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# Evolution of E-Waste and its Profound Impact on Climate Change

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**ABSTRACT**

*The proliferation of electronic devices has transformed modern life but generated an escalating problem of electronic waste (e-waste). This literature-based review traces the historical evolution of e-waste generation, examines current global and Indian trends, analyzes extended producer responsibility (EPR) and related policies, and explores the nexus between e-waste and climate change. Key findings show that global e-waste volumes are rising sharply (a record 62 million tonnes in 2022, up 82% since 2010), yet less than a quarter is formally recycled. India is now among the world's largest e-waste generators (roughly 1.75 Mt in 2023–24), even as an estimated 90% of its e-waste is handled by an informal recycling sector. Recent policy developments have aimed to address these challenges: for example, India's E-Waste (Management) Rules 2022 (effective April 2023) greatly expand product coverage and mandate EPR, including mandatory registration of manufacturers on a central portal. The climate implications of e-waste are significant but often indirect. Electronics manufacture is highly carbon-intensive (e.g. ~10 t $CO_2$ per tonne of laptops produced) and extending product lifetimes or recycling materials can reduce this footprint. Unmanaged disposal (open burning and acid extraction) releases pollutants and greenhouse gases. This review underscores that sustainable e-waste management – through strengthened EPR, technological innovation, formalization of recycling, and circular economy principles – is critical for reducing toxic pollution and mitigating the carbon footprint of the digital economy.*

**Keywords:** *Electronic waste; Extended producer responsibility; Climate change; Informal sector; Circular economy; India.*

## I. INTRODUCTION

In the digital era, electrical and electronic equipment (EEE) have become ubiquitous, dramatically improving productivity and connectivity. However, the rapid innovation and consumption of electronic devices have led to an unprecedented growth of end-of-life e-waste. By definition, e-waste comprises discarded products with a plug or battery, including

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computers, smartphones, TVs, and appliances.[3] While containing valuable recoverable resources, e-waste also harbors toxic constituents (e.g. lead, mercury, cadmium) that threaten environmental and human health if improperly managed.[4] Global generation of e-waste has surged: according to the UN's Global E-Waste Monitor, a record **62 million metric tonnes** of e-waste was produced in 2022,[5] and this figure is projected to reach 82 Mt by 2030. Less than a quarter of this is collected and recycled in an environmentally sound manner.[6]

This review synthesizes recent literature (2023–2025) to trace the evolution of e-waste and its climate change footprint, with emphasis on policy responses and the Indian context. First, the historical drivers of e-waste – chiefly the accelerating turnover of consumer electronics – are outlined. Next, current global trends in e-waste quantities and recycling rates are summarized. Subsequent sections examine regulatory frameworks, notably Extended Producer Responsibility (EPR) policies, and recent amendments (e.g. India's 2022 E-Waste Rules) designed to improve e-waste management. A special focus is placed on India, where informal recycling systems dominate and pose unique challenges.[7] Finally, the climate implications of e-waste are explored: the electronics sector's carbon footprint is largely upstream (in manufacturing and logistics),[8] but disposal-phase emissions and lost circularity also matter. We conclude with implications for sustainable e-waste management, highlighting the need for circular economy approaches to mitigate both environmental pollution and climate impacts.[9]

## II. EVOLUTION OF E-WASTE GENERATION

The phenomenon of electronic waste has grown in tandem with advances in technology. Early in the 21st century, rapid innovation (miniaturization, multifunctionality, and falling prices) caused the lifespan of devices to shrink. For example, desktop computers and mobile phones once used for a decade are now typically replaced every few years. This "planned obsolescence" has flooded markets with electronics: UN reports note that global e-waste jumped from 44.4 Mt in 2016 to 53.6 Mt in 2019,[10] and reached 62 Mt in 2022[11]. The

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[3] **The Growing Environmental Risks of E-Waste**, Geneva Environment Network (Oct. 9, 2024), https://www.genevaenvironmentnetwork.org/resources/updates/the-growing-environmental-risks-of-e-waste/.

[4] **A.A. Fawole et al.,** *Climate Change Implications of Electronic Waste: Strategies for Sustainable Management*, 47 **Bull. Nat'l Res. Ctr.** 147 (2023), https://doi.org/10.1186/s42269-023-01124-8.

[5] **Global e-Waste Monitor 2024: Electronic Waste Rising Five Times Faster than Documented E-waste Recycling**, UNITAR (Mar. 20, 2024), https://unitar.org/about/news-stories/press/global-e-waste-monitor-2024-electronic-waste-rising-five-times-faster-documented-e-waste-recycling.

[6] Ibid

[7] **Electrical and Electronic Waste Recycling**, Council on Energy, Environment and Water (Apr. 2024), https://www.ceew.in/electrical-and-electronic-waste-recycling.

