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A Systematic Review of the Challenges and Opportunities of Electronic Waste Management in India

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Abstract: Electronic waste has emerged as one of the most rapidly expanding waste categories worldwide. India currently produces more than 1.1 million tonnes of discarded electrical and electronic equipment each year, a figure expected to escalate sharply as digital adoption and urban expansion accelerate. This review consolidates findings from scientific literature, global datasets, Indian government documents, and policy statements to evaluate the major barriers and emerging possibilities associated with e-waste management in India. A systematic search was carried out in major academic databases (Scopus, Web of Science, PubMed, Google Scholar) and official repositories following PRISMA guidelines. Thirty-eight relevant publications were analysed. The review identifies persistent challenges such as the dominance of informal recycling systems, labour-intensive and unsafe dismantling practices, weak enforcement of existing regulations, limited public awareness, and fragmented recycling infrastructure. At the same time, opportunities exist through strengthened Extended Producer Responsibility (EPR) mechanisms, expansion of authorised recycling facilities, circular-economy interventions, job creation in green industries, and the adoption of technologies such as automated dismantling, digital tracking, and urban mining. Overall, although India has introduced progressive regulations, the gap between policy and on-ground implementation remains wide. Integrating informal workers, upgrading infrastructure, and enhancing compliance mechanisms are essential for developing a sustainable and equitable e-waste management pathway.

Keywords: e-waste, informal recycling, Extended Producer Responsibility, circulareconomy, Policy implementation gap.

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1. Introduction

Electronic devices have become inseparable from modern living, and India is no exception. With rising incomes and rapid technological turnover, households increasingly purchase new models of mobile phones, computers, televisions, kitchen appliances, and other digital equipment. Higher-income groups often upgrade frequently, leading to older but functional devices passing into lower-income communities. Although this process extends product life spans, it also prolongs the circulation of outdated electronics that are more difficult and hazardous to recycle at end-of-life. Despite the growing stock of obsolete equipment, India still lacks a sufficiently organized and environmentally sound system for recovering, reusing, and recycling electronic waste. A significant portion of discarded electronics is channeled through informal networks, where workers manually dismantle components using rudimentary techniques such as open-burning and acid-soaking. These activities occur with minimal protective equipment and without adherence to environmental standards. Electronic waste includes any electrical or electronic item no longer in use. These products contain valuable materials such as copper, gold, silver, and palladium, but also include hazardous substances like lead, cadmium, mercury, and brominated flame retardants (Parvez SMet al., 2021). Global studies report that the world generated about 62 million tons of e-waste in 2022, and projections from the Global E-Waste Monitor estimate this will surpass 82 million tons by 2030. India is now among the top producers of e-waste, driven by rapid urbanization, digital expansion, and widespread adoption of consumer electronics (Garlapati VK, 2016). Although authorized recycling facilities exist, more than 90% of discarded electronics are processed by informal handlers, often under unsafe conditions that lead to soil, air, and water contamination (Awasthi AK et al., 2016; Awasthi AK et al., 2018). Research has documented increased levels of toxic metals in workers and nearby communities (Parvez SMet al., 2021; Upadhyay K et al. 2021). India has implemented several regulatory frameworks, including the E-Waste (Management) Rules of 2016 and subsequent amendments in 2018 and 2022 that strengthened EPR obligations and introduced digital tracking (Central Pollution Control Board, 2022). However, limited enforcement, weak collection systems, and low consumer participation continue to impede progress (Arya S et al., 2020).

This systematic review aims to synthesize current knowledge on the major challenges hindering effective e-waste management in India, and the opportunities and pathways for transitioning toward a circular and sustainable e-waste system.

2. Methods

2.1 Search strategy

A comprehensive search was performed in line with PRISMA guidelines across major scientific databases—Scopus, Web of Science, PubMed, and Google Scholar. Grey literature, including government notifications, annual reports, and national regulatory documents, was obtained from CPCB and the Ministry of Environment, Forest and Climate Change (MoEFCC) portals. Search terms combined variations of “electronic waste,” “informal recycling,” “EPR India,” “e-waste health impacts,” and “contamination from e-waste.”

