

RESEARCH ARTICLE

E-Waste Management Challenges in India From the Perspective of Producer Responsibility Organizations

TEJENDRA SINGH GAUR¹, VINOD YADAV¹, SAMEER MITTAL², SHAILENDER SINGH³, AND MUZTOBA AHMAD KHAN⁴

¹Department of Mechanical Engineering, Manipal University Jaipur, Jaipur 303007, India

²Institute of Management, JK Lakshmi University, Jaipur 302026, India

³Institute of Business Management, GLA University, Mathura 281406, India

⁴School of Business, Carroll University, Waukesha, WI 53186, USA

Corresponding author: Vinod Yadav (vinod.yadav@jaipur.manipal.edu)

ABSTRACT Producer Responsibility Organizations (PROs) are professional organizations that take responsibility for collecting and treating E-waste in an eco-friendly way on behalf of producers. However, they face several challenges in effective e-waste management (EWM). The current study aims to identify and model key challenges in EWM from PROs' perspective in the Indian context. We identified key challenges to EWM through a literature review and discussions with experts. The expert team validated and mapped key challenges into the EWM process, from collection to disposal. We employed the DEMATEL method to model key challenges. Nine key challenges were identified. Findings suggest that a knowledge-sharing platform is a crucial step in EWM as it allows PROs to share best practices. In addition, collaboration among stakeholders, usage of tracking systems, and eco-design could play a key role in sustainable and effective EWM. This study provides various mitigation strategies to overcome key challenges in the adoption of sustainable EWM. Furthermore, PROs can use the proposed conceptual framework to identify challenges that may be faced during different EWM process stages.

INDEX TERMS E-waste management, producer responsibility organization, extended producer responsibility, DEMATEL, India, recycling.

I. INTRODUCTION

Globally, E-waste (Waste from electrical and electronic equipment) is considered the fastest-growing waste stream. There are several reasons behind the E-waste generation such as rapid technological advancement, higher affordability, increasing purchase power, decreasing cost, shorter useful life cycle, increased customization, and promotional events like exchange schemes [1], [2]. There is a need to manage end-of-life disposal of E-waste sustainably because improper disposal may impact sustainability. For example, precious metals such as gold and silver may be lost due to improper recycling. In addition, ineffective disposal of E-waste may

cause acute and chronic diseases as it generally contains harmful metals such as lead, mercury, and arsenic [3].

However, both developed and developing economies struggle to manage E-waste effectively. Developing economies like India face more challenges in EWM because of many reasons such as limited consumer awareness about E-waste, the dominance of informal sectors, and inadequate infrastructure for E-waste collection and treatment in an environmentally sound manner [3], [4]. Furthermore, developed economies are exporting their E-waste to developing economies because of lower labor costs. India is the second largest E-waste generator in Asia after China [5]. Therefore, E-waste Rules were introduced by the government of India to provide guidelines for EWM stakeholders such as producers, collectors, recyclers, and consumers [2], [6]. One of the key features

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of the E-waste Rules was Extended Producer Responsibility (EPR), introduced in E-waste Rules 2011, which mandates the producers to collect E-waste from consumers and dispose of it responsibly [7], [8]. Since it could be difficult for producers to collect E-waste from consumers, the government introduced the concept of Producer Responsibility Organization (PRO) under E-waste Rules 2016. PROs are third-party organizations that assist producers by taking on their responsibilities for E-waste collection and treatment. This concept has been retained in subsequent updates to the rules, including the 2018 and 2022 versions [9]. However, the PRO concept was already widely accepted for EWM in other countries also, including Belgium, Ireland, Norway, Germany, and the UK [10].

Although PROs play a critical role in EWM, they still face several challenges in sustainable EWM. Existing literature highlights the challenges faced by recyclers and collectors. For instance, recyclers lack advanced technologies for E-waste segregation and recovery of materials from E-waste [4], [11], [12]. In addition, they lack tracking technology which may lead to disturbances in transportation, storage, and eventually recycling [2], [13]. Moreover, consumers are not collaborating with recyclers as they give their E-waste to informal sectors that lack eco-friendly recycling [14], [15], [16]. Since most of the PROs are serving as collectors, recyclers, and disposers, therefore the challenges for PROs could be different. The scientific literature has identified challenges for recyclers and collectors although still overlooked key challenges from Indian PROs' perspective. Therefore, it is crucial to identify the key challenges faced by PROs. Identifying key challenges can help PROs develop effective strategies to address technological and infrastructural issues and inform necessary policy and regulatory improvements related to EWM. Mapping key challenges in the EWM process, from collection to disposal, can help PROs identify where specific issues arise (e.g., collection, segregation, or recycling). Additionally, prioritizing these challenges can reveal their interrelationships, aiding in understanding which are most impactful. Categorizing challenges into cause-and-effect groups further assists PROs in decision-making, as it highlights how cause challenges drive the system and influence other issues. Therefore, the study aims to achieve three research objectives:

- RO1: To identify key EWM challenges from the perspective of PROs in the Indian context.
- RO2: To map the key challenges into the EWM process.
- RO3: To prioritize and categorize key challenges into causes-and-effects groups.

To achieve the research objectives, key EWM challenges from the Indian PROs were identified and validated with the help of current literature and an expert team of eight members working at four different PROs. With the help of opinions from the expert team, key challenges were mapped in the EWM process. Further, the Decision-Making Trial and Evaluation Laboratory (DEMATEL) approach was employed

to prioritize and categorize the challenges into cause-and-effect groups.

The novelty of the current study is the proposed theoretical framework which identifies key challenges from Indian PROs' perspective along with their potential solutions. The proposed framework could be helpful for other emerging economies facing similar challenges in implementing sustainable EWM. The current study offers several policy recommendations for sustainable EWM in India such as developing knowledge sharing platforms for PROs and fostering collaboration among EWM stakeholders. Additionally, the study underscores the importance of formalization of informal sectors as they are big players in collecting E-waste from consumers. The financial and infrastructural support to informal sectors by the government and recyclers could play a paramount role in collaboration among informal sectors and PROs. The current study aligns with four sustainable development goals (SDGs) namely SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 17 (Partnerships for the Goals).

