Vol. 7 Issue No. 2, April - June 2025 e-ISSN 2456-7701
Journal of Science and Technological Researches
A Peer Reviewed Journal
Origin of Innovation
Domain: www.jstr.org.in, Email: editor@jstr.org.in

CIRCULARITY IN E-WASTE MANAGEMENT: CHALLENGES AND OPPORTUNITIES, A PERSPECTIVE FOR HIMALAYAN STATE UTTARAKHAND, INDIA

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Date of Received	**28 May, 2025**
Date of Revised	**22 June, 2025**
Date of Acceptance	**29 June, 2025**
Date of Publication	**30 June, 2025**

DOI Link : https://doi.org/10.51514/JSTR.7.2.2025.31-42

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ABSTRACT

The accelerated development of technology resulted to a tremendous increase in e-waste, which is having considerable environmental concern and economical challenges, particularly in ecologically fragile regions like Uttarakhand, and Himalayan State of India. The hilly terrain of the State makes it complicated for waste collection, transportation, and disposal and moreover often face suspect to contaminate air, soil, water bodies. The traditional linear economy model for e-waste management not only contributes significant waste disposal burden on environment but also undermines sustainability and economic potential, which is necessary for a shift toward circular economy principles that emphasize reuse, refurbishment, and material recovery. An effective e-waste management strategy can unlock the value of embedded elements and precious metals, reduce environmental threats and enable growth of green economy. Decentralized recycling units and sustainable product life cycles can enhance efficiency while reducing ecological risks. This paper highlights the crucial role of an Extended Producer Responsibility (EPR)-based framework in tackling environmental concerns. This practice outlines a systematic approach to shift the informal sector into a formalized collection and recycling sector, supported by decentralized processing hubs and financial incentives. Aligning policies with Uttarakhand’s conservation priorities ensures environmental protection alongside economic benefits. India's commitment to global sustainability targets, including COP26 and Net Zero Emissions, demands a structured e-waste strategy to reduce reliance on virgin materials and lower carbon footprints. The state is utilizing only one third of its potential for e waste recycling. A comprehensive circular economy policy, backed by advanced waste tracking technologies and transparent governance, can position Uttarakhand as a leader in sustainable e-waste management along with balancing economic growth and sustainability.

Keywords: *Recycling, Collection, E-Waste, Regulatory, Monitoring, Incentive etc.*

INTRODUCTION

In developing countries, change in consumption patterns over the years with huge quantities of different types of waste is reported to be one of the major environmental concerns [1]. Initiatives are being taken by framing regulations for effective waste management. Rapid urbanization and modernization have accelerated technological advancements and increased the use of electronic and electrical equipment (EEE). Although, modern technology has significantly improved living standards and introduced various lifestyle conveniences, it has also contributed to environmental damage and the overexploitation of natural resources [2]. The concept of a circular economy, which considers waste as a valuable resource, is being adopted for holistic waste management. Circularity in management of Waste EEE is essential, as this waste is not just a growing environmental challenge but also the most valuable waste stream for economic recovery. It comprises precious metals such as gold, silver, and rare earth elements, which play a vital role in industrial growth and manufacturing processes [3].

Circular Economy (CE) and Sustainability

The concept of Circularity in Waste Management i.e. Circular Economy refers to a multi-dimensional concept that promotes resource productivity, sustainable materials management, and socio-economic benefits. It replaces the linear model with circular model, as shown in Fig.-1 [4]. The Circular Economy aims to achieve sustainability through the 10R's framework given by PBL Netherlands Environmental Assessment Agency [5]. These 10 Rs

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are R0-Refuse, R1-Rethink, R-2 Reduce, R-3 Reuse, R-4 Repair, R-5 Refurbish, R-6 Remanufacture, R-7 Repurpose, R-8 Recycle, R-9 Recover. Moreover, Circular Economy concept aligns with and supports the compliance of several United Nations Sustainable Development Goals (SDGs) like SDG 3: Good Health and Well-being; SDG 5: Gender Equality; SDG 6: Clean Water and Sanitation; SDG 7: Affordable and Clean Energy; SDG 8: Decent Work and Economic Growth; SDG 11; SDG 12: Responsible Consumption and Production; SDG 13: Climate Action [5].