[8] **Meenakshi Sushma**, *The Rising Tide of E-Waste*, CAG (Sept. 25, 2024), https://www.cag.org.in/blogs/rising-tide-e-waste.

[9] Ibid

[10] Ibid

accelerating pace is driven by consumer demand for the latest technologies (smartphones, tablets, IoT devices) and by limited repair or upgrade options. Regions such as East Asia, Europe, and North America were early adopters of consumer electronics and thus generated large e-waste volumes. Today, however, developing economies are seeing rapid growth: rising incomes and digitalization have made devices ubiquitous even in rural areas.

Notably, much of e-waste currently remains undocumented. The UN's 2024 monitor highlights that globally only about 22–23% of e-waste is formally collected and recycled.[12] The vast majority is either landfilled, stored at homes, exported, or processed by informal recyclers. This gap means enormous potential for both resource recovery and pollution. The historical trajectory thus shows an emerging waste crisis following decades of innovation – a pattern captured by the paper's title: the "impact" of electronic "innovation" is the generation of e-waste and its environmental fallout.

## III. Global trends and policy responses

The global e-waste challenge has attracted growing policy attention. Internationally, most countries have adopted some form of E-Waste legislation. For example, the European Union's Waste Electrical and Electronic Equipment (WEEE) Directive (first enacted in 2002 and recast in 2012) was a landmark in requiring manufacturers to finance take-back and recycling. Similarly, China's e-waste regulations (2009, updated in 2015) and various state-level laws in the United States incorporate extended producer responsibility (EPR) principles. These frameworks typically obligate producers of electronic goods to meet collection and recycling targets or to fund third-party recycling organizations.

A common policy tool is EPR: under EPR, producers (manufacturers, importers, brand-owners) bear responsibility for the end-of-life management of their products. This internalizes the cost of disposal and incentivizes eco-design. In India, for example, EPR requirements were introduced in 2016 and progressively strengthened. Producers are defined broadly (including assemblers and importers) and must register with regulatory agencies, submit annual returns, and meet phased collection targets.[13] Globally, the stringency of EPR targets varies, but the trend is toward higher collection rates and more transparency.[14]

Recent analyses report mixed performance: while many jurisdictions have seen improved e-

[11] Ibid
[12] Ibid
[13] **Parliament Question: Management of Growing E-Waste in the Country**, Press Information Bureau (Feb. 13, 2025), https://www.pib.gov.in/PressReleasePage.aspx?PRID=2102701.
[14] **Ishaan Chopra**, *Navigating India's E-Waste Regulation*, BTG Advaya (Oct. 24, 2024), https://www.lexology.com/library/detail.aspx?g=e85300c9-e1fb-4745-b007-b94eefa97005.

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waste collection, the growth of devices outpaces recycling efforts. The 2024 UN monitor stresses that "e-waste is rising five times faster than documented recycling".[15] This underscores the need for stronger enforcement, infrastructure, and public awareness. Some innovative policy mechanisms are emerging: for instance, India's Green Credit Rules (notified in 2023) create tradeable credits to incentivize collection and eco-design, complementing EPR targets.[16]In sum, the global policy landscape is evolving, but significant gaps remain between targets and actual recycling outcomes.

## IV. E-WASTE IN INDIA: GROWTH AND GOVERNANCE

India exemplifies the e-waste dilemma: a rapidly growing economy with burgeoning electronics consumption, yet a largely informal recycling system. Government data presented to Parliament indicate that India's e-waste generation climbed from about **1.01 million tonnes** in 2019–20 to **1.751 million tonnes** in 2023–24 – a 73% increase over five years.[17] This explosive growth is driven by factors such as rising smartphone penetration, computer use, and new categories like solar panels and medical devices. Notably, India's per capita e-waste is still below global averages (reflecting lower per capita consumption), but the large population makes it the **world's third largest e-waste generator** after China and the US. The country ranks second in Asia behind China.[18]

Despite higher volumes, India has struggled to expand formal recycling. Official estimates suggest that only about one-third of generated e-waste is collected by authorised entities.[19] The remaining two-thirds bypass official channels. A recent Council on Energy, Environment and Water (CEEW) study found that only 0.5 Mt out of 1.6 Mt generated in 2021–22 was recycled through formal channels.[20] Informal recycling (depicted below) absorbs the rest. The low recycling rate is alarming from both resource and environmental standpoints: e-waste contains precious metals (gold, silver, palladium, etc.) that could be recovered, but these often go to waste in informal processes.