The remainder of the paper is segmented into five sections. Section II throws light on the literature and Section III highlights the research methodology, results are included in Section IV, and a discussion of results is highlighted in Section V. Section VI comprises the conclusion, implications, and limitations of the study.

II. LITERATURE REVIEW

E-waste management (EWM) is a global issue, every nation faces challenges in effectively managing E-waste [17], [18]. Circular Economy (CE) plays a critical role in sustainable EWM as it is based on reusing resources as long as possible through several practices such as refurbishment and recycling. Through CE practices for EWM, several economic, environmental, and social benefits, including creating employment, decreasing the requirement of virgin materials, and reducing the environmental impacts of E-waste, can be achieved [8].

A. E-WASTE POLICIES AND REGULATIONS IN INDIA

Many countries have already begun developing policies and regulations for effective EWM. EWM frameworks vary by country, illustrating distinct strategies for addressing E-waste. The EU's WEEE (Waste of Electrical and Electronic Equipment) Directive mandates EPR, requiring producers to collect 65% of E-waste and to finance and manage recycling, as exemplified by Germany's ElektroG Act. To China's E-waste policies and regulations, the government offers subsidies and licenses to promote authorized recyclers. Australia offers e-waste drop-off points through a co-regulatory framework such as TechCollect. Extended Producer Responsibility (EPR) concept holds producers accountable for E-waste collection, treatment, and disposal. India also integrated EPR into its initial E-waste Rules [19], [20], [21]. In the E-waste Rules, specific targets were set for producers

regarding E-waste collection and recycling. Producers generally manage E-waste through third parties like PROs [19], [21]. The primary purpose of PROs is to act as authorized entities responsible for E-waste collection and ensuring its environmentally friendly treatment and disposal. A PRO can serve multiple producers [9]. In the Indian context, PROs are key stakeholders for an effective EWM strategy. The concept of PRO is still covered in E-waste Rules 2023. According to E-waste Rules 2023, producers are given e-waste collection targets. In addition, auditing of EWM practices is also covered in these rules. In addition, the management of solar photovoltaic modules, panels, and cells are also covered. According to Central Pollution Control Board (CPCB), currently, India has 94 PROs [22], however, the recycling rate by the formal sector is still only 5%. This could be because of the hurdles faced by PROs while collecting and treating E-waste.

B. CHALLENGES IN E-WASTE MANAGEMENT

In India, recyclers lack advanced recycling technologies that help recover more metals efficiently and effectively [2], [8], [23], [24]. Similarly, E-waste collection supply chains have not been digitalized yet. Digitizing entire supply chains would benefit E-waste collection and treatment by enabling the tracking of products and recycled materials [10]. However, the lack of proper IT systems makes digitalization difficult, which impacts EWM processes [23]. Additionally, the lack of technical training of workers hinders E-waste management practices like sorting, segregation, dismantling, and recycling [2], [8]. The absence of well-defined business strategies addressing these technical skills and training aspects may result in reduced metal recovery, pollution, and workers' health issues [25], [26], [27], [28]. Furthermore, workers' limited knowledge of mixed waste may cause difficulties during E-waste segregation. Toxic materials present in E-waste may endanger labor involved in the segregation, dismantling, and recycling processes [14], [29], [30]. Companies are not effectively adopting green practices like restriction of toxic substances in their business strategies, despite the prohibition in E-waste rules [31], [32], [33], [34].

In developing countries, the informal sector collects more E-waste, especially domestic E-waste, than the formal sector because it offers higher payments to consumers [35], [36]. Due to limited awareness of formal and informal sectors, consumers engage in backyard recycling and give E-waste to informal sectors [32], [37]. Limited collection centers and disposal facilities, especially in rural and semi-urban areas, are also among the main reasons for backyard recycling, informal recycling, and E-waste collection [38], [39]. Several studies show that the lack of business strategies regarding cooperation models between producers, recyclers, and consumers makes EWM difficult. For example, producers do not give due attention to eco-design in electronic products [2], consumers directing E-waste toward informal sectors, and formal sectors failing to provide recycling information to the government [3], [11]. Tax relaxations and subsidies also play

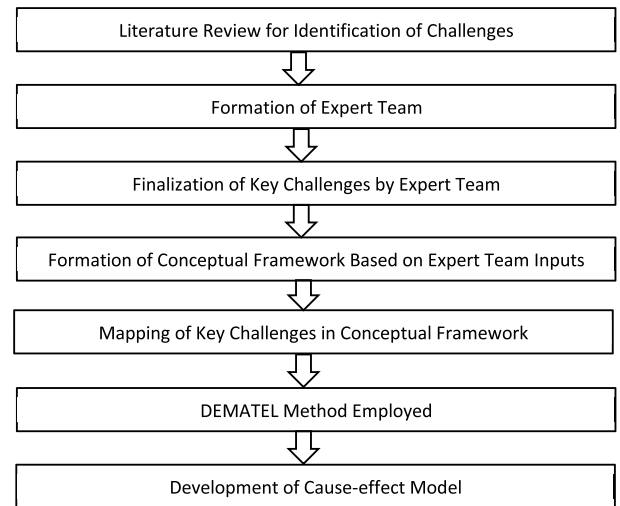


FIGURE 1. Research methodology.

a key role in EWM [19], [40]. Tax relaxations and subsidies can influence the whole system, as recycling, segregation, and collection of E-waste require substantial funding [31], [41], [42].