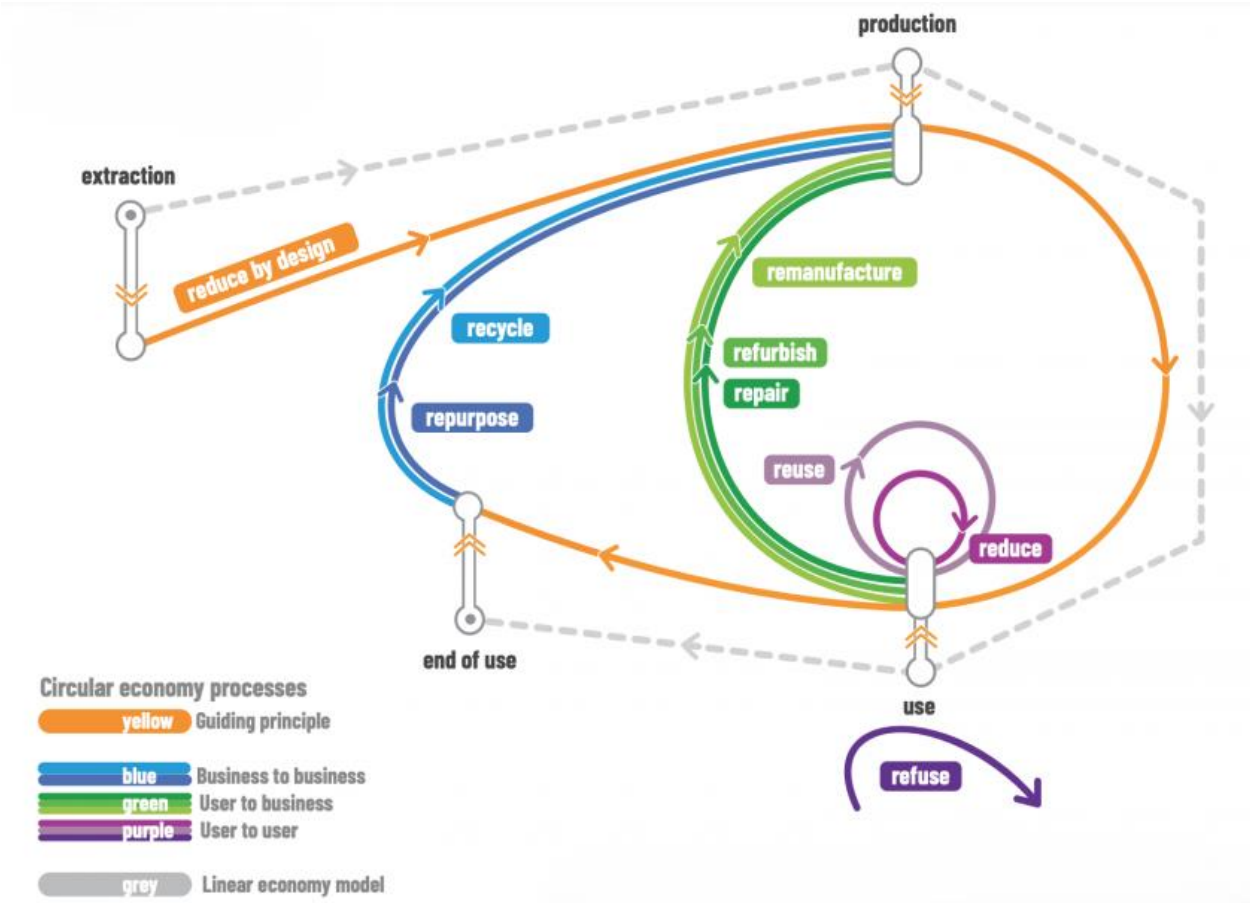

Fig.-1. Circular Economy Model for Waste EEE Management.
Source: United Nations Environment Programme: UNEP Circularity Platform 2019 [4]

Waste EEE: Need of its Management

Waste EEE refers to discarded electronic devices and household electrical appliances that have reached the end of their functional life or are no longer suitable for use. With more than 1,000 components, e-waste includes many harmful substances that can be dangerous to human and the environment if not properly treated [6]. Waste EEE is amongst the most rapidly expanding waste stream, with an estimated annual increase of 3% to 5% [7-8]. In 2018, global e-waste generation was estimated as 50 million tons, with approximately half comprising personal electronics like smartphones, tablets, computers, monitors, and televisions. [9]. As illustrated in Fig.-2, the According to the Global E-Waste Monitor 2020 [10] global e-waste generation in 2019 was 53.6 million metric tons which is estimated to be increased as 74 million metric tons by 2030. The projections suggest that by 2050, the demand for natural resources will be three times greater than the Earth's ability to regenerate them, and by 2060, the global usage of materials like metals and minerals is expected to double [11]. Hence a robust model for recovery of valuable from the waste is highly needed.

