collection, suggesting that integrating them into the formal e-waste industry could improve management and value recovery in India.

Lu et al., 2015 demonstrate that China is among the world's largest electronic product manufacturing and consumption countries, hence producing a tremendous amount of e-waste. The author claims in the paper that the management and recycling of e-waste in China have raised serious environmental and health concerns worldwide. It identifies and discusses barriers and potential solutions for China's e-waste management and offers policy implications to enhance eco-efficiency. According to WEF, 2023, the United States generates approximately 46 pounds of e-waste per capita annually, and this sums up to 53.6 million metric tons in the world yearly. Of this waste, only 17% is recycled; the rest sits idle or is improperly disposed of. Overcoming data security concerns, making recycling convenient, and perhaps introducing incentives or regulations will be necessary to increase recycling rates. The inherent value in e-waste makes solving these challenges economically viable.

The emerging issue of e-waste, particularly in India due to rapid economic growth and technological advancements, leads to increased electronic consumption is an area that K. Patel, 2021, discusses. study addresses the growing issue of e-waste, particularly in India, where rapid economic growth and technological advancements have led to increased electronic consumption. E-waste management in India is divided between formal and informal sectors, with the latter dominating and being poorly regulated.

Streicher-Porte et al., 2005 examine the rapid increase in e-waste in China and the country's efforts to address it through laws and regulations based on Extended Producer Responsibility (EPR) principles, introduced by the government in 2009. The paper evaluates China's e-waste management system by analysing government policies, enterprise involvement, and public awareness. It covers the evolution of regulations, policy changes, and the development of formal e-waste recycling companies, along with the advances in recycling technology, capacity, and infrastructure, such as key companies and a national industrial park.

Dutta & Goel, 2021 explores the landscape of e-waste recycling in India, pointing out the domination of the informal sector that processes 95% of e-waste at a huge cost to health and the environment. The study sought to assess both formal and informal e-waste recycling facilities, focusing on seven authorized facilities across West Bengal, Maharashtra, Karnataka, and Delhi. Most formal facilities are involved in the dismantling and compliance with environmental regulations by recovering metals, plastics, and glass.

Kaur et al, 2022, addresses the growing challenge of e-waste, driven by increasing electronic equipment usage, which resulted in a reported generation of 53.6 million metric tonnes (MMT) globally in 2019. It critiques how EPR implementation is still inadequate due to the issues in infrastructure and transparency. E-waste leaks into the informal sector, which processes e-waste in an unsafe manner. She calls for a revamped National EPR framework that would incorporate circularity, better stakeholder responsibility, and improved infrastructure for enhanced e-waste management in India.

According to IBEF 2024, the IT & BPM sector is one of the major growth drivers for the Indian economy. It contributed 7.5% to India's GDP in FY23 and is expected to reach 10% by 2025. With digital applications expanding across sectors, India is also set for further IT growth, boasting one of the largest Internet user bases and the lowest Internet rates, with 760 million citizens online.

Bo & Yamamoto, 2010, aims to identify processes, current situations, and issues of recycling systems for four home appliances, namely, air conditioners, television receivers, refrigerators, and washing machines, among e-waste in China and Japan for understanding and comparison of their characteristics and by results of a literature search, review of information disclosed online, and questionnaire survey conducted, the conclusions of the study boil down to the results show that in Japan most of the home appliances mentioned above have been collected through home appliance recycling tickets, resulting in an issue of "requiring some effort" in treatment and recycling stages, and most plants have contracted out their e-waste recycling (Bo & Yamamoto, 2010) .

Lines et al., 2016, report that e-waste is one of the fastest-growing waste streams today, and proper management can recover valuable materials while reducing emissions. However, improper processing by informal and unregulated enterprises leads to health and environmental damage while exacerbating worker vulnerability and using case studies from China and India, this paper looks into building more inclusive greener economies that benefit from informal markets

but also redress exclusion from formal activities where in both countries, regulatory efforts are often overridden by the fact that their informal e-waste sectors are overlooked in importance (Lines et al., 2016).

Yang & Zhang, 2022, addresses the rapidly growing problem of e-waste management in developing and underdeveloped regions, specifically focusing on China and the paper brings out the extreme environmental and health risks associated with informal recycling and disposal processes of electronic waste, mainly in manual dismantling workshops where this study seeks to advance theoretical and empirical understanding of e-waste management and contribute to developing a sustainable industrial ecosystem within the industry 4.0 framework (Yang & Zhang, 2022).