C. RESEARCH GAP

Several studies have been conducted regarding the obstacles to implementing sustainable EWM. For example, [43] pinpointed sixteen obstacles to E-waste circularity in India from the viewpoint of recyclers. Reference [44] identified twenty obstacles to the recycling of electric vehicle batteries. Reference [45] identified the factors that facilitate and hinder the implementation of EPR for sustainable EWM in Nigeria. Reference [46] identified eleven factors that influence E-waste recycling in India. Reference [47] examined thirteen obstacles in the shift towards a fully developed EWM system in Brazil. Reference [48] examined the obstacles to the adoption of CE practices in EWM from the viewpoint of the UK. Reference [49] identified thirty barriers to CE practices in managing E-waste in the Indian state of Tamil Nadu. In addition to this study, several research have highlighted the challenges to EWM from the viewpoint of recyclers [4], [7], [8], [14], [50]. However, the existing literature has overlooked the examination of challenges to EWM from the perspective of Indian PROs. Consequently, the objective of the study is to address this knowledge gap.

III. METHODOLOGY

This section outlines the proposed methodology, as depicted in Figure 1, which was adopted to accomplish the research objectives. Initially, challenges specific to PROs were identified by the literature review. An expert team representing Indian PROs validated the identified challenges and mapped them to various EWM processes. Using the DEMATEL methodology, they prioritized and categorized these challenges, ultimately constructing a cause-and-effect model

TABLE 1. Expert team details.

Expert	Current Designation	Experience (in years)	Case PRO	Details
Expert 1	Assistant Manager	6	PRO 1	Recycling Capacity- More than 50000 Metric Tonnes Location- Northern India
Expert 2	Business Development Manager	5	PRO 2	Recycling Capacity- More than 5000 Metric Tonnes Location- Eastern India
Expert 3	Chief Marketing Officer	8		
Expert 4	Senior Manager Business Operations	10	PRO 3	Recycling Capacity- More than 30000 Metric Tonnes Location- Northern India
Expert 5	Assistant Manager	5		
Expert 6	Assistant Manager	8		
Expert 7	Environmental consultant	19		
Expert 8	Senior Engineer	6	PRO 4	Recycling Capacity- More than 100000 Metric Tonnes Location- Northwestern India

based on DEMATEL calculations. Further elaboration on the proposed methodology can be found in the subsequent sub-sections.

A. IDENTIFICATION OF KEY CHALLENGES

To achieve RO1, the review methodology proposed by the previous study [2] was adopted to identify the key challenges from the PROs' perspective. As PROs work for EWM, two types of search strings ("producer responsibility organization" OR "third party") AND ("e-waste" OR "WEEE" OR "electronic waste") were used in the Scopus database to ensure comprehensive search results. A total of 131 articles were found. After applying screening criteria (such as Document Type - Article, Conference Paper, Review; Source Type - Journal; and Language - English), 88 articles were shortlisted. After reading the titles, keywords, abstracts, and full articles, 63 articles were finally selected for this study. After reviewing relevant articles, several key challenges to the adoption of EWM were identified from the Indian perspective.

B. VALIDATION OF CHALLENGES AND MAPPING OF KEY CHALLENGES INTO THE EWM PROCESS

To validate challenges from Indian PROs' perspective (to achieve RO1), all 94 Indian PROs were contacted via email. Eight experts from four different PROs agreed to join the team. According to the existing literature, the eight members are significant for the study. In literature, several studies have established expert teams consisting of five or fewer members [51], [52], [53], [54]. The criteria for selecting experts included experience in EWM not being less than five years. The members should be working in reputable companies that collect, recycle, and dispose of E-waste. In addition, the members should be working in premier positions (such as Manager, Chief Marketing Officer, and Environmental consultant) and responsible for making decisions for effective EWM. Table 1 shows the expert team details. As all PROs are collecting E-waste from most of the states in India and the experts have significant experience in effective EWM, it can be considered that the expert team has adequate knowledge about EWM challenges and can validate the key challenges

for India. In validation of key challenges, comprehensive and balanced approach was used by ensuring the experts' diversity in roles and experience.

Interviews with the team were conducted online via MS Teams. Initially, the expert team received a list of EWM challenges. Subsequently, they were asked to validate these challenges from the perspective of Indian PROs. This could help in reducing biasness as all experts can individually assess the validity. Experts were also encouraged to add or remove challenges as deemed relevant. For the mapping of identified challenges into the EWM process (to achieve RO2), a framework developed by [2] was adapted for this study. The expert team was tasked with mapping all identified challenges into the EWM framework.

C. DEMATEL METHODOLOGY

The literature frequently used multi-criteria decision-making (MCDM) techniques to prioritize factors. Various MCDM techniques, such as DEMATEL, AHP, ANP, and TOPSIS, are available, but most cannot deal with interdependence among factors except DEMATEL [40], [55], [56]. Therefore, this research will consider DEMATEL technique, given that most EWM challenges involve interdependence. The DEMATEL method prioritizes and visualizes the structure of intricate causal relationships using impact relation diagrams and matrices (to achieve RO3). This method, which uses matrices and impact relation diagrams, not only turns interdependence into groups of causes and effects, but it also finds the key parts of complex structures [57], [58]. DEMATEL has gained traction in the last decade, with many researchers using it to solve complex system problems across various fields. Several studies related to EWM also employed DEMATEL [40], [55], [56], [59], [60]. It could be difficult for DEMATEL approach to model large number of factors. But in the current situation, the current study has limited factors which can be modeled easily. The DEMATEL methodology is divided into six steps, as follows:

Step 1: Choosing the criteria: The first step is identifying the various factors that need to be modelled. In this study, the identification of challenges is done as per Section III-A.

Step 2: Generating Average Direct Relation Matrix (A): Experts were asked to rate the extent to which they thought

each challenge affected the others in this step. Five points on a Likert scale (ranging from 0 to 4) were utilised.

Where 0 → “no influence”, 1 → “low influence”, 2 → “medium influence”, 3 → “high influence”, and 4 → “very high influence”.