2.2 Inclusion and exclusion criteria

Studies were included if they were published between **2010 and 2024**, focused explicitly on the Indian context, and addressed one or more aspects of e-waste generation, recycling practices, environmental contamination, health impacts, or policy and regulatory frameworks. Both **systematic and narrative reviews**, empirical research articles, and reports from government or international organisations were considered eligible.

Publications were excluded if they focused on countries other than India, addressed waste streams unrelated to electronic waste, or lacked access to full text. Opinion pieces, editorials, and conference abstracts without sufficient methodological detail were also excluded to maintain the quality and reliability of the review.

2.3 Study selection

Out of 418 identified initial records, 38 studies met eligibility criteria after removing duplicates and screening abstracts and full texts. (Reference number 12 to 49).

3. Results of the Systematic Review

3.1 Rising e-waste generation and composition

India produced approximately 1.6 million tonnes of e-waste in 2021–22, and estimates suggest that this figure may surpass 2 million tonnes by 2030. Rapid turnover of IT equipment, increased smartphone penetration, expanded consumer electronics markets, and growing electric-vehicle components contribute significantly to rising waste volumes (Forti V et al., 2024).

3.2 Informal sector dominance

Despite regulatory frameworks, informal actors continue to collect, dismantle, and recover materials from the majority of e-waste generated in India. Manual dismantling, open-burning of wires, crude shredding, and chemical leaching are common practices (Awasthi AK et al., 2016; Awasthi AK et al., 2018). Occupational exposure to heavy metals, including lead, cadmium, and mercury has been documented in major recycling clusters such as Seelampur (Delhi), Moradabad, Meerut, Dharavi (Mumbai), and Bengaluru. Contamination extends beyond workers to nearby residents, with studies reporting elevated heavy metal levels in soil, water, and blood samples (Parvez SM et al., 2021; Upadhyay K et al., 2021).

3.3 Environmental contamination

Multiple studies document high levels of heavy metals in soil, water, and air in and around e-waste recycling clusters.

Examples include Soil Pb levels exceeding safe limits in Delhi recycling sites (Arya S et al., 2021), Acidic effluents contaminating groundwater (Awasthi AK et al., 2018), Particulate matter containing brominated flame retardants (Awasthi AK et al., 2016).

These findings indicate severe localised pollution hotspots.

3.4 Policy and regulatory challenges

Although India has comprehensive rules (2016, 2018 amendments, 2022 digital EPR updates), major barriers persist. These include weak enforcement due to limited manpower in State Pollution Control Boards (Arya S et al., 2020), low levels of public awareness regarding disposal channels (Garlapati VK, 2016), insufficient authorised collection centres even in metropolitan areas (Arya S, et al., 2021; Central Pollution Control Board, 2022), weak integration of informal collectors into formal systems (Awasthi AK et al., 2018) and lack of producer compliance in meeting EPR obligations (Central Pollution Control Board, 2022).

3.5 Opportunities for sustainable e-waste management

3.5.1 Strengthened EPR and digital tracking

The updated 2022 Rules introduce a digital portal for monitoring recycling and certificate trading. If implemented rigorously, digital tracking could reduce leakages and improve transparency (Central Pollution Control Board, 2022).

3.5.2 Circular economy and urban mining

E-waste contains substantial recoverable materials, including precious and rare-earth metals. As primary mining becomes more environmentally destructive and cost-intensive, urban mining presents a

resource-efficient alternative and a potential economic opportunity for India. E-waste contains valuable materials (Kaza S, et al., 2018).

3.5.3 Formalisation of the informal sector

A sustainable e-waste ecosystem requires integrating informal workers, who are essential for collection yet vulnerable to exploitation and health risks. Key strategies include technical training to improve safety and efficiency, provision of personal protective equipment, encouraging cooperatives or organised groups for better bargaining power and linking informal collectors with Producer Responsibility Organisations (PROs). Such measures can improve livelihoods while ensuring safer, traceable recycling processes.