In response, Indian policymakers have tightened regulations. The E-Waste (Management) Amendment Rules, 2022 (effective April 2023) broadened the scope of regulated products to over 130 categories (beyond IT and telecom equipment, now including solar panels, toys,

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[15] Ibid

[16] **Green credits, incentives to boost EPR regime: E-waste industry**, *Economic Times Telecom* (Feb. 24, 2025), https://telecom.economictimes.indiatimes.com/news/devices/green-credits-incentives-to-boost-epr-regime-e-waste-industry/118410809.

[17] **Kiran Pandey**, *India's E-Waste Surges by 73% in 5 Years*, **Down To Earth** (Dec. 17, 2024), https://www.downtoearth.org.in/waste/indias-e-waste-surges-by-73-in-5-years.

[18] Ibid

[19] Ibid

[20] ibid

etc.).[21] Key provisions include mandatory registration of producers, phased collection targets (e.g. 20% of sales-weight by 2024–25),[22] and requirements to channel e-waste to certified recyclers. Critically, the 2022 Rules explicitly seek to "facilitate and channelize" the informal sector into formal recycling streams.[23] The Central Pollution Control Board (CPCB) has developed an online portal for EPR registration and issued guidelines for environmentally sound recycling.[24] State governments are also directed to provide land or sheds for e-waste parks under Rule 10(1).[25] These steps indicate a policy shift: recognizing the informal sector's role, authorities now aim to integrate it through training, licensing, and partnerships with Producer Responsibility Organizations (PROs).

Nonetheless, implementation challenges remain. Compliance is uneven, and many producers still miss targets. Penalties for non-compliance and "environmental compensation" measures have been introduced, but enforcement capacity is limited. Regular drives by pollution control boards are targeting informal dismantling yards, but the very livelihoods of workers are at stake. Observers note that formalizing the e-waste sector is crucial: as a government report emphasizes, India's e-waste processing is "mostly handled by the informal sector," so organizing this segment is vital for regulation to succeed.[26] In summary, India's regulatory framework is improving rapidly, but its efficacy depends on bridging formal and informal systems while expanding recycling infrastructure.

## V. THE INFORMAL RECYCLING SECTOR AND ENVIRONMENTAL HAZARDS

In India (as in many developing countries), the informal sector dominates e-waste recycling. It is estimated that around **90%** of India's e-waste is currently processed informally.[27] This involves thousands of small-scale actors, including waste pickers, scrap dealers, and home-based dismantlers. Their activities often occur in unregulated workshops or open dumps, using manual or rudimentary methods. For example, workers may break apart circuit boards by hand, burn insulated wires to recover copper, or soak boards in acid baths to leach gold and palladium.[28] These practices are economically driven (recovering a few rupees worth of metal per device), but they have severe health and environmental consequences.

[21] **Ishaan Chopra**, *Navigating India's E-Waste Regulation*, BTG Advaya (Oct. 24, 2024), https://www.lexology.com/library/detail.aspx?g=e85300c9-e1fb-4745-b007-b94eefa97005.
[22] ibid
[23] **Parliament Question: Management of Growing E-Waste in the Country**, Press Information Bureau (Feb. 13, 2025), https://www.pib.gov.in/PressReleasePage.aspx?PRID=2102701.
[24] Ibid
[25] ibid
[26] Ibid
[27] Ibid
[28] Ibid

Open-air burning and acid extraction release a cocktail of toxic pollutants – lead, mercury, cadmium, arsenic, brominated flame retardants, and dioxins – into the air, soil, and water.[29] Breathing the smoke and fumes leads to neurological damage, respiratory problems, and cancers among workers and nearby residents. Studies have documented elevated heavy metal concentrations in soil and air at informal e-waste sites. Children are especially vulnerable: toxic exposure can impair IQ and development. Beyond toxins, the informal methods generate greenhouse gases: for instance, burning PVC cable insulation emits hydrochloric acid and carbon-rich soot that contribute to climate warming (black carbon is a potent climate forcer). Although quantitative data on GHG from informal e-waste treatment are scarce, the link between e-waste mishandling and climate change is conceptually clear: any carbon released further exacerbates anthropogenic emissions.

Socioeconomically, the informal sector provides livelihoods to a large marginalized population, many of whom lack education or alternatives. The sector's existence reflects market demand for recycling and a gap in formal jobs.[30] Recognizing this, Indian policy has begun to engage informal workers: for example, some state governments facilitate training or cooperative models for waste pickers. At the national level, the 2022 Rules' provision to "channelize" informals essentially acknowledges that they cannot be simply banned without harming livelihoods.[31] Still, integrating this sector into safer, formal supply chains remains a major challenge. It requires building trust, ensuring fair compensation for collected e-waste, and providing accessible formal recycling outlets. Technological solutions (like small-scale modular recycling units) and corporate take-back initiatives may help transition informal workers into formal employment.