The preliminary data can be gathered in the form of a pairwise matrix. This means creating a non-negative matrix of size $(n \times n)$, denoted as $a_k = [a_{ij}^k]$. Each element in this matrix represents how much criterion ‘I’ influences criterion ‘j’. Equation (1) is employed to construct ‘A’ matrix, considering all responses from “H” respondents.

$$A = \frac{1}{H} \sum_{k=1}^H a_{ij}^k \quad (1)$$

where $K \rightarrow$ number of respondents with $1 \leq ik \leq H$, $n \rightarrow$ number of challenges.

Step 3: Generating Normalised Relation Matrix (X): Each component of the ‘A’ matrix is divided by the total largest row or column sum (s) to obtain ‘X’ matrix.

$$X = sA$$

$$\text{Here, } s = \left[\frac{1}{\max_{1 \leq i \leq n} \sum_{j=1}^n a_{ij}}, i, j = 1, 2, ..n \right]$$

$$\text{or } s = \left[\frac{1}{\max_{1 \leq j \leq n} \sum_{i=1}^n a_{ij}}, i, j = 1, 2, ..n \right] \quad (2)$$

Step 4: Calculating the Total-relation matrix (T): ‘T’ matrix can be computed as,

$$T = X(I - X)^{-1} \quad (3)$$

where $I \rightarrow$ identity matrix

Step 5: Calculating priority ranking and categorization of challenges: In ‘T’ matrix, the row sum (Di) and column sum (Rj) were obtained for each challenge (C1 to C9). To determine priority ranking and group challenges into cause-and-effect groups, (D+R) and (D-R) values were calculated respectively. The challenges that have the highest (D+R) value have a greater overall system impact, whereas the challenges that have the lowest (D+R) value are less closely related. (D-R) values signify the type of relationship between the challenges. If it is positive, the challenge goes to the cause group, meaning it influences other challenges. If it is negative, the challenge goes to the effect group, meaning it is influenced by other challenges.

Step 6: Calculating inner-dependency matrix and formation of cause-and-effect relationship diagram: An inner-dependency matrix was created using the ‘T’ matrix method to identify significant impacts. Values below a threshold value (θ) determined by averaging the matrix were eliminated from the ‘T’. The (D+R) and (D-R) values for each challenge were graphed, by taking (D+R) as Y-axis and (D-R) as X-axis. This was done to generate a cause-and-effect association diagram. The connections between challenges were depicted using one-way and two-way arrows based on the entries in the inner dependency matrix.

IV. RESULTS

The results section is segmented into following subsections.

A. IDENTIFICATION AND VALIDATION OF KEY CHALLENGES FACED BY PROS IN THE INDIAN CONTEXT

Upon examining 63 articles, fifteen challenges were identified. Experts classified five of the fifteen challenges as irrelevant for Indian PROs. The five excluded challenges were ‘Financial burden of tax’, ‘Funding for infrastructure’, ‘Informal sectors’, and ‘Forecasting of e-waste’. All PROs must operate under the same taxation policies, and they lack control over tax-related regulations. Consequently, the challenge, specifically the financial burden of taxation, was omitted. Since PROs are private entities assuming EPR targets at their own risk, the challenge of funding for infrastructure was not relevant for the current study. PROs may encounter challenges in obtaining E-waste from consumers; consequently, they are sourcing E-waste from informal sectors that predominantly collect it from consumers. Consequently, the informal sector was omitted as a challenge. Due to analogous factors, the forecasting of E-waste may be challenging, yet it is not a significant obstacle for PROs. This challenge was therefore excluded.

After discussion with experts, two challenges with similar meaning were merged. These two challenges were ‘Lack of support from parties in the supply chain’ and ‘Lack of coordination and collaboration among supply chain partners’. These two challenges were combined into a single challenge namely ‘Lack of collaboration among EWM stakeholders’. Ultimately, nine challenges were selected for further analysis, as shown in Table 2.

B. MAPPING OF KEY CHALLENGES IN EWM PROCESS

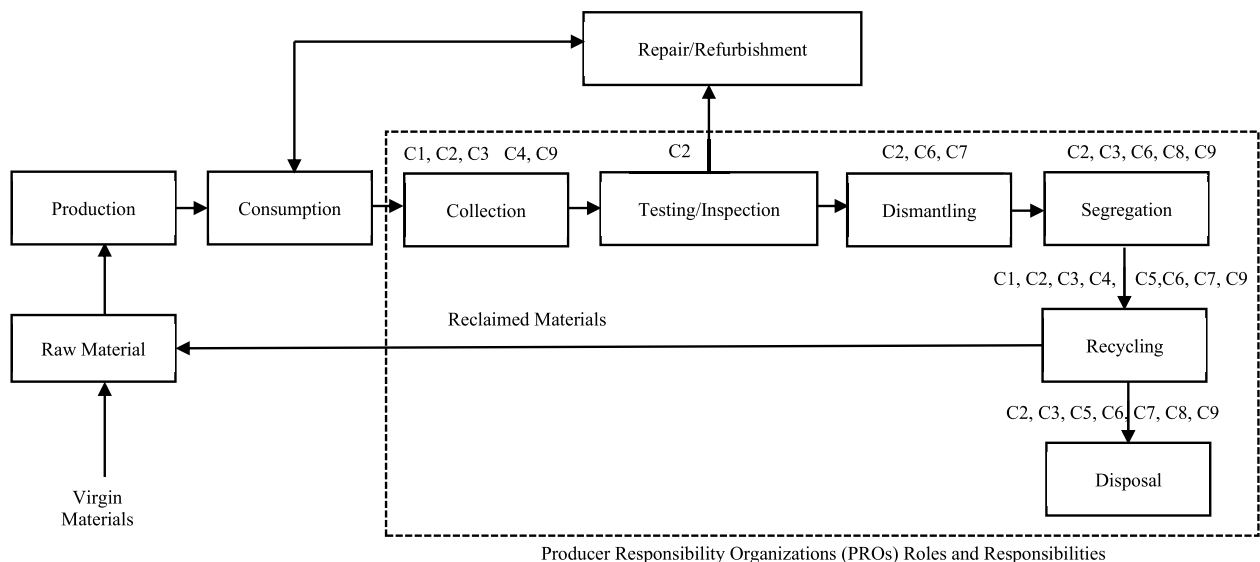
Based on the experts’ opinions, the nine key challenges were mapped across the EWM process, from collection to disposal. (see Figure 2). Key challenges mapping can provide a better understanding regarding which challenges can be encountered at which phase. For example, at the collection phase, challenges C1 (lack of collection centers and transportation), C2 (lack of tracking technology for E-waste), C3 (lack of knowledge sharing among PROs), C4 (lack of collaboration among EWM stakeholders), and C9 (high operating costs involved in treatment and disposal) are encountered.