Cao et al., 2016, look into the rapid growth of e-waste in China and efforts from the government side through laws and regulations based on Extended Producer Responsibility (EPR) principles initiated in 2009 and it also examines the effectiveness of China's e-waste management system from three aspects: government policy, enterprise involvement, and public awareness while at the same time it reviews government regulations, policy amendments, and the development of formal e-waste recycling enterprises, alongside advancements in recycling technology, capacity, and infrastructure, including leading enterprises and a national industrial park. The paper also surveys public awareness of e-waste hazards, disposal habits, and participation in environmental initiatives, although much has been done in the last six years, together, by the government, businesses, and citizens, towards easing e-waste management challenges in China, the study indicates some of the perpetual problems with suggested solutions for further improvement (Cao et al., 2016).

Research Gap

There is a substantial body of research on e-waste management practices in Germany, China, and India through various case studies, but an important gap remains in developing an adaptive framework that is effectively applicable in India. Although the insights from individual country analyses are valuable, comprehensive models integrating diverse strategies into a unified approach for India are missing. Our research paper attempts to bridge this gap by building an adaptive practical framework with practical radar chart analyses of some of the key influencing factors of successful e-waste management in Germany and China. With this integration, we expect to construct a model adaptable to India's own socio-economic and regulatory circumstances. The proposed framework shall draw together best practices and identify actionable steps for their execution in India. Our research, through a thorough analysis of regulatory frameworks, technological innovation, public awareness campaigns, and industry collaborations, would ultimately provide a roadmap for enhancing e-waste management initiatives by Indian policymakers and relevant stakeholders in their endeavour towards sustainable practices, reduction in environmental impact, and maximum resource efficiency.

Research Methodology

E-waste management practices in Germany, China, and India were chosen for secondary data analysis for a comprehensive review. Sample size comprised the three countries mentioned above. The study uses a radar chart methodology, which measures performance across seven critical indicators: the involvement of the unorganized sector, national infrastructure capabilities, the effectiveness of e-waste collection mechanisms, adherence to Extended Producer Responsibility (EPR) by manufacturers, the robustness of regulatory frameworks, rates of recycling and recovery, and levels of innovation in e-waste management. This research uses the radar chart analysis to identify areas in which India needs improvement and areas in which it is already doing well in managing e-waste. The findings are used to develop an adaptive strategic and practical model tailored for implementation in India. The model aims to fill the identified gaps and capitalize on strengths to enhance the overall effectiveness of e-waste management practices in the country.

Comparative Analysis of E-Waste Management

Table 1 presents the analysis of E-waste Management Performance in Germany, India, and China. Factors used were selected based on their substantial impact on the performance and sustainability of e-waste systems in each country. Though using a wide range of indicators is necessary for an in-depth analysis, it is essential to maintain a balanced number of factors to achieve clarity and practicality in the radar chart analysis.

Table 1: Performance of E-waste management practices in Germany, India, and China.

Factors	Unorganized Sector Involvement	Infrastructure	Collection Mechanism	Producer Accountability on EPR	Effectiveness of Regulatory Framework	Recycling and Recovery Rate	Innovation

Germany	50%	Strong	Official system PuWama, 50%(average)	Very accountable	Effective	44.10%	Leading
India	95%	Weak	1.5% by the official system 95% by kabadi walas	Not accountable for their responsibilities	minimally effective	22.07%	Lagging
China	60%	Growing	40%official 60% scavengers	Somewhat accountable	minimally effective	15%	emerging

Rating of E-Waste Management in Germany, India and China

Countries are ranked on a scale of 1 to 4, where 4 is the highest and 1 is the lowest. A score of 4 reflects measurements that are strong, highly accountable, very effective, and at 76%-100%, leading. A score of 3 is growing, accountable, moderately effective measurements in the 51%-75% range and classified as emerging. A score of 2 represents average measurements that are partly accountable and effective, which have a performance of 26%-50%, and are stagnant. Lastly, a score of 1 represents weak, unaccountable, least effective measurements that achieve only 1%-25% and are lagging. This scoring system is devised to give a clear and standardized way of assessment. This structure is shown in Table 2.