## VI. E-WASTE AND CLIMATE CHANGE FOOTPRINT

Although often viewed primarily as a toxic waste issue, e-waste is also relevant to climate change. The carbon footprint of electronics is substantial, most of it occurring upstream during production. As one analysis notes, manufacturing one tonne of laptops can emit on the order of **10 tonnes of $CO_2$**, largely due to energy-intensive processes (semiconductor fabrication, metal smelting, etc.). More broadly, every electronic device ever made contributes to global greenhouse gas (GHG) inventories via its lifecycle (materials extraction, manufacturing, transport, use, and disposal). Extending the life of devices, promoting reuse, and using recycled materials can therefore yield significant climate benefits. For example,

[29] ibid
[30] ibid
[31] ibid

every kilogram of recycled electronics offset in production of new materials saves energy and emissions compared to virgin mining.

Empirical studies underscore the growing climate impact of e-waste. A recent analysis estimated that GHG emissions associated with e-waste increased by **53% between 2014 and 2020**.[32] The study projected that, without intervention, e-waste sources could emit roughly **852 million metric tons** of $CO_2$ equivalent annually by 2030.[33] This surge results from both more devices being discarded and continuing heavy reliance on high-carbon manufacturing. The findings highlight that e-waste is not a static issue; as digital consumption rises, its climate footprint grows unless mitigated.

Disposal-phase processes can also emit potent GHGs. For instance, combustion of polyurethane foam (from TVs or speakers) and incineration of plastics produce carbon dioxide and black carbon. Additionally, unintended releases from waste sites (landfills) can include methane (if organic components are present) and other halogenated gases (from broken refrigerant-containing units or flame retardants). Informal recycling methods contribute as well: the open burning of cables is a source of $CO_2$, soot, and various toxics. While the exact contribution of e-waste to global warming is harder to quantify than industrial emissions, it is conceptually linked to both greenhouse gases and short-lived climate pollutants.

Crucially, the link to climate change underlines the need for circular economy strategies. If manufacturers design products for disassembly and use recycled inputs, the production emissions fall. Likewise, policies that lengthen product use (through repair incentives, take-back programs, or software support) keep devices in service longer, amortizing the embedded carbon over more years. International initiatives reflect this: for example, the UN's e-waste and climate coalition advocates lifecycle approaches to ensure electronics are produced and managed in ways consistent with Paris Agreement targets. In sum, mitigating climate impacts of e-waste calls for reducing total material throughput – via reuse, recycling, and sharing economy models – thereby "dematerializing" the digital economy's footprint.

## VII. CONCLUSION AND IMPLICATIONS

This review has traced how the innovation-driven growth of electronics has led to an e-waste crisis with far-reaching environmental and climate consequences. Key insights emerge: (1)

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[32] **Oladele Ogunseitan**, *UCI Study Finds 53 Percent Jump in E-Waste Greenhouse Gas Emissions Between 2014, 2020*, **UC Irvine News** (Oct. 26, 2022), https://news.uci.edu/2022/10/26/uci-study-finds-53-percent-jump-in-e-waste-greenhouse-gas-emissions-between-2014-2020/.

[33] ibid

 

**Unchecked Growth:** E-waste volumes are rising rapidly worldwide, outpacing the expansion of recycling systems. India's data exemplify this trend, with a 73% jump in five years. (2) **Policy Response:** Governments are ramping up regulations. In India, successive rule amendments have made the EPR regime more comprehensive and have begun to address the informal sector. Globally, too, there is a shift toward circular economy thinking in electronics policy. (3) **Informal Sector Challenge:** In developing economies like India, the vast informal recycling network poses a management dilemma: it enables a degree of reuse but often under hazardous conditions. Formalizing and modernizing this sector is essential. (4) **Climate Link:** The lifecycle climate footprint of electronics is substantial, and improper waste handling only adds to emissions. Policies that extend device lifetimes, improve recycling rates, and harness secondary materials can yield dual environmental benefits: reducing GHG emissions and pollution.

For policymakers and stakeholders, the implications are clear. Achieving sustainable e-waste management requires a multifaceted approach. Effective EPR implementation should be coupled with investment in formal recycling infrastructure and worker training. Public awareness and consumer incentives (e.g. take-back deposits) can raise collection rates. Technological innovation – from advanced recycling technologies to eco-design – is needed to make recycling economically viable for complex devices. Crucially, recognizing e-waste management as part of climate strategy can mobilize additional resources: for instance, carbon finance mechanisms or circular economy funds could support recycling projects.

The legacy of electronic innovation must include responsible end-of-life strategies. Only by fully integrating e-waste management into environmental and climate agendas can society turn the digital revolution into a truly sustainable one.

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