C. DEMATEL CALCULATIONS

The Average matrix, as shown in Table A1 (Appendix), was developed using Eq. (1). Further by following all the DEMATEL steps presented in Section III-C (See Table A2, A3 in appendix), challenges were ranked and categorized as indicated in Table 3. The priority ranking of identified key challenges to PROs in the Indian context was calculated based on (D+R) values. Difficulties in waste segregation (C8) ($D+R = 8.232$) and lack of advanced technology for recycling and disposal (C5) were the top two challenges.

TABLE 2. Identified key challenges to EWM from perspective of PROs in the Indian context.

S.N.	Challenges	Description	References
1	Lack of collection centers and transportation (C1)	Infrastructure facilities like transportation, storage, and collection centres might be lacking for collectors and recyclers. The improper placement of collection centres affects e-waste transportation and collection as well.	[2], [12], [14], [34], [53], [62], [63]
2	Lack of tracking technology for E-waste (C2)	The lack of IT systems makes it difficult to track E-waste in EWM process.	[8], [23], [53], [64], [65], [66]
3	Lack of knowledge sharing among PROs (C3)	PROs do not share their best practices such as collection, recycling, segregation, and disposal techniques, with other PROs.	Expert input
4	Lack of collaboration among EWM stakeholder (C4)	EWM stakeholder such as producers, consumers, and PROs are not collaborating with each other. For e.g., consumers may pass-on E-waste to informal sectors, and producers don't provide product details (like materials used) to PROs.	[4], [7], [8], [11], [12]
5	Lack of advanced technology for recycling and disposal (C5)	Due to lack of advanced technologies recyclers are unable to recover metals efficiently. Even some metals cannot be recovered with current technologies.	[2], [4], [14], [16]
6	Limited technical skills and safety of workers (C6)	Manpower has inadequate technical skills such as processing skills, and disposal skills. Due to toxic materials, workers may face health issues.	[2], [14], [23], [30], [32], [34], [53]
7	Lack of eco-designed products (C7)	Eco-designed products are easy to disassemble and recycle and contain less harmful materials. But most of the EEE products are not eco-designed properly which impact the EWM.	[7], [8], [21], [38], [41], [67], [68],
8	Difficulties in segregation of waste (C8)	E-waste is collected in mixed manner and PROs find it difficult to segregate them.	[2], [23], [29], [69]
9	High operating costs involved in treatment and disposal (C9)	High funds are required in EWM e.g., PROs need significant funds to set up collection centers and segregate the E-waste.	[16], [21], [34], [67]

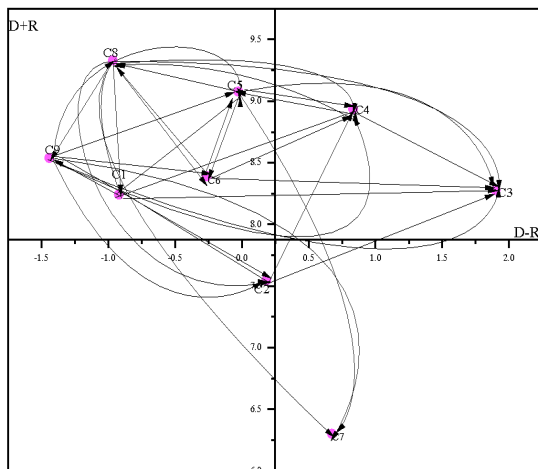
**FIGURE 2.** Mapping challenges in the E-waste management process.

Lack of knowledge sharing among PROs (C3), lack of collaboration among EWM stakeholders (C4), lack of eco-design of products (C7), and lack of tracking technology for E-waste (C2) were classified as cause challenges,

which have higher influence. The remaining challenges in the effect category were lack of advanced technology for recycling and disposal (C5), limited technical skill and safety of workers (C6), lack of collection centers and transportation

TABLE 3. Ranking and categorization of challenges.

Challenge	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	D	D-R	D+R	Ranking	Group
Lack of collection centers and transportation (C1)	0.33	0.30	0.28	0.38	0.37	0.40	0.21	0.48	0.48	3.23	-0.81	7.27	7	Effect
Lack of tracking technology for E-waste (C2)	0.42	0.27	0.31	0.39	0.42	0.40	0.25	0.47	0.47	3.41	0.17	6.65	8	Cause
Lack of knowledge sharing among PROs (C3)	0.55	0.46	0.31	0.51	0.57	0.54	0.35	0.63	0.57	4.49	1.68	7.30	6	Cause
Lack of collaboration among EWM stakeholder (C4)	0.54	0.45	0.40	0.38	0.54	0.49	0.35	0.60	0.57	4.31	0.74	7.88	3	Cause
Lack of advanced technology for recycling and disposal (C5)	0.47	0.40	0.35	0.43	0.39	0.50	0.32	0.57	0.56	3.99	-0.02	8.01	2	Effect
Limited technical skills and safety of workers (C6)	0.46	0.36	0.32	0.39	0.46	0.34	0.28	0.51	0.47	3.58	-0.23	7.40	5	Effect
Lack of eco-designed products (C7)	0.34	0.28	0.27	0.35	0.43	0.35	0.19	0.44	0.44	3.08	0.60	5.55	9	Cause
Difficulties in segregation of waste (C8)	0.50	0.37	0.32	0.43	0.45	0.43	0.28	0.41	0.51	3.69	-0.85	8.23	1	Effect
High operating costs involved in treatment and disposal (C9)	0.43	0.35	0.25	0.33	0.39	0.38	0.23	0.43	0.34	3.13	-1.27	7.53	4	Effect
R	4.04	3.24	2.81	3.57	4.02	3.81	2.48	4.54	4.40					