Table 2: Rating assigned based on the secondary data collected

strong	very accountable	very Effective	76%-100%	leading	4
Growing	Accountable	moderately effective	51%-75%	emerging	3
average	Somewhat accountable	Somewhat Effective	26%-50%	stagnant	2
weak	not accountable	minimally effective	1%-25%	lagging	1

Table 3: A new table of Table 1 Referenced to Table 2

Factors	**Unorganized Sector Involvement**	**Infrastructure**	**Producer Accountability on EPR**	**Effectiveness of Regulatory Framework**	**Recycling and Recovery Rate**	**Innovation**	**Collection Mechanism**
Germany	2	4	4	4	2	4	3
India	4	1	1	1	1	1	1
China	3	3	2	1	1	3	2

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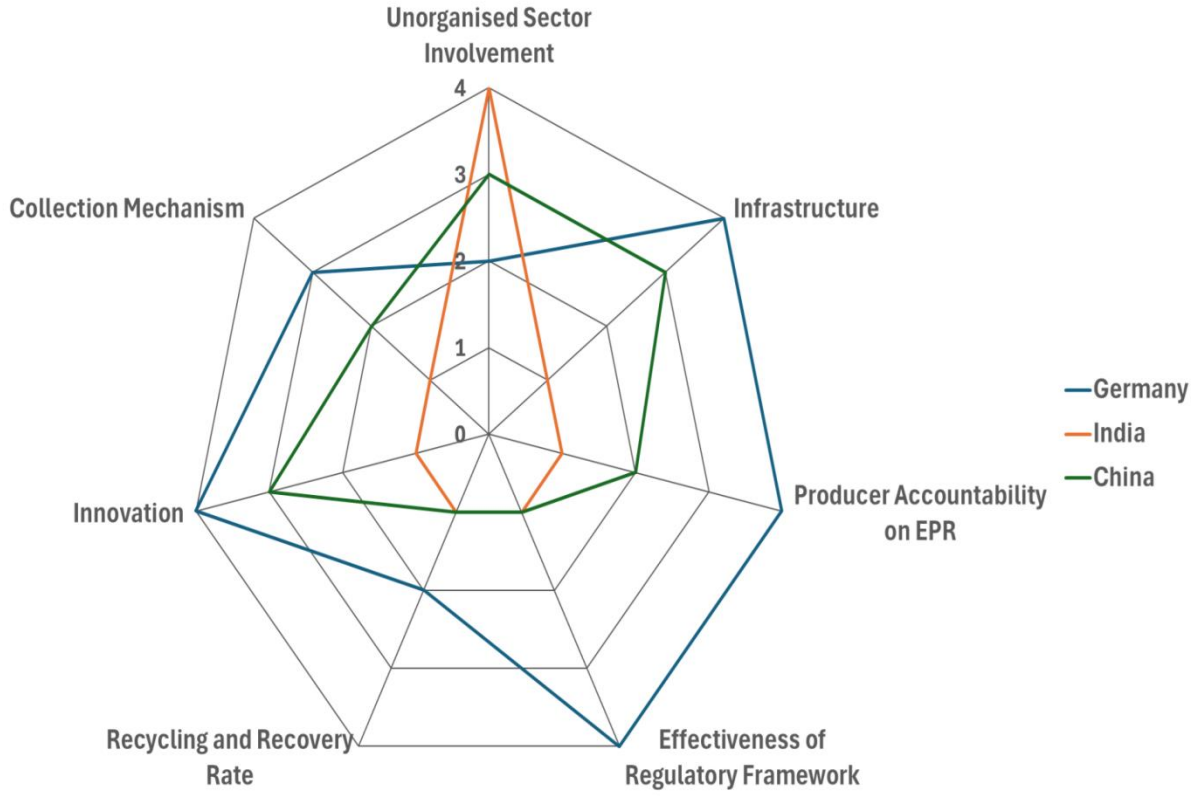

Figure 4: A radar chart presentation of e-waste management performance for Germany, India, and China.

Results and Discussions

Implications from Radar Chart Model

As we can see from the implication from Table 3, India has shown to score lowest in 6 major parameters in Fig. 4. Germany excels in all seven parameters of e-waste management except for the involvement of the unorganized sector, indicating a highly organized approach to managing e-waste. This systematic management ensures efficient collection, processing, and recycling of e-waste, contributing to the country's leadership in environmental sustainability and innovation. In comparison, both India and China score alike on the rating scale for effectiveness of the regulatory framework as well as recycling and recovery rate. But, with respect to infrastructure, EPR producer accountability, innovation, and collection mechanisms, China fares better than India. Therefore, this reflects that despite challenges being the same in many respects for both countries, China has really made tremendous strides by developing strong infrastructure and developing innovative solutions for the disposal of e-waste.

