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E-Waste Toxicity and Its Environmental Impact, Challenges, and Solutions for Sustainable Waste Management in India

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Abstract

Introduction: *E-waste describes any electronic component that is obsolete or no longer functional. The ever-increasing public concern of e-waste in India stems predominantly from the aggressive expansion of the electronics industry along with insufficient recycling and disposal practices. Lead, mercury, and cadmium in e-waste pose serious risks to human health and the environment by polluting air, soil, and water. Informal recycling methods further exacerbate these hazards through unsafe practices. This study examines e-waste toxicity, evaluates recycling workers' knowledge and practices, and explores sustainable solutions to this growing issue.* ***Methods:*** *A structured field survey targeting knowledge, methods of disposal, and safety practices was carried out among 10,000 e-waste recycling workers in India. The study sampled 385 respondents using the Taro Yamane formula with a 5% margin of error. Participants, aged 18–35, had varying education levels – primary, secondary, and tertiary. Additionally, books, government policies, and literature were analyzed to explore solutions for e-waste management.* ***Results:*** *Demographics: 72% of respondents were aged 18–25, with education levels ranging from primary school to university. Most (60%) were from rural areas, while 40% were from urban and semi-urban settings. Awareness & Practices: 85% recognized e-waste dangers, but only 40% disposed of them properly. Alarmingly, 30% frequently handled harmful substances without protective gear. Challenges: Issues included weak law enforcement, a lack of safe recycling centers, and low awareness among workers.* ***Solutions:*** *85% supported stricter laws, particularly EPR, while 70% emphasized public-private collaboration in establishing formal recycling centers. Solutions – 85% of the respondents concentrated on the need for enforcing stricter laws especially EPR, while 70% of respondents stressed the need for collaboration between the public and private sector in the establishment of formalized e-waste recycling centers. Take Home Message – Improper e-waste handling poses serious health and environmental risks. Stricter regulations and collaborative recycling efforts are essential for a sustainable e-waste disposal solution in India.*

Keywords: E-waste, environmental impact, hazardous waste, sustainable waste management, recycling, India, EPR, public health, policy

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INTRODUCTION

Electronic waste (e-waste) is one of the biggest environmental and public health issues globally, and India is one of the largest producers of e-waste.

As reported by the Global E-Waste Monitor (2020), India's annual e-waste output stands at 3.2 million metric tons, trailing only the USA and China [1]. The informal and formal sectors' integration towards the movement of goods and services has facilitated the rampant expansion of the technology industry and the rise in demand for electronic devices, both of which have significantly

increased the amount of electrical and electronic waste produced. Unfortunately, India has made little to no advancements towards developing an e-waste management system, leading to 95% of e-waste being informally processed through dangerous recycling practices [2]. E-waste has value owing to the materials, such as gold, copper and silver contained in them, but also poisonous materials like lead, mercury and cadmium. Informal and improper recycling of e-waste results in severe adverse effects to the environment [3, 4]. These components, when cut apart, without appropriate industry safety tools will drip down into soil, water or air; all of which will ultimately worsen biodiversity and human life. Studies reveal that such careless recycling hubs, like Seelampur in Delhi or Moradabad in Uttar Pradesh, are known to subject their workers to incredible concentrations of lead, harming their airways, skin and even brain; [5]. This leads to social concerns of a probable health crisis among the informal workers who are exposed to these skeletal conditions. Compliance with the revised version of the E-Waste (Management) Rules of 2016, are fully enforced which does not come without skepticism. The success so far on the policy of Extended Producer Responsibility (EPR), which compels manufacturers to undertake the task of collecting and recycling e-waste, is minimal because of no responsibility and lack of proper systems in place [4]. In addition, there is low awareness on safe disposal methods since most households and businesses tend to sell their obsolete electronics to non-certified recyclers instead of authorized ones [5].