**FIGURE 3.** DEMATEL relationship model.

(C1), difficulties in waste segregation (C8), and high operating costs involved in treatment and disposal (C9). These challenges were influenced by the cause-group challenges.

The inner dependency matrix was generated using the threshold value ($\theta = 0.40632$ (See Table A4)). The threshold value (θ) was obtained by averaging the total relation matrix. The overall cause-effect relationship diagram (Figure 3) simultaneously displays general trends and relationships among all challenges, plotting only entries above the threshold value in inner-dependency matrix. In the DEMATEL model, the arrows depict the relationships between challenges. The challenges positioned to the left of the central vertical line are effect-group challenges and challenges positioned to the right of the central vertical line are cause-group challenges. Furthermore, the challenges above horizontal line have high relationships with other challenges and vice-versa. Therefore, PROs could give higher attention to challenges positioned to the right of the central vertical line.

V. DISCUSSION

In India, PROs are playing a paramount role in EWM, however, they are still facing many challenges. Likewise other developing economies may also face similar challenges because of financial and infrastructural constraints. In addition, the informal sectors are also key factors which makes India different from other countries as most of the E-waste in India is collected by the informal sectors. However, the Indian PROs are trying to collaborate with informal sectors to collect E-waste from them and treat it in eco-friendly manner.

According to the mapping of challenges with the EWM process (Figure 2), the recycling process is crucial as it faces maximum challenges. The reason could be PROs often lack the specific technologies needed to recycle different types of e-waste efficiently, and producers do not provide the complete product material details essential for effective treatment.

‘Difficulties in waste segregation’ (C8) was the most prominent challenge for the interviewed Indian PROs. E-waste segregation is one of the difficult processes in India because of product design complexity, mixed waste and manual processes. Several studies also mentioned that segregating non-metals and metals is very difficult due to lack of advanced machinery [7], [8], [12]. This supports previous studies’ findings [23], [70]. In this regard, innovative technologies like computer vision systems and ConvoWaste could also reduce dependence on manual segregation [23], [29], [71].

The second major challenge is the lack of advanced recycling and disposal technology (C5). Different PROs excel in different areas, such as recycling printer cartridges or PCBs. However, various types of e-waste require specific technologies, complicating the recycling process. Due to inadequate recycling and disposal technologies, PROs often fail to properly extract materials from e-waste, resulting in the need to send it to other recyclers at higher costs. Therefore, develop-

ing and implementing advanced technologies is essential for effective and profitable e-waste treatment [41].

Since the cause-group challenges drive the entire system, they should be addressed as a priority. Overcoming these challenges will likely result in the automatic resolution of the effect-group challenges, as they are influenced by the cause-group challenges. Therefore, the current study provides several solutions for addressing the cause-group challenges, which are discussed below. Such solutions with key challenges could be beneficial for other countries facing the same challenges.

The findings of the study indicate that the lack of knowledge sharing among PROs (C3) is the most influential cause, with the highest positive (D-R) value of 1.6822 (Table 3). Figure 3 also shows that C3 has the most significant relationship with other challenges (except C7). One PRO may specialize in collecting e-waste from consumers, while another excels in recycling; strategic collaboration and sharing of best practices could enhance e-waste collection and treatment for both. Additionally, a knowledge-sharing platform for sustainable collection, recycling, and disposal practices could improve transportation and storage efficiency. Reference [8] also categorized the lack of knowledge sharing as a cause challenge. However, [72] categorized it as an effect challenge. The reason behind the contradictory results was that [72] included policies and regulation-related challenges as well as consumer-related challenges. Moreover, knowledge sharing among PROs could benefit new PROs. Similarly, Indian PROs could learn from the European WEEE Forum, a non-profit association of 34 European PROs, and compliance schemes that foster idea-sharing and best practices for effective WEEE management [73]. Such a platform in India could help PROs reduce collection, segregation, recycling, and disposal costs. Results show that C3 has the maximum impact on the top two priority challenges - C8 (Difficulties in E-waste Segregation) and C5 (Lack of advanced technology). Therefore, PROs better at segregation and treatment could share methods and technology knowledge to address both C8 and C5. However, PROs could feel their competitive edge is secured when sharing and collaborating.

Effective EWM management requires stakeholder collaboration. Experts revealed producers and consumers are not collaborating with PROs (C4). Producers withhold critical details, such as types and quantities of plastics and metals used in their products, alongside information about the products sold on the market. When producers do not provide these material details, they can have repercussions for recycling and disposal technologies. Consumers often give their e-waste to informal sectors for financial benefits because PROs don't offer much money to consumers. That is the main reason that consumers are not collaborating with PROs. However, most of the PROs are giving monetary benefits to informal sectors to collect e-waste from them but they are struggling because many informal sectors gain more profit from recycling themselves than funds provided by PROs. Therefore,

the lack of collaboration is a crucial challenge in EWM. The results categorized challenge C4 (lack of EWM stakeholder collaboration) as cause challenge with a high positive (D-R) value. However, [7] categorized it as an effect challenge. The contradictory results could be because [7] employed DEMATEL with three challenges only that were grouped in the infrastructural category. Experts said producers are the main stakeholder, driving the entire chain. Therefore, producers need to be more receptive to collaboration.