3.5.4 Technological Innovations and Future Technological Opportunities

Advancements in automation, robotics, and AI-driven sorting can improve recovery rates and reduce human exposure to hazardous materials (Garlapati VK, 2016; Arya S et al., 2020). Hydrometallurgical extraction methods offer cleaner alternatives for retrieving precious metals from circuit boards. Designing products for easier disassembly and recyclability also offers long-term gains. Finally, advancements in material and product design, such as modular electronics, recyclable components, and reduced use of hazardous substances, can significantly improve end-of-life recyclability. Collectively, these innovations point toward a more circular electronics economy, supporting both environmental sustainability and economic value recovery in India's future e-waste management landscape.

4. Discussion

India's e-waste problem is unique because of its dual system: advanced policy frameworks coexisting with extensive informal operations. The informal sector's dominance remains the biggest barrier but also an opportunity, formalisation can create millions of green jobs while improving environmental and health outcomes (Awasthi AK et al., 2018; Arya S et al., 2020).

Environmental studies clearly show contamination hot spots with health risks equivalent to industrial toxin exposure (Parvez SM et al., 2021; Arya S et al., 2021). Therefore, improving dismantling infrastructure and enforcing safe recycling practices are essential.

EPR remains underperforming due to producer non-compliance, insufficient audits, and a lack of transparent data (Central Pollution Control Board, 2022). Digital EPR (2022 Rules) may improve accountability, but integration with on-ground enforcement is crucial.

5. Policy Recommendations

Strengthening India's electronic waste management system requires coordinated policy action across

regulatory, technological, and social dimensions. First, the enforcement capacity of regulatory authorities, particularly the Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs), must be enhanced through improved staffing, technical training, and adoption of digital monitoring tools to ensure effective implementation of existing e-waste regulations. Equally important is the formal integration of the informal recycling sector, which currently dominates collection and dismantling activities. Structured training programmes, micro-certification schemes, and occupational health and safety initiatives can enable informal workers to transit into safer and environmentally sound practices while preserving livelihoods.

In parallel, the establishment of accessible public collection centres across all Tier-1 and Tier-2 cities is essential to improve consumer participation in formal disposal pathways and reduce leakage of e-waste into informal channels. Producer responsibility frameworks should be further strengthened by mandating eco-design principles that promote modularity, material recovery, and recyclability, thereby reducing environmental risks at the product end-of-life stage. Finally, sustained public investment in research and development related to urban mining, advanced material recovery technologies, and AI-based sorting systems is necessary to enhance recycling efficiency. These technical measures should be supported by nationwide consumer awareness campaigns that encourage responsible consumption and proper disposal behaviour, ensuring long-term success of India's e-waste management strategy.

6. Limitations

This review has several limitations that should be acknowledged. First, there is substantial variation in data quality across studies, particularly concerning estimates of e-waste generation, informal recycling volumes, and environmental contamination levels. Many studies rely on small or region-specific samples, which reduces the generalizability of the findings. Second, there is a notable lack of long-term exposure studies in India, especially those assessing chronic health impacts among informal e-waste workers, nearby communities, and vulnerable groups such as children. Most available research focuses on cross-sectional assessments, limiting the ability to understand cumulative effects. Third, there are limited publicly accessible datasets on formal and informal recycling flows, owing to poor reporting practices, weak enforcement of Extended Producer Responsibility (EPR) regulations, and the decentralised nature of informal recycling networks. This restricts the accuracy of national-level estimates and complicates policy planning.

7. Conclusion

India is at a critical stage in transitioning towards sustainable e-waste management. Although challenges remain substantial, including the dominance of informal recycling, environmental contamination, and weak enforcement, the opportunities through EPR, circular economy principles, and technological innovations are equally strong. Integrating the informal sector and strengthening regulatory enforcement are essential steps. By combining technological innovation, inclusive policy design, and robust institutional enforcement, India can move toward a safer, more efficient, and economically viable e-waste management system. This transition is vital not only for reducing ecological risks but also for unlocking the resource recovery potential embedded within the country's rapidly expanding electronics sector.

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