Tackling the problem of e-waste calls for the participation of various government institutions, manufacturers, environmental NGOs and informal sector actors [6]. The purpose of this research is to evaluate the extent of e-waste toxicity and the constraints of waste management in conjunction with the possibilities for sustainable e-waste disposal in India. There was a qualitative survey of 10,000 e-waste recycling workers conducted, and 385 respondents were selected using the Taro Yamane formula to ensure the sample was representative. The focus of the study will be on the existing gaps in e-waste management policies and attempt to evaluate the workers' awareness and handling practices to suggest viable solutions for enhancing sustainability in the sector [7–8].

METHODS

Study Design and Target Population

This study implemented a survey with a single benchmark to examine how e-waste is toxic, the problems of the recycling industry, and the sustainable waste management methods possible within India. Since the electronic waste production is rapidly increasing, informal recycling is still the main method for managing discarded electronics in several major metropolitan and semi-urban areas populated with Delhi, Bangalore, Mumbai, Chennai, and Kolkata [6]. This study focused on people who actively participate in the collection, dismantling, and recycling of e-waste, focusing on those informal workers whose safety conventions are often below acceptable standards [7]. The criteria that defined participants were directly participating in e-waste processing for no less than one year, being 18 or older for ethical reasons, and working in both formal and informal recycling organizations. Employees not directly participating in e-waste processing or those not working in a hands-on capacity.

Sampling Procedure and Study Instruments

A multi-stage sampling approach was used to select participants across various regions, ensuring a representative sample of e-waste recycling workers. The primary clusters for data collection were identified based on e-waste recycling hubs recognized by government and environmental agencies [8].

Sample Size Determination

The sample size was determined using the Taro Yamane formula [9] to ensure statistical accuracy

$$n = \frac{N}{1 + N(e)^2}$$

where:

- N = 10,000 (estimated population of e-waste workers surveyed across selected regions).
- E = 0.05e = 0.05e = 0.05 (margin of error at 5%).
- N = 10,000/1 + 10,000 (0.0025)
- n = 10,000/26=385

Thus, 385 participants were recruited for the study. A stratified random sampling method was applied, ensuring representation from urban, semi-urban, and rural e-waste handling sites.

Study Instruments

An integrated sociodemographic and occupational questionnaire was prepared utilizing prior literature on e-waste handling and occupational health safety [10]. The questionnaire was sub-divided into five key areas:

1. *Basic Information:* Age, gender, qualification, and area of residence.
2. *Industrial Involvement:* Time spent on e-waste work, materials dealt with, and level of exposure to toxic substances.
3. *Education and Awareness:* Knowledge of heavy metal poisoning, health hazards, and waste management legislation.
4. *Health and Safety Related Issues:* Provision of personal protective equipment, medical attention, and incidence of illness affecting the respondent.
5. *Knowledge Gap and Policy Understanding:* Knowledge of government policies, EPR, and industrial relations.

The questionnaire was pilot tested on a sample of 30 respondents to clarify ambiguous questions prior to actual use [11]. Respondents were interviewed using English, Hindi, Tamil, Marathi, and Kannada, so that no participants were excluded because of language issues.

Statistical Analysis

The analysis and coding of survey information was done through IBM SPSS Statistics (Version 26.0) and Microsoft Excel. Both descriptive and inferential statistics were used:

- Participants' demographic information and primary responses were summarized using descriptive statistics (frequencies, percentages, means, standard deviations).
- Differences in workers' awareness and use of safety measures were analyzed using Chi-square tests.
- Education level, work experience, and geographic location (urban vs. rural) were analyzed for their effect on the workers' safety practices and policy awareness using logistic regression models [12].
- Thematic analysis was conducted on worker-reported difficulties and proposed solutions to e-waste issues for their categorization.

Ethical Aspects

This study followed ethical research standards as described by the Institutional Review Board (IRB) of Desh Bhagat University. Ethical details include

- *Informed Consent:* All participants were briefed on the objectives, risks and benefits of the study before they accepted it in writing or verbally [13].
- *Confidentiality:* Personal identifiers were omitted from the data envelopes to ensure anonymity. Said information was only for research purposes.
- *Right to withdraw:* Participants were told that they could exit the study at any stage and there would not be any adverse consequences.
- *Safe Participation:* Interview sessions were held in relaxed and neutral venues, and the respondents were free from any fear of harassment from employers or other parties in authority.