Additionally, if e-waste regulations required producers to share product material details and provide financial support, PROs could acquire advanced machinery to address challenges C1, C5, C8, and C9, facilitating more efficient recycling and disposal. Furthermore, PROs can share hurdles faced during segregation and treatment with producers so product design and materials selection can be improved. As consumers also play a vital EWM role, they could share E-waste quantity and quality data to aid PRO collection and transportation [3], [12], [74], [75]. Experts suggested that there should be a policy regarding formalization of informal sectors so that e-waste will be treated in an environmentally sound manner. Additionally, policies should be made in such a way that consumers will also be responsible for giving e-waste to PROs only. They should be fined if they don't give their e-waste to PROs. One of the experts highlighted the importance of development of e-waste recycling parks where all the e-waste of region or state will be treated, and the informal sectors will be formalized. Thus, EWM stakeholder collaboration is key for effective management and sustainability.

Eco-designed products can significantly aid EWM by containing fewer harmful substances and enabling easy recycling, but most products lack these principles, complicating disassembly and increasing treatment costs. Consequently, PROs face challenges in dismantling toxic materials and achieving high metal recovery rates. The DEMATEL results further confirm this, as challenge C7 (lack of eco-designed products) exhibits a substantial (D-R) value, categorizing it as a cause challenge. The study of [8] also categorized this challenge as cause challenge reported that there is lack of implementation of green practices in design of electronic product.

Producers should prioritize eco-design to facilitate e-waste processing by PROs and enhance the safety of EWM workers. Eco-designed products with fewer toxic materials improve safety for both consumers and workers involved in dismantling, segregation, recycling, and disposal. Additionally, their ease of disassembly could reduce the need for highly technical dismantling workers, making E-waste segregation more straightforward. These advantages could result in reduced operating costs for treatment. Consequently, eco-designed products have the potential to alleviate challenges such as C6 (Limited technical skills and safety of workers), C8 (Difficulties in segregation of waste), and C9 (High operating costs involved in treatment and disposal). Experts have suggested

that PROs could advocate for government policies mandating producers to prioritize eco-designed products. While Indian E-waste Rules 2022 ensure that EEE manufacturers adhere to RoHS practices, there is a lack of specific rules pertaining to eco-design. Policymakers could address this gap by incorporating eco-design regulations into new policies.

E-waste tracking technology presents several advantages [76], including its potential to streamline waste sorting by identifying materials and aid PROs in optimizing the configuration of collection centers and transportation, thereby reducing costs and improving collection efficiency. However, the absence of such technology poses a significant challenge for PROs, categorizing C2 (lack of tracking technology) as a cause challenge. The DEMATEL results corroborate this, with C2 exhibiting a positive (D-R) value, signifying its high impact on effect challenges. The studies of [7] and [12] also identified the challenge “lack of advanced technology for E-waste recycling” as a key challenge in EWM. The study of [49] also categorised this challenge as cause challenge. However, to address this issue, PROs can explore the utilization of innovative tracking technologies such as blockchain and computer vision systems [53]. For improved E-waste tracking, producers could consider providing financial support to facilitate the adoption of these technologies by PROs.

VI. CONCLUSION

The study has identified nine key challenges (RO1). Additionally, key challenges were mapped into EWM steps from collection to disposal (RO2). Additionally, DEMATEL prioritized and categorized challenges (RO3). PROs should prioritize challenges C3, C4, C6, and C7 because they have significant impact on effect-group challenges C1, C2, C5, C8, and C9. A DEMATEL digraph shows how these challenges relate, helping policymakers and PROs make informed decisions to manage E-waste efficiently and effectively. The present study contributes to the attainment of four Sustainable Development Goals (SDGs): SDG 9, SDG 11, SDG 12, and SDG 17, by advocating for the utilization of advanced technologies, including IoT and blockchain, for sorting, segregation, and recycling processes, as well as by fostering producer responsibility, eco-design, and collaboration among stakeholders in EWM.

A. THEORETICAL IMPLICATIONS

The study has several theoretical implications for addressing research gaps. This study can be a prior study in the field of EWM which is focused on EWM challenges from the perspective of Indian PROs. In the proposed study, key challenges in EWM from the Indian PRO perspective were identified that have been overlooked in existing literature. Second, the mapping of key challenges in the EWM process was done to fill a gap in current research. Additionally, through empirical analysis, prioritization and categorization of key challenges into cause-effect groups were done. This provides insights into where to direct attention—an aspect previously missing from the scientific literature. Lastly,

a DEMATEL digraph was developed that visualizes the inter-relationships among these challenges.

B. PRACTICAL IMPLICATIONS

The current study provides useful insights for practitioners. The study identified that sharing of knowledge among PROs plays a crucial role in sustainable EWM. Indian PROs could develop a common platform where they could share the best practices of E-waste collection, segregation, and disposal of end-products. Sharing of knowledge could be done through seminars and conferences also. It could increase E-waste collection as well as efficiency of recycling. New PROs also could benefit from such sharing platforms. Collaboration among stakeholders also plays a key role. Producers could provide details about product design and materials so that PROs could disassemble products easily and recycle them effectively and efficiently. In addition, producers could provide financial support so that PROs can buy advanced machinery for recycling and disposal. Additionally, PROs could provide incentives to consumers to prevent E-waste flow in informal sectors. The study identified that eco-design products could provide ease of disassembly and recycling of E-waste. Therefore, producers could pay attention to producing eco-designed products. Eco-design products could reduce operational cost of recycling and disposal of E-waste. PROs could implement advanced technologies or smart technologies such as blockchain and IoT that could help in tracking of E-waste as well as in segregation and recycling. Other applications of smart technologies such as machine learning, cloud learning, and artificial intelligence (AI) could help in forecasting of e-waste and segregation of e-waste.