e-ISSN 2456-7701
Vol. 7 Issue No. 2, April - June 2025

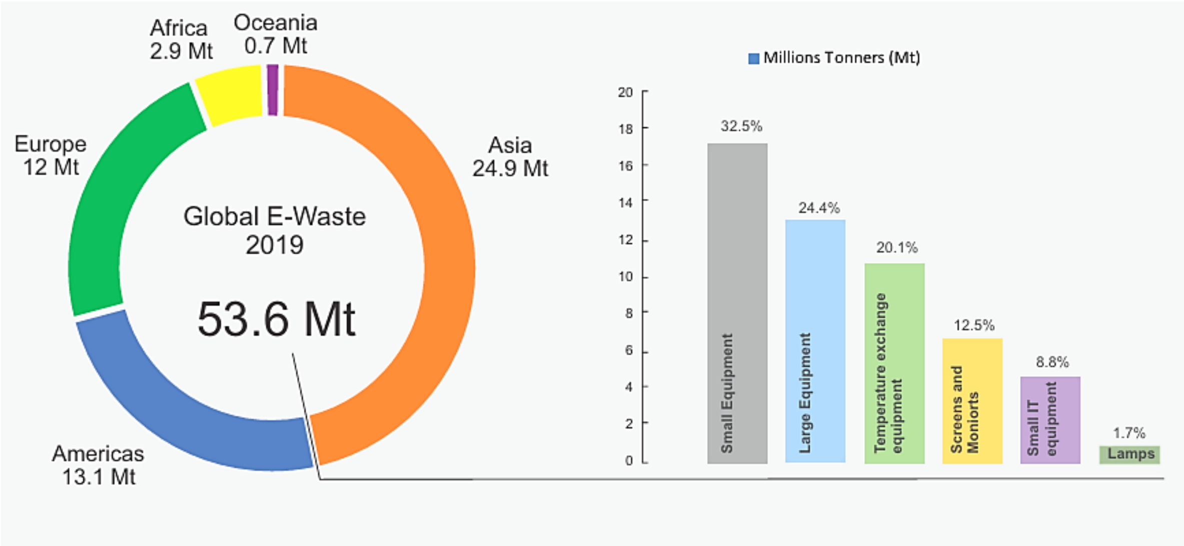

Fig.-2 Global e-waste generation in 2019 [10]

E-waste consists of a wide range of metallic and non-metallic elements, with its components varying across different product types and categories. Besides commonly found base metals, e-waste may contain varying levels of ceramics, plastics, rare earth elements, and precious metals [12]. On the other hand, it also source of toxic components, including heavy metals such as chromium, lead, mercury and nickel, as well as persistent organic pollutants (POPs) like polychlorinated biphenyls (PCBs) and brominated flame retardants (BFRs) [13-14], and unscientific disposal of these substances may cause their direct release or cause the formation of toxic byproducts, contributing to ecological damage and adverse health impacts [15-16]. Generation of e-waste from different sources along with the percentage of heavy metals is compiled from various sources and presented in table-1.

Aligning e-waste management with circular economy principles can significantly contribute to India's economic and sustainability goals, especially under the COP26 Agenda 2030 and the Net Zero Emission targets [17]. Among the seven key sectors driving net-zero commitments, the industrial sector plays a pivotal role in economic recovery, and efficient resource utilization through e-waste recycling can reduce dependency on virgin raw materials, lower carbon emissions, and promote sustainable manufacturing. By integrating a circular model—focusing on refurbishment, component recovery, and material reintegration—India can enhance resource security, drive green industrialization, and position itself as a global leader in sustainable technology. The e-waste management become more crucial for the hilly terrains and nature rich hilly area like Himalayan State of India namely Uttarakhand. There are challenges in Waste EEE collection and transportation for its handling & management in the hilly state. For ease of understanding the location of the Uttarakhand State, Fig.-3 may be referred.