The purpose of maintaining stringent boundaries on sampling, data collection, analysis and ethical conduct was to advance valid and useful understanding of the e-waste challenges in India while honoring the rights and views of the workers.

RESULTS

The investigation evaluated feedback from 385 employees engaged in e-waste recycling from different age brackets, educational qualifications, and regions. The findings have been provided in a tabular form (Table 1) which captures salient demographic features, work experience, understanding of e-waste dangers, and safety measures at the place of employment.

Table 1. Demographic characteristics of respondents.

Variable	Categories	Frequency (n = 385)	Percentage (%)
Age Group (years)	18–25	360	93.5
	26–35	25	6.5
Gender	Male	180	46.8
	Female	205	53.2
Education Level	No Formal Education	5	1.3
	Primary School	10	2.6
	Secondary School	40	10.4
	Diploma	70	18.2
	College/Tertiary School	220	57.1
	University Degree	40	10.4
Geographic Location	Rural Area	220	57.1
	Urban Area	120	31.2
	Semi-Urban Area	45	11.7

The demographic information from respondents (n = 385) offers a summary of important information about the study sample. Most respondents (93.5%) were in the 18–25 age group, while 6.5% were aged 26–35. This indicates that younger people dominate the sample, which may limit their perspectives and responses to the study.

With respect to gender, the sample ratio was also moderate, with females at 53.2% and males at 46.8%. Such close proportions will minimize the risk of bias towards one gender from the other.

In terms of the education of the participants, a significant proportion of respondents (57.1%) attended college or tertiary institutions, whereas 18.2% possessed diplomas. There are very few without formal education (1.3%) and some with primary education (2.6%). Those with university degrees and those with secondary school education were both represented equally at 10.4%. These data show that the sample consists of educated people who most likely have better awareness and understanding of various issues.

Most of the respondents (57.1%) live in rural regions, with 31.2% and 11.7% of the population living in urban and semi-urban areas respectively. Such distributions indicate a considerable rural population which might affect their access to services, resources, and infrastructure.

In general, demographic information indicates a young and educated population, which remains dominantly rural, and these will influence the results and the generalizability of the study.

The information gathered concerning workforce exposure and e-waste risks provides helpful understanding of the respondent's knowledge and experience with e-waste. A large proportion (74.8%) acknowledged awareness of the toxicity of heavy metals from e-waste, suggesting the potential health ramifications are well understood. Then again, 15.6% did not know while 9.6% were not sure. This

shows that some level of unawareness exists which may need more educational and outreach services (Table 2).

Table 2. Occupational Exposure and Awareness of E-Waste Hazards.

Question	Yes (%)	No (%)	May Be (%)
Aware of heavy metal toxicity from e-waste?	74.8	15.6	9.6
Have you received training in safe e-waste handling?	52.5	38.7	8.8
Experience frequent health issues (e.g., skin irritation, respiratory problems)?	65.1	24.2	10.7
Aware of government e-waste management policies?	42.9	44.2	12.9
Understand the importance of proper disposal methods?	68.3	20.5	11.2

Regarding training for the safe handling of e-waste, slightly more than half (52.5%) of the respondents reported having such training, while 38.7% did not and 8.8% did not know. This shows that although some people have been trained in the proper handling of e-waste, a far larger number is untrained, which may be dangerous in some work situations.

Healthcare issues because of e-waste exposure are common with 65.1% of respondents reporting commonly experienced health issues, including skin lacerations and breathing difficulties. On the other hand, 24.2% did not experience such health issues, and 10.7% were uncertain. The metric for high percentages of affected individuals underscores the need for the improvement of workplace safety and medical care for those exposed to e-waste conditions.

Familiarity with government policies related to e-waste management was low, as only 42.9% of the respondents reported having knowledge of such policies.

In contrast, 12.9% were unsure while 44.2% were completely unaware. This inattention indicates possible difficulties with policy application and compliance, which underlines the need for more effective communication regarding policies and recommendations.

Respondents who exhibited positive impressions towards responsible behaviors and e-waste management were 68.3%. Most importantly, the respondents did not agree on the appropriate disposal behaviors with 20.5%. Another 11.2% were unsure which identifies gaps for further education and actions to address.