India can learn a lot from the best practices of Germany and China. If India can adopt the organized sector approach of Germany and utilize the developments of China in infrastructure, accountability, and innovation, then the e-waste management system of India can be developed further. This could be through improvement in the regulatory framework, investment in recycling infrastructure for e-waste, innovation in recycling technologies, and effective collection mechanisms. Improving recycling and recovery rates, leading toward better environmental outcomes and public health benefits would also be significantly enhanced by the reduction of unorganized sector involvement and increase in producer responsibility through EPR.

Unorganized Sector

In Germany, around 50% of e-waste escapes the official e-waste management system and one of the main sources of this uncontrolled waste is street collections. Here, private users place their discarded electrical and electronic equipment (EEE) on the streets during scheduled household collections by PuWaMA (public waste management authorities) and the informal collectors often precede formal collection teams and scavenge through these items where They might also directly approach private consumers to collect used EEE, sometimes even paying them for these items (Deubzer, 2011). India is the fifth largest generator of electronic waste or e-waste in the world, however, 95% of this e-waste is still being managed by the unorganized sector through unsafe processes (Vrat et al., 2017). This informal industry contributes to enormous environmental pollution and health hazards caused by the practice of open burning of the electronic components for extracting metals, which emit toxic pollutants (Adhana, 2020)

China also deals with high informal e-waste recycling practices, through which more than 60% of the country's e-waste is handled in informal channels and this informal sector conducts operations without the regulation of the formal system, thus extracting metals such as copper, gold, and palladium through manual dismantling and open burning. These activities pose serious environmental as well as health risks where hazardous chemicals are released to the environment and workers in unsafe conditions are exposed in the absence of adequate safety measures (Malika, 2022). The wide proliferation of the informal sector within e-waste recycling activity in both India and China underscores the need for some strong regulatory reforms and better management approaches for effective improvement of these issues.

Infrastructure

Germany has a strong infrastructural base for e-waste management under the Electrical and Electronic Equipment Act (ElektroG) (Chaudhary & Vrat, 2018). ElektroG assigns clear duties to manufacturers, traders, municipalities, owners, and disposers to efficiently manage e-waste. ElektroG emphasizes the prevention of waste, ensures the reuse of appliances and components, and ensures extensive recycling. Key stakeholders are public waste management authorities (PuWaMA), private EEE producers, and the Elektro-AltgeräteRegister (EAR) clearing house, which oversees compliance and facilitates coordination among the parties and the e-waste management infrastructure in India is perceived to be weak today owing to the inability of India to effectively implement policies as well as establish reverse supply chain management systems, that are strong (K Patel, 2021). It's quite different from the scenario for more developed countries as they have the problem of making it possible to collect, transport, and recycle e-waste in a planned manner that is environmentally sound. One other critical issue is testing and processing facilities; otherwise, there is no good assessment of the condition of electronic devices and their method of disposal or recycling. China has put in place a comprehensive legal framework to manage e-waste from collection, transportation, treatment, and the lifecycle of electrical and electronic equipment(R. Wang et al., 2021). This infrastructure is growing, with an emphasis on environmental sustainability and health protection through strict regulations.

Collection Mechanism

In Germany, the collection of e-waste is mainly organized by PuWaMa (public waste management authorities), which collect around 50% of the total collections(Chaudhary & Vrat, 2018). Producers also have a significant role in the e-waste management chain, where they are required to organize and finance the collection, transportation, and recycling of e-waste according to their market share. In India, about 95% of e-waste is dealt with by the informal sector that functions outside the formal regulatory framework (Vrat et al., 2017). The remaining 1.5% is handled by the formal sector, which includes government-approved recycling facilities and regulated collection systems(Adhana, 2020). The remaining 1.5% is handled by the formal sector that involves government-approved recycling facilities and regulated collection systems (Adhana, 2020). In China, about 60% of e-waste is managed through informal channels, and the formal sector gets the remaining 40%, highlighting a significant reliance on unregulated practices for electronic waste handling (Malika, 2022).