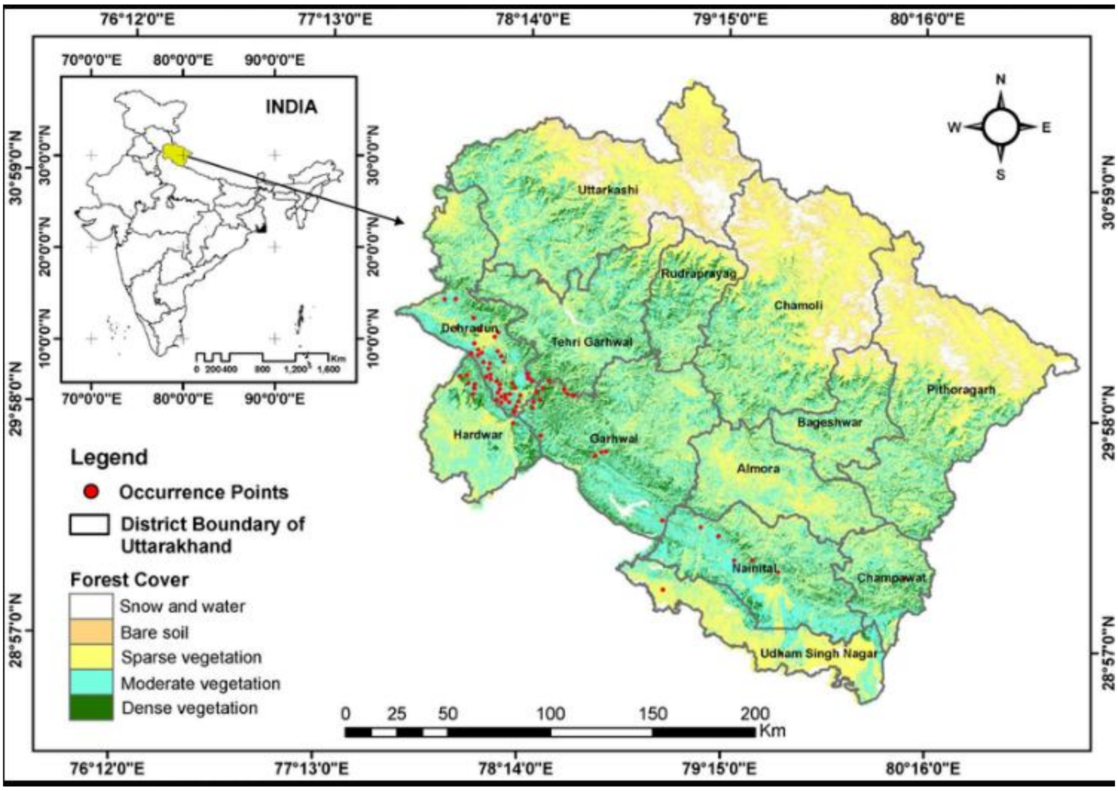

Fig.-3. Map of Uttarakhand, India showing its geographic location

Table 1: Sources of E-Waste and prominent metals found into it.

E-Waste Type	Prominent Heavy Metals percentage
Large household appliances like refrigerators/ freezers, washing machines dishwashers.	Aluminium (1.3–2.0), Tin (1.6–2.0), Copper (2.0–4.1), Silver (0.0042–0.045), Lead (0.021–2.5) Cadmium (0.036–1.9) [34]
Small household appliances like vacuum cleaners, kitchen machines.	Copper (18.8), Lead (4.79), Aluminium (0.912) Chromium, Cadmium and Nickel collectively (0.0051–0.0179) [35]
Information technology and telecommunication equipment like computers, telephone, mobile phones, copying equipment, printers.	Copper (7.0–30), Aluminium (1.41–14.17) Lead (1.20–6.29), Tin (1.0–3.15) Nickel (0.85–2.5) [36-37]
Consumer Equipment Electrical and electronic tools (except large scale stationary industrial tools) like televisions, stereo equipment, Handheld drills, saws, screwdrivers.	Copper (10), Aluminium (10) Lead (1.0) Nickel (0.3) [38]
Toys, Leisure and sports equipment like Video games, sports computers, car racing, etc.	Lead (31–34), Cadmium (30–38) Mercury (4.0–16) Copper (0.014) Tin (0.0039) [39-42]

OBJECTIVE

This paper aims to analyze practices for management of Waste EEE global frameworks, comparing Extended Producer Responsibility (EPR) models, recycling strategies, policy effectiveness across different regions with a key focus to identify the gap and development of structured circular economy model-based E-Waste Management policy for the Uttarakhand, India and aligning these strategies with India's commitments to COP26, Net Zero Emissions, and the SDGs.

METHODOLOGY

A multi-layered analysis of e-waste scenario across global, national, and state levels, combined with a temporal policy review, forms the foundation of this article. The article emphasizes opportunities for policy enhancement, regulatory improvements, and sustainable strategies to promote circularity in e-waste management.

Multi-Level Comparative Analysis

This paper examines e-waste trends and policies at three levels:

- Global Level: Comparative analysis of e-waste generation, recycling rates, and Extended Producer Responsibility (EPR) models across continents (Europe, North America, Asia). Reports from The Global E-Waste Monitor (2020), OECD, and UN reports are utilized to assess international best practices.
- National Level (India): A detailed assessment of India's management framework of e-waste through the evolution of E-Waste (Management and Handling) Rules 2011, 2016, and 2022. The study also examines e-waste generation and processing data retrieved CPCB reports (2017–2021).
- State Level (Uttarakhand): A micro-level analysis of Uttarakhand's e-waste generation, recycling infrastructure, and compliance status based on UKPCB reports. A case study of state of art e-waste recycling facility namely M/S Attero E-Waste Recycling Pvt. Ltd. in Roorkee, Uttarakhand India, is included to assess localized circular economy applications.