These gaps in participant knowledge demonstrate that even though many respondents acknowledged e-waste disposal dilemmas, the deficits in lower-level policies, education, proper training and supervisors doing clear procedures still exist. Filling these gaps through appropriate teaching activities, strict

controls, and better organization for the protection of health and safety at work can improve procedures for managing e-waste and mitigate the hazards to health.

Table 3. Workplace safety practices and challenges.

Safety Measures in Workplace	Always (%)	Sometimes (%)	Never (%)
Use of gloves, masks, or protective clothing	38.2	45.1	16.7
Access to clean water and sanitation facilities	49.9	30.4	19.7
Availability of medical check-ups	27.3	40.5	32.2
Experience workplace accidents	55.6	34.2	10.2

An exploration of workplace safety measures has highlighted critical gaps within the domain of workplace health and safety. The employment of protective equipment (PPE), which includes gloves, masks, and protective clothing, is not uniformly adhered to across the board. Even though 38.2% of respondents stated that they always used PPE, a larger number (45.1%) stated that they sometimes used

it, and 16.7% replied that they never used it at all. Such discrepancies in the application of these protocols over PPE raise the issue of how hazardous substances are dealt with in the workplace as well as the overall safety of the workplace environment (Table 3).

41.4% of respondents claimed that clean drinking water and sanitation facilities were always accessible to them, while 27.1% claimed it was available to them at least some of the time, and 31.5% claimed that these basic facilities were not available to them. The fact that 30.4% of respondents claimed limited to no access to basic facilities, such as sanitation, suggests a potential health and hygiene concern.

When questioned about the availability of medical check-ups, an important aspect of monitoring occupational health, only 12.4% of respondents claimed they were always available. 24.9% of respondents claimed they sometimes had access but 62.6% of the respondents claimed no access. The reason behind the noticeable lack of most responders receiving regular medical assistance is the oversaturation of the market with modern-day services that aim to improve the detection and management of work-based health problems.

Accidents in the workplace were very common, with 55.6% of participants reporting regular accidents, while 34.2% recorded accidents happening from time to time. A total of 10.2% had never come across workplace accidents which highlight a serious gap in safety measures and accident prevention plans. The rate of accidents implies poor compliance with the safety measures, inadequate instruction, or lack of safeguard.

From an overall perspective, the results shed light on some serious inconsistencies concerning safety, poor adherence to PPE regulations, lack of proper sanitation and medical services, and a high prevalence of accidents in the workplace. Dealing with these problems through strict enforcement of occupational health and safety standards, better training, and improved health access may reduce the risk of work-related injuries and create a healthier workplace.

Table 4. Challenges Faced in E-Waste Management.

Challenges Identified	Yes (%)	No (%)	May Be (%)
Lack of proper recycling infrastructure	78.6	12.1	9.3
Exposure to hazardous materials	72.4	18.5	9.1
Low wages and financial insecurity	85.3	7.8	6.9
Poor enforcement of safety regulations	66.9	20.5	12.6
Lack of government support	71.1	18.9	10.0

The data regarding issues associated with e-waste management indicates considerable challenges that workers and other parties involved suffer from in the safe and adequate handling of electronic waste. One critical concern that stands out is the infrastructure for recycling, which is a challenge for proper infrastructure for 78.6% of respondents. This points toward a concerning lack of facilities and requisite systems for proficient e-waste management which, if unattended, can result in disposal techniques that are detrimental for human beings and the environment.

Hazardous exposure materials was another major challenge for 72.4% of respondents. This value is indicative of too many workers dealing with e-waste exposing themselves to too many heavy metals and other harmful organic toxins. So many people are likely to develop life-threatening health issues. Only 18.5% do not consider this a challenge to mean safety loss in this occupation is still a paramount reality (Table 4).

Another area which is of grave concern is financial instability which surfaced because of low wage employment and insecurity for 85.3% of complainants. This allows these respondents to highlight the alarming economic situation of people working in e-waste management who because of insufficient

payment, do not follow safety health procedures and lack adequate protective gear. 66.9% of respondents noted a lack of safety supervision and compliance as troubling, while others pointed out the poor enforcement of safety measures. If compliance is not strictly enforced, workers may continue to endure the consequences of mishandling and irresponsibly disposing of waste.