Producers' Responsibility on EPR

Extended Producer Responsibility (EPR) in Germany, regulates that producers should not only assume responsibility for managing electronic waste but also finance the entire process. The regulations include collection, transportation, recycling, and disposal of e-waste in proportion to the quantity of EEE that is introduced into the market (UNU-ISP, 2011). These financial burdens encourage producers to engage in effective e-waste management, thereby protecting the environment and conserving resources. In India, for instance, under EPR, the responsibility of e-waste management lies with the producers, who are not held accountable in most cases. This leads to an informal sector, which handles 95% of e-waste(*Kaur*, 2022). This informal management poses issues such as poor recycling and environmental pollution due to a lack of strict regulatory supervision. China is slowly becoming answerable under EPR regulations to manage e-waste, and this is the gradual transition towards more structured and regulated management practices in the recycling industry (Jian Cao et al., 2016).

Effectiveness of Regulatory Framework

In India's e-waste management landscape, significant challenges persist there are no penalties for illegal disposal of e-waste, producers frequently evade accountability for neglecting their responsibilities, and there is a lack of mechanisms to recognize and incentivize organizations that excel in managing e-waste. Monitoring and control efforts are also inadequate, particularly in addressing the issue of illegal imports of e-waste(Vrat et al., 2017). E-waste management in China is currently minimally effective, facing challenges such as inadequate enforcement of regulations, insufficient infrastructure, and limited capacity to handle the vast volume of electronic waste generated(Malika, 2022).

Recycling and Recovery Rate

Germany may have collected slightly over 1 million tonnes of WEEE in 2020, but its recycling rate stands at 44.1%, which is still below the minimum recovery rate set by the EU as 65% (Meunier, 2022). This means that Germany still has

a lot to do in terms of recycling e-waste to effectively meet the set regulatory standards. India could recycle only about 22.07% of its generated e-waste during the fiscal year 2019-2020 (The India Express, 2024). This recycling rate is indicative of the fact that the country is continuously working to address electronic waste management but still has much to do in terms of developing recycling infrastructure and practices. In China, only around 15% of the annual e-waste is recycled (Zhen Wang, 2023).

Innovation

Germany is ahead in the management of e-waste, not only in compliance and infrastructure but also innovation (Deubzer. 2011). The country is always developing and implementing new technologies and processes that ensure the efficient collection, sorting, and recycling of electronic waste. In India, e-waste management lags behind due to poor implementation of penalties against defaulters, lack of funds, institutional weaknesses, inappropriate technology selection, and public apathy toward municipal solid waste (Adhana, 2020).

Guiyu in China is an innovative example of innovating in e-waste management. The government of this place has partnered with the informal sector to boost recycling efforts and increase the recycling rate. Government funding supports the strategy of bringing technological advancement and sustainability practices into local recycling initiatives(C. Wang et al., 2022).

Proposed Framework for India

Table 4: Adaptive Strategy Model Implementable in India

Factors	**Current State**	**Reasons**	**Goal**	**Proposed Action Steps**
Unorganized Sector Involvement	95% involvement by the unorganized sector	● Limited consumer awareness of proper disposal of e-waste ● The formal sector has less local presence and ineffective regulatory frameworks ● high production of e-waste but insufficient collection mechanism from the government	Formalize and integrate the unorganized sector into the official waste management system	● Formalize the unorganized sector by integrating kabadiwalas into the official waste management system through training, certification programs, and financial incentives ● Implement a certification system for e-waste collectors and recyclers ● Establish cooperatives for informal recyclers and provide government support ● Form a formal association of local e-waste collectors, recyclers, and dealers that receive incentives, schemes, and market opportunities through governmental supports

infrastructure	Weak	● Lack of adequate facilities for processing e-waste ● Insufficient consumer participation due to lack of awareness and hence less support to the government	Build a robust infrastructure for waste management	● Develop state-of-the-art e-waste recycling plants and promote public-private partnerships ● Invest in centralized e-waste processing zones with modern facilities.
Producer accountability on EPR	Not accountable to their responsibilities	● Dominance of unorganized sector causing negligence to the producers ● Lack of financial incentives ● Weak enforcement mechanism ● Inadequate infrastructure ● Consumers not aware of proper e-waste disposal ● Ineffective monitoring systems	Ensure producers take responsibility for the lifecycle of their products.	● Implement stringent EPR regulations with mandatory take-back schemes ● Enforce producer responsibility through strict penalties and incentives for compliance.
Effectiveness of regulatory framework	Minimally effective	● Ineffective penalties for improper disposal of e-waste ● Inadequate monitoring and control, unchecked illegal import of e-waste ● E-waste generated is too much to handle by the available infrastructures,	Minimally effective	● Establish independent regulatory bodies to oversee compliance and enforcement ● Increase government oversight and introduce more rigorous penalties for non-compliance.