Temporal Analysis of E-Waste Policies

A timeline-based comparative analysis has been conducted to evaluate the evolution and effectiveness of e-waste regulations:

- Global E-Waste Policies: Examining the transition from voluntary recycling models to mandatory EPR frameworks in Taiwan, China, and the EU.
- Evolution of India′s E-Waste Regulatory Framework: A comparative study of 2011, 2016, and 2022 e-waste rules, tracking changes in EPR compliance, producer responsibility, and recycling mandates.
- Uttarakhand′s E-Waste Performance Over Time: Evaluating state-level e-waste recycling trends (2017–2023), based on UKPCB and CPCB data.

Analytical Framework

- Gap Analysis: Identifying key challenges such as lack of e-waste inventory, compliance monitoring gaps, auction transparency issues, and informal sector integration.
- Circular Economy Model Assessment: Evaluating the feasibility of decentralized recycling hubs, incentive-based intra-state recycling, and digital tracking mechanisms for effective waste management.
- Policy Recommendations: Proposing state-specific regulatory enhancements and structured monitoring mechanisms to improve Uttarakhand's e-waste management system.

Limitations

The study relies primarily on secondary data sources (reports, policy documents, academic studies). No primary surveys or interviews were conducted. While the comparative findings provide broader policy insights, further on-ground validation would be necessary for direct implementation in other regions.

RESULT AND DISCUSSION

E-Waste Regulatory Regime

The concept of Extended Producer Responsibility (EPR) is core of most of waste management policies, enhancing producer accountability by holding them responsible for management of environmentally sound management of waste arising out of their products and brand [18-24] as it shifts the responsibility of managing and recycling of the end-of-life products to producers, positioned at the upstream of the supply chain [25-27].

EPR serves as a policy tool in the governance of waste management systems, with diverse implementation across different regions. Sweden's car scrapping scheme, as analyzed by Forslind in 2005 and Ferrao et al in 2006 [20-21], highlighted the success of financial incentives in ensuring high compliance rate. Canada has state of art EPR through structured regulations that mandate producer responsibility for post-consumer waste, leading to improved recycling rates and resource recovery [22]. Standardized framework for EPR implementation of OECD, emphasizing the role of policy design in ensuring economic feasibility and environmental sustainability [23]. However, challenges persist in developing nations, where weak enforcement and a dominant informal sector hinder EPR's effectiveness [24]. South Africa's packaging waste EPR model, studied by Nahman [25], demonstrates the importance of financial incentives and stakeholder engagement in achieving sustainability goals. Furthermore, Walls in 2006 [26] emphasizes the role of EPR in driving product design improvements, encouraging manufacturers to develop recyclable and environmentally friendly products.

The implementation of EPR varies significantly, reflecting differences in regulatory frameworks, enforcement mechanisms. The Global E-Waste Monitor 2020 [10] indicates that, Europe has the most structured EPR framework, with legally binding collection and recycling targets; North America, by contrast, follows a decentralized model where EPR implementation varies by state or province, leading to inconsistencies in recycling efficiency. While some regions have robust programs with producer-funded recycling schemes, others lack stringent enforcement. The Global E Waste Monitor shows that Asia presents a diverse landscape where China operates a hybrid system combining regulatory mandates with financial incentives, while Japan employs a product-specific recycling law emphasizing consumer participation. Despite progress, many developing Asian nations continue to bring informal sector into ambit of formalized EPR frameworks. These variations highlight the need for region-specific adaptations while fostering international alignment with best practices to enhance sustainability in e-waste management.

Government of India has made EPR as an integral part of the different streams of waste including e-waste by encapsulating it in to legislature framework [28]. E-Waste Management Rules of 2016 framed by Government of India and subsequent new Rules of 2022 has come into existence which is in force since 01.04.2023 clearly laid down the provisions for EPR along with targets for quantum of e-waste management. According to the rules E-Waste is to be managed either by refurbishing or dismantling or recycling. Evolution of E-Waste management Rules in India can be seen in the table 2. Also, the EPR targets for e-waste producers are given under table 3.

Table 2: Comparative Analysis of E-Waste Management Rules in India

E-waste Management & Handling Rules 2011	***E-waste Management Rules 2016***	***E-Waste Management Rule 2022***
• It gives voluntarily provision of recycling of E-waste. • Promoting Collection, Dismantling and Recycling of E- waste. • Three Level of Recycling has been defined.	• Provision of Producer responsible organization for helping producer in collection of E-waste and Recycling • Extended Producer Responsibility (EPR) targets were given to producers • The recycling has been fragmented into three components: Refurbishing, Dismantling, Recycling	• Manufacturer, Producer, Refurbishes and Recycler need to register on EPR Portal of CPCB. • Producers will be given targets of EPR on the portal. • Recycler will be given EPR certificate on the portal which can be purchased by producers to fulfil the EPR targets. • Recyclers are responsible to recover maximum metals from the waste • Producers will be given composition of metal waste by Central Pollution Control Board (CPCBP for which they have to align with recyclers for metal recovery. • The EPR certificates once approved by CPCB shall be valid for 2 years. • Producer can take refurbishing certificate from refurbishers to get extension of EPR targets by 3 years.