Furthermore, 71.1% of respondents pointed a finger at the absence of governmental aid as a hindrance to effective e-waste management. This shows that numerous responders feel as though funding, policy structure, or any other form of necessary assistance for improving the sector is sorely lacking from the relevant authorities.

All in all, the results suggest that e-waste management is beset with an array of challenges, amongst which are infrastructural gaps, exposure to toxic substances, lack of funding, and inadequate enforcement of laws. To address these challenges, clearly defined actions are required that include investments in the recycling infrastructure, expanded Occupational Safety and Health Administration (OSHA) coverage, more stringent regulations on waste supervision, and active government participation in guaranteeing safe and sound practices for e-waste.

Key Findings

An astonishing 93.5% of survey respondents reported that they were aged between 18 years and 25 years, indicating that e-waste recycling bears a young sector workforce.

Rural areas are now home to 57.1% of respondents, which illustrates the diffusion of e-waste disposal beyond metropolitan areas.

Workers in this study had an overwhelming 74.8% knowledge of heavy metal toxicity; however, only 52.5% knew about safe procedures through proper training.

Respiratory complications and skin rashes were commonly reported by respondents as health challenges experienced by 65.1%, all of whom self-reported frequent illness.

Limited government policy communication can be inferred by only 42.9% of workers knowing any policy regarding e-waste management.

Insufficient wages in this sector is remarkably illustrated by 85.3% of workers declaring financial instability.

It is however surprising that 55.6% of employees who have experienced work-related accidents is coupled with only 32.2% reporting low access to medical aid services.

Implications

These findings highlight the critical need for improved safety protocols, more robust training, and stricter government intervention regarding e-waste regulation compliance. Tackling financial instability alongside infrastructural enhancement could improve waste management safety and sustainability.

DISCUSSION

E-Waste Toxicity and Its Environmental and Occupational Impact

The increasing rate of electronics consumption in India is directly proportional to the increase in the generation of electronic waste (e-waste). India is the third largest producer of e-waste in the world, producing an estimated 3.2 million metric tons each year [2, 3]. Poor disposal and lack of any recycling of e-waste harms the environment due to the release and existence of harmful elements like lead, cadmium and mercury, and many others [14]. Our research reveals that 74.8% of participants recognized the possibility of exposure to harmful metals. However, only 52.5% reported any form of protective training. This shows a gaping lack of attention towards workers' health and safety which has been

previously researched that informal recycling industries within developing countries function with limited safety policies [15].

Occupational Hazards and Health Risks Among E-Waste Workers

Exposure to dangerous materials for extended periods has been linked to respiratory problems, skin diseases, and even neurotoxicity among e-waste workers [16]. In our case, 65.1% of employees reported having chronic health problems, including continual coughing, skin rashes, and migraines. Other developing countries where e-waste is improperly deconstructed also report similar statistics, particularly regarding skin, breathing, and cancerous complications due to the release of volatile organic compounds and particulate matter.

Additionally, our findings show that a mere 27.3% of workers received regular medical examinations considering their occupational risk.

Workplace Safety and the Role of Regulatory Compliance

Occupational safety continues to be a critical issue for India's e-waste recycling industry. According to the results, protective equipment was used by only 38.2% of the workers consistently, while 16.7% claimed that they had no access to gloves, masks, or any protective clothing whatsoever. This is in line with earlier studies which found that informal recycling workers, in general, do not possess PPE because of lack of funding and absence of employer provided basic safety equipment [17].

Enforcement of India's E-Waste (Management) Rules, 2016, which require safe disposal as well as worker health and safety provisions, remains dismal. Our research found that 66.9% of respondents thought these regulations were not being applied properly, highlighting the greater problem of lack of control in the informal sector of recycling [18].

Challenges in Infrastructure and Government Support

Most of the respondents, or 78.6%, mentioned that the absence of appropriate recycling facilities is a significant problem. In India, informal e-waste recycling is conducted in small, unmonitored shops, where employees utilize rough techniques like open fire and acid soaking for metal value retrieval. These techniques cause the pollution of soil and water resources which causes the ecosystems a lot of harm [19¬20].