C. POLICY IMPLICATIONS

The study offers numerous policy implications that may assist policymakers in formulating effective EWM strategies. The existing Indian E-waste Regulations may be revised to require manufacturers to furnish product information, including material composition and design, to PROs to facilitate efficient disassembly and recycling of E-waste. Moreover, the existing E-waste Regulations require RoHS compliance, yet they do not mandate eco-design practices. Therefore, the government could mandate production of eco-designed products so that they can be disassembled and recycled easily. It could also reduce the operational costs for PROs. Given that platforms for the exchange of best practices among PROs are essential for sustainable EWM, policymakers should incorporate such platforms into existing policies. Furthermore, the government could offer financial assistance to PROs for the acquisition of advanced technologies for the tracking and recycling of E-waste. The government could invite all key stakeholders such as producers, PROs, consumers, and informal sectors while preparing a regulatory framework for sustainable EWM so that all perspectives regarding challenges and strategies to overcome them can be addressed. Such an approach can enhance the collaboration among the

EWM stakeholders by encouraging stakeholders to share their insights.

D. LIMITATIONS AND FUTURE WORK

The study has some limitations. A broader pool of experts could potentially unveil more nuanced aspects. It's important to acknowledge that DEMATEL results may exhibit biases due to expert judgments, making them challenging to generalize. Furthermore, supplementing the study with additional empirical data and case studies conducted under varied circumstances could further substantiate the study. Most studies have focused on consumers, policies, and regulations, while this work especially considered the overlooked PRO perspective. Future studies could include all EWM stakeholders - government, producers, consumers, and PROs. Additionally, exploring and comparing identified challenges from the perspectives of developed and developing countries could be a potential avenue for future research. A study can be conducted on the application of smart technologies such as AI, blockchain, IoT, machine learning, and cloud computing in the management of e-waste. Further, study related to challenges in the implementation of smart technologies for sustainable e-waste management can be conducted.

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TEJENDRA SINGH GAUR is currently a Research Scholar with Manipal University Jaipur, specializing in e-waste management, circular economy practices, and the adoption of Industry 4.0 technologies. His research focuses on addressing critical challenges at the intersection of technology and environmental sustainability, contributing to innovative solutions for a more sustainable industrial future. He has demonstrated expertise in employing advanced methodologies, including multi-criteria decision-making (MCDM) techniques, such as the Decision-Making Trial and Evaluation Laboratory (DEMATEL) and the Interpretive Structural Modeling (ISM), to model and analyze complex organizational and environmental systems. His research explores themes, such as barriers to digital transformation, mitigation strategies for industry 4.0 adoption, and challenges in integrating circular economy principles within E-waste management practices. His academic journey reflects a commitment to tackling contemporary challenges through interdisciplinary research, driving innovation in environmental responsibility, and industrial efficiency.



VINOD YADAV received the bachelor's degree in production and industrial engineering and the master's degree in industrial management and engineering from the Department of Production and Industrial Engineering, M. B. M. Engineering College, J. N. V. University, Jodhpur, Rajasthan, India, and the Ph.D. degree in industrial engineering from the Malaviya National Institute of Technology Jaipur. He is currently an Assistant Professor with Manipal University Jaipur. He has published research articles in *Business Strategy and the Environment*, *Production Planning and Control*, *Industrial Management and Data Systems*, *Journal of Manufacturing Technology Management*, *Journal of Enterprise Information Management*, *International Journal of Lean Six Sigma*, *Journal of Modelling in Management*, and *Benchmarking: An International Journal*. His research interests include industry 4.0, circular economy, multi-criteria decision-making, SMEs, lean thinking, supplier selection and supply chain management, and blockchain. He is a Life Member of IIIE.



SAMEER MITTAL received the Ph.D. degree from West Virginia University. He is currently an Assistant Professor with the Institute of Management, JK Lakshmipat University, Jaipur, India. Earlier, he completed his postdoctoral research at Tampere University, Finland. His primary research interests focus on topics related to the changes in operational practices in manufacturing industries due to the advent of industry 4.0 technologies. He is also keen to study trends in the sterilization of products, e.g., product-service systems and outcome-based contracts. Moreover, he is also interested in experiential learning approaches in operations management. He has published original research in high-impact journals, such as *Business Strategy and the Environment*, *Journal of Manufacturing Systems*, *Journal of Cleaner Production*, *International Journal of Production Research*, and *Production Planning and Control*.



SHAILENDER SINGH received the B.E. degree in production and amp; industrial engineering and the M.E. degree in industrial management and amp; engineering from the MBM Engineering College, Jodhpur, India, in 2011 and 2014, respectively, and the Ph.D. degree in supply chain management from BITS Pilani, Rajasthan, India, in 2023. He is currently an Assistant Professor with GLA University, Mathura, India. He has published extensively in international journals, including *Environmental Science and Pollution Research*, and *Journal of Material Cycles and Waste Management* and presented at reputed conferences. His honors include contributions to state-level projects under DST Rajasthan, and memberships in Indian Institution of Industrial Engineering and the International Association of Engineers. His research interests include supply chain analytics, circular economy, e-waste management, and data-driven decision-making in operations.



MUFTOBA AHMAD KHAN primary research interests include topics that arise from the convergence of manufacturing, digital transformation, and business model innovation. He takes an interdisciplinary perspective to study the two emerging trends in manufacturing: 1) servitization, i.e., the shift from selling products to selling integrated product-service systems (PSS), and 2) industry 4.0 adoption. He has published original research in high-impact journals and peer-reviewed conferences, including 26 publications and more than 2900 citations to date. His research appears in *Journal of Cleaner Production*, *Business Strategy and the Environment*, *Production Planning and Control*, *International Journal of Production Research*, and *Journal of Enterprise Information Management*. He has also served as an Associate Editor for *IET Collaborative Intelligent Manufacturing* journal, since November 2020.

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