Table 3: E-Waste Recycling Targets under E-Waste Management Rules 2022, Government of India [6]

S.No.	Financial Year	E-Waste Recycling Target (by weight)
1.	FY2023-2024	15% by weight of the sales of FY2021-22
2.	FY2024-2025	20% by weight of the sales of FY2022-23
3.	FY2025-2026 and subsequent years	20% by weight of the sales of two years back

E-Waste Management: India Scenario

In spite of the growing volume of e-waste, current recycling capabilities and efforts for formation of robust policies remain insufficient to bridge the gap of waste generation and disposal. Data of E-Waste generation and E-Waste processing since 2017-18 to 2020-21 is presented in the table 4. A total of 400 E-waste recycling/ dismantling units are operating in the country having potential of recycling is 10.68 Lakh ton. These units are getting only 2.22 Lakh ton of waste so, only 28% of their capacities are being utilized.

Table 4: E-waste Generation and Processing details from 2017–18 to 2020–21 in India (CPCB)

Components	FY2017–18	FY2018–19	FY2019–20	FY2020–21
E-waste generation	708,445	771,215	1,045,031	1,346,496
E-waste processed	69413.61	164,663	224,041	354540.7

E-Waste Management Scenario in Uttarakhand

As per the Annual Report for the F.Y. 2021-22 on E-Waste (Management) Rules, 06 E-waste recycling units are established. In the state the e-waste recycling potential is 1.58 lakh tons per year. However, only one third recycling capacity is being utilized. The report outlined a total of 49297 MT of E-waste generation [29]. Despite of this Fig., Uttarakhand ranked second in the Country in terms of e-waste collection and processing, as per the tabulated information given by Union Minister of State for Environment, Forest and Climate Change in a written reply in the Upper House of the Hon'ble parliament of India. [30]. One of the major units of E-waste recycling namely M/s Attero E-waste Recycling Pvt ltd, Roorkee is having 90% of total E-waste recycling installed capacity of the state. This unit is engaged in extracting of glass, plastic, metals and other valuable and precious components like Gold, Silver etc from the E-Waste. Fig.-4 represents the current e-waste recycling status in Uttarakhand whereas, projected waste recycling in Uttarakhand is presented in Fig.-5, indicating that availability of e-waste for recycling is expected to increase three to five times by 2030 which is predicted as 1.30 lakh Metric Ton per annum to 5.00 Lakh Metric Ton per Annum.

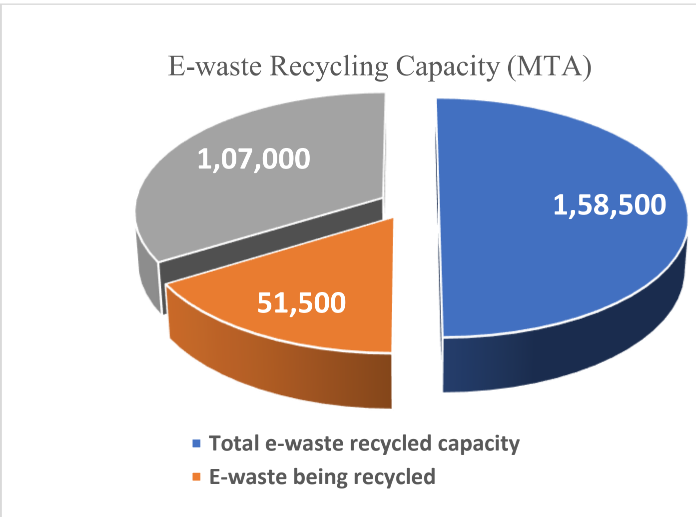

Fig.-4. E-Waste recycling status in Uttarakhand showing only (33% capacity utilisation of E-Waste in Uttarakhand