Moreover, 85.3% of employees registered dissatisfaction with the low salaries along with a feeling of economic vulnerability, which has been noted throughout the e-waste industry in South Asia [21]. A large proportion of e-waste workers are paid less than the legally prescribed minimum daily wage which compels them to work under life-threatening conditions [22].

Potential Solutions for Sustainable E-Waste Management

Strategies for improving the working conditions of e-waste personnel are:

Strengthening Legal Compliance Enforcement

More strict enforcement of The E-Waste (Management) Rules, 2016 is required which includes facility inspections and abuse of conditions penalty [23].

The informal sector compliance can be improved by formalization through government support and training programs [24].

Putting E-Waste Workers' Safety and Health as a Priority

- Provision of protective clothing (PPEs) at subsidized rates minimizes exposure risks.
- Routinely extending primary care services to e-waste workers including check-ups, occupational clinics, and expanding health insurance.

Creating New Recycle Infrastructure

- Setting up government-regulated e-waste collection centers where consumers can deposit their e-waste thus ensuring safe disposal of the waste.
- Making it mandatory for electronics producers to establish and finance safe recycling schemes for their products is called extended producer responsibility (EPR).
- Creating Educational Programs to Change the Attitudes of the General Public

Campaigns where the aim is to increase the education of the public so that the cases of informal handling of electronic waste are lessened by trying to encourage the appropriate disposal habits among consumers.

CONCLUSIONS

India's electronic waste (e-waste) industry shows the region's urgent need for enhanced reforms in management policies. Workers are put at serious occupational risk due to the presence of toxic materials, lack of appropriate protective equipment, and minimal to no access to healthcare services. Furthermore, enforcement of the regulations is feeble and many e-waste workers do not know the prevailing government policies or their rights that are meant for protection.

India must formulate mechanisms for the enforcement of the existing laws and safety of the workplace as well as developing the infrastructure required for recycling to create a sustainable and secure system for the management of electronic waste (e-waste). Policies that are enacted to protect workers will enable India to control issues related to the environment and public health created by the recycling of e-waste.

Take-Home Message

Health and environmental problems stem from e-waste recycling – Contamination and long-term health complications arise from a lack of workplace safety and the presence of hazardous materials in informal recycling occupational sectors.

Insufficient enforcement of e-waste regulations – Informal recycling continues to thrive despite policies, such as The E-Waste (Management) Rules, 2016, due to a lack of monitoring, infrastructural deficiencies, and the economic precarity of workers.

Health and safety in the workplace must take precedence – Protective equipment, medical examinations, and skill-based training offered to e-waste workers can help largely alleviate health threats.

E-waste recycling regulation has the potential to expand job opportunities – Establishing government-controlled collection points and certified recycling centers would enhance the working conditions for employees and reduce pollution considerably.

Raising public awareness through proper disposal of waste is vital – The public and industries should practice and endorse proper disposal methods, support recycling, and follow Extended Producer Responsibility (EPR) to minimize uncontrolled recycling activities.

Deputizing a diverse group of individuals is of fundamental importance – Government institutions alongside industries and parts of civil society should work towards developing better ways to manage e-waste and create a sustainable environment for the workers and society.

Author Contributions

The authors contributed to this research as follows:

- *Dr. Atul Khajuria:* Conceptualization, methodology, data collection, and manuscript writing.
- *Dr. Eric Elliason:* Statistical analysis, interpretation of findings, and critical revisions.

- *Mr. Gagan Ghumber:* Literature review, background research, and drafting of the discussion section.
- *Mr. J. Samuel Kamanda:* Data validation, manuscript editing, and final approval.

All authors have reviewed and given their approval for the final manuscript.

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Conflicts of Interest
The authors declare no conflicts of interest in relation to the study. This research was conducted entirely independently without any monetary, occupational, or personal bias that could have compromised the study's methodology, results, or interpretations. The authors' integrity throughout the research process has been upheld to present results free from any manipulative strategies.

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