Recycling and recovery rate	22.07%	● Lack of proper infrastructure ● Ineffective EPR ● Dominance of the unorganized sector	Increase the recycling and recovery rates to match or exceed global standards.	● Offer subsidies for companies investing in high-efficiency recycling technologies ● Promote public awareness campaigns on the benefits of recycling. ● Introduce annual progress reports and performance metrics for recycling rates for every producer in India
Innovation	Lagging	● Lack of incentive, ● Weak R & D ● High cost to finance e-waste technology,	Encourage innovation in waste management practices and technologies.	● Foster partnerships with countries that have advanced e-waste technologies ● Invest in modular and scalable technologies that allow for gradual upgrades and lower initial costs ● Utilize crowdfunding platforms to raise capital for e-waste technology startups. ● Promote collaborative research efforts between universities, research institutions, and industry players to share costs and accelerate innovation. ● Support R&D through government grants and promote collaboration between academia and industry. ● Launch national competitions for innovative e-waste management solutions. Provide seed funding for startups with scalable and impactful technologies.

Collection mechanism	1.5% by officials	● Insufficient reach and awareness by government officials, domination by unorganized sector ● kabadiwalas offers payment to consumers, lack of familiarity with the organized sector	Increase the share of waste collection by the official system	● Establish widespread and easily accessible e-waste collection points. ● Implement community collection programs and incentivize proper disposal through monetary rewards. ● Create partnerships between formal waste management companies and informal sector players to streamline e-waste collection and processing.

Conclusion

E-waste management in India stands at a crossroads where it must be overhauled completely to tackle some of the most critical challenges facing it. The informal sector accounts for approximately 95% of e-waste; this is an astonishing statistic that both supports and militates against the large role played by this sector. Kabadiwalas, therefore, are integral to the collection and first-stage handling of e-waste. However, the practices lack environmental and safety standards, leading to large risks to public health and the environment. The integration of the informal sector into the formal system through training, certification, and financial incentives is essential. This move will help standardize the practices and ensure safer and more effective e-waste management. Equally important is having strong national infrastructure for processing electronic waste. State-of-art recycling facilities and developing an enhanced existing infrastructure in combination with advanced technologies are what would improve sorting, breaking down, and recycling in these facilities. Investment into specific central e-waste-processing zones, as well as engaging public-private partnerships to collaborate in these areas, significantly strengthen these efforts. Utilizing cost-effective modular designs and facilitating technology transfer agreements support managing the high investment prices associated with advanced recycling systems by promoting innovation within this market.

There is also a need for substantial improvement in the effectiveness of e-waste collection mechanisms. Increasing the availability of collection points, integrating collection systems with other waste management services, and using smart bins can improve collection efficiency. Public awareness campaigns and incentive programs are necessary to encourage consumer participation in formal e-waste collection channels. Educating the public on the environmental and health impacts of improper disposal and promoting the benefits of organized e-waste management are fundamental steps in building a more effective collection network. Another area requiring attention is the adherence of manufacturers to Extended Producer Responsibility (EPR) regulations. Strict EPR regulations, with clear guidelines and penalties for non-compliance, can drive producers to take responsibility for the lifecycle of their products. This includes the take-back schemes and investment in recycling technologies. Strengthening the regulatory framework with independent oversight, regular audits, and government support will ensure that EPR regulations are enforced effectively. Improving e-waste management in India also involves enhancing the low levels of public awareness. The government has to educate the public about the proper disposal of e-waste and benefits in organized recycling services. By conducting extensive educational campaigns, offering incentives for proper disposal, and working with retailers and community leaders, the government can increase public involvement and support for e-waste management initiatives. Through such concerted efforts, India can build a more effective and sustainable e-waste management system that addresses both current challenges and future needs.

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