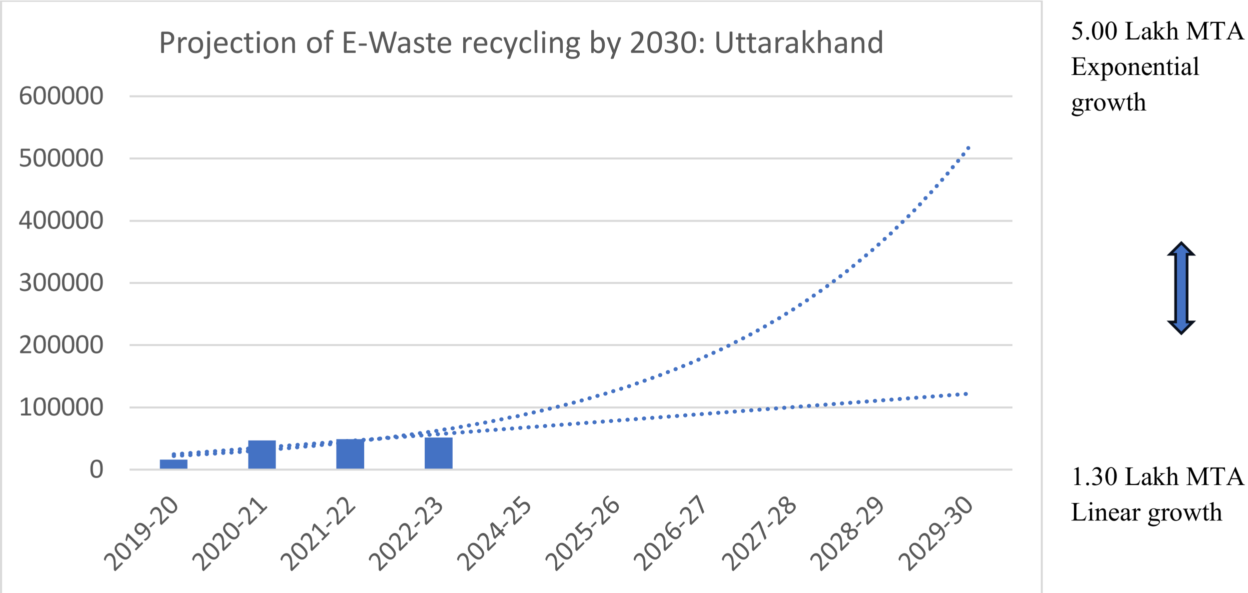

Fig.-5. Projection of E-Waste Recycling by 2030 in Uttarakhand

Gaps in the E-Waste Management in Uttarakhand

Lack of Inventory: There is no inventory of Waste EEE for the state of Uttarakhand, making it challenging to develop effective management strategies.

Compliance: On-site inspection mechanisms for e-waste recycling processes to verify compliance does not meet the requirements. Lack of digital tracking mechanism of hazardous e-waste fractions, currently recorded in physical forms (Form 4 and Form 10 which fall under Rule 20 and Rule 23, respectively, of the Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016 [6]), hinders efficient monitoring. Without a vehicle monitoring mechanism, there's a heightened risk of e-waste being illegally dumped.

E- Waste Auction Transparency Gap: The absence of mandatory e-auctions for licensed recyclers, dismantlers, and refurbishers undermines transparent and competitive bidding, facilitating e-waste leakage into the informal sector.

Limited Public Awareness: Limited public awareness about e-waste hazards and proper disposal methods is another issue. E-waste management is compromised due to insufficient education and training for stakeholders, especially the general public and students. The absence of incentives for producers using secondary raw materials and recyclers fulfilling intra-state recycling targets discourages sustainable practices.

Inadequate value addition:_The public receives no value for their e-waste, discouraging proper disposal. Lack of proof of e-waste collection make the public insecure about their waste being reused illegally.

Absence of Quality Check Mechanism: The absence of a quality check mechanism for secondary raw materials generated by e-waste recycling poses environmental and health risks.

Proposed Policy Framework for E-Waste Management for The State of Uttarakhand, India

After evaluation of the various data source and present applicable policies the e-waste management framework is proposed which includes Regulatory Measures, Monitoring Measures, Capacity Building, Responsible E-Waste management programmers and Incentives. These proposed measures with respect to the Himalayan State re discussed hereunder:

Regulatory Measures:

E-Waste Inventory Development: Component Material Method

For efficient e-waste management in hilly state of Uttarakhand, requirement of a comprehensive is proposed. Implementing a Component Material Method-based inventory will be helpful for real-time data on e-waste volumes, constituent materials, and disposal methods. By tracking e-waste flows, stakeholders can identify hotspots and prioritize interventions, optimize collection and recycling infrastructure, and monitor the overall e-waste ecosystem. Additionally, this data-driven approach will support research and development while making collaboration and resource sharing among key stakeholders.

Quality Check of Secondary Raw Materials from E-Waste Recycling

It is also proposed that the Uttarakhand Government should prioritize quality control of secondary raw materials derived from electronic waste to prevent environmental pollution, protect public health, and maintain product integrity by verification of performance of recycling through third parties. Additionally, random inspections for quality verification are also proposed to be carried out by State Regulatory Agency i.e. Uttarakhand Pollution Control Board (UKPCB). This will enable state to make compliance with international standards such as the Carbon Border Adjustment Mechanism (CBAM) [31], Global Recycled Standard (GRS) [32], and Life Cycle Assessment (LCA) [33] to enhance sustainable recycling practices, ensuring a safer and more efficient circular economy.

Registered Recyclers, Dismantlers, Refurbishers for E-Waste Auctions

It is proposed for the policy that mandate only registered recyclers, dismantlers and refurbishers can participate in e-waste auctions, ensuring safe and sustainable management of Waste EEE. The UKPCB may monitor auction participants' compliance with registration requirements and environmental regulations. For this purpose, E-Auction platform synchronization with other online auction platforms like E-tenders and Government E-market Place portal may be developed for monitoring and validation of the auctions.

Monitoring Measures:

E-Waste On-site Inspection and Monitoring

In order to ensure responsible electronic waste management, the monitoring should be done through geo-coordinate onsite inspections and visual documentation to incorporate good governance via transparency and accountability. There is urgent need to monitor e-waste recycling processes and ensure compliance with the CPCB norms in Uttarakhand to prevent leakage into informal sector.

Real -Time Tracking System for Hazardous E-Waste

The Uttarakhand Government may introduce a real-time tracking system to monitor hazardous e-waste generation, transportation, storage, and disposal, ensuring transparency and accountability. Digitalizing existing Forms 4 and Form 10, will track hazardous waste data and disposal through a dedicated portal on UKPCB’s website and GPS-enabled vehicles with tilted zoom cameras to be monitored by control room.

Capacity Building Measures

This initiative should aim to educate and engage school student, university students, and the general public on responsible electronic waste management. By leveraging ambassador-led outreach, educational seminars, and digital platforms, the project cultivates environmentally responsible e-waste disposal habits. By promoting public awareness, community engagement, and collaboration with local stakeholders, this initiative supports Uttarakhand's transition to a circular economy, mitigating environmental harm and promoting sustainable development.

Responsible E-Waste Disposal Program

A comprehensive e-waste management system for Uttarakhand, integrating door-to-door monthly collection, secure documentation, and monetary incentives for households and businesses is proposed to be developed. The model should also recognize and reward companies for responsible e-waste disposal. To strengthen the existing recycling system, hierarchy-based recycling centers should be established in remote areas, ensuring efficient sorting, disassembly, and recycling/refining.

Incentives

Producers Using Secondary Raw Materials

To promote sustainable electronic waste management, producers must be encouraged to incorporate secondary raw materials into their production processes. It is proposed that the Government of Uttarakhand should introduce incentives for producers who adopt circular economy practices, thereby minimizing e-waste generation and enhancing resource efficiency. Such measures would not only encourage the use of recycled materials but also contribute in reducing overall waste, fostering innovation, and promoting collaboration among stakeholders. By integrating these strategies, the state can move towards an efficient WEEE management system.

Incentivizing Intra State Recycling target

To boost intra-state electronic waste recycling it is

e-ISSN 2456-7701
Vol. 7 Issue No. 2, April - June 2025

proposed that the recycling units should encourage to meet predetermined targets, promoting environmentally responsible e-waste management within the state. Those recycling units that achieve or exceed the stipulated intra-state e-waste recycling targets will be eligible for enhanced incentives. This approach seeks to minimize e-waste transportation, reduce environmental hazards, and foster a circular economy.

CONCLUSION

Incorporating the informal sector into formal recycling frameworks is key to improving e-waste management, especially in developing economies. It is observed greater success of EPR based frameworks in regions where informal recycling is less active, such as Taiwan, where producers contribute to a centralized Recycling Fund Management Committee (RFMC). For Uttarakhand, integrating informal recyclers into a structured system is seems essential to ensuring sustainable e-waste management while safeguarding livelihoods. A well-designed EPR mechanism can leverage the informal sector's extensive network by offering better incentives to waste collectors, redirecting e-waste towards formal recycling. This strategy has been successfully implemented in China and Thailand, where government-led EPR schemes provide subsidies and enforce buy-back programs. The policy emphasizes public awareness, sustainable product design, and eco-friendly recycling practices and also highlights the need for institutional arrangements to track waste generation, promote green public procurement, and set guiding price ranges for registered recyclers. Proposed ttechnological advancements in tracking of e-waste collection and transportation with a robust inventory can further strengthen policy implementation in the Uttarakhand State & bridge the gap for underutilized e waste recycling potential and thus making Uttarakhand a real Circular Economy Driven State for E-waste.

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