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Life Cycle Assessment of Institutional E-Waste: A Multi-Year Carbon Emission Analysis and Environmental Impact Evaluation at an Engineering Institution in Karnataka, India

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ABSTRACT: The rapidly accelerating pace of technological adoption within higher educational institutions has generated significant volumes of electronic waste (e-waste), posing substantial environmental, human health, and policy challenges. This study presents a comprehensive Life Cycle Assessment (LCA) of institutional e-waste generated over five academic years: 2018-19, 2019-20, 2021-22, 2024-25, and 2025-26 at an Engineering Institution, Mysuru, Karnataka, India. The assessment quantifies the carbon implications of two end-of-life disposal pathways: controlled recycling and landfill disposal, using category-specific greenhouse gas (GHG) emission factors derived from established WEEE benchmarks.

Over the study period, a cumulative mass of 11,870.5 kg of e-waste was generated and processed. Recycling-based disposal yielded net carbon savings of 8,374 kgCO_2e, while the landfill counterfactual scenario would have resulted in emissions of 109.2 kgCO_2e, yielding an overall net avoided emission of approximately 8,265 kgCO_2e. The peak carbon savings year was 2021-22 (2,843 kgCO_2e), driven by high-emission-factor electrical laboratory equipment. A critical methodological finding is the evolution of the landfill emission factor from 0.004 to 0.04 kgCO_2e/kg in 2025-26, reflecting improved accounting of leachate toxicity and decomposition-related emissions. The study also identifies a compositional shift in waste streams from IT hardware to infrastructure-level electrical components over the study period. To the best of the authors' knowledge, this study represents the first comprehensive multi-year Life Cycle Assessment of institutional e-waste conducted at an engineering college in India. By analysing five academic years of primary institutional inventory data using category-specific emission factors, the study establishes a reproducible framework for campus-level carbon accounting and environmentally sustainable e-waste management. Findings establish a data-driven baseline for institutional e-waste carbon accounting and offer transferable recommendations for engineering institutions across India and similar developing economies.

1. INTRODUCTION

The twenty-first century has witnessed an unprecedented proliferation of electronic and electrical equipment (EEE) across all sectors of society, with the educational sector being no exception. Engineering and technology institutions, by the very nature of their instructional mandate, operate large inventories of laboratory instruments, computing infrastructure, networking equipment, power electronics, and ancillary electrical components. As these devices reach the end of their functional lives, typically within three to seven years for IT equipment and five to fifteen years for electrical infrastructure, they enter the e-waste stream, creating a complex environmental management challenge.

E-waste, formally regulated under the Waste Electrical and Electronic Equipment (WEEE) directive, has emerged as one of the most rapidly expanding categories of solid waste worldwide, outpacing conventional municipal waste streams in both volume and compositional complexity (Forti et al., 2020). The Global E-Waste Monitor 2024 reports that approximately 62 million metric tonnes of e-waste entered the waste stream globally in 2023, with India ranked among the top three national generators at an estimated 3.2 million metric tonnes per year. Engineering and technology institutions are disproportionate contributors to this stream, owing to their rapid equipment turnover cycles and reliance on specialised laboratory-grade instrumentation that rarely attracts viable secondary markets.

The consequences of inadequate e-waste management have been extensively documented in the peer-reviewed literature. When disposed of in uncontrolled landfills, device components such as circuit boards, cathode ray tubes, and rechargeable batteries release toxic metal compounds, including those of lead, cadmium, mercury, and arsenic, into surrounding soil and water bodies, posing chronic contamination risks. Thermal treatment of e-waste without appropriate controls generates polycyclic aromatic hydrocarbons (PAHs) and dioxins. Even informal dismantling, widespread in unregulated contexts, subjects workers to hazardous exposures through acid-leaching and open-air burning of components. Among available disposal options, controlled mechanical recycling represents the most environmentally sound approach: it prevents the releases described above and simultaneously offsets the energy and emission costs of extracting virgin copper, aluminium, steel, and rare earth materials — effectively generating a carbon credit through material substitution.

Life Cycle Assessment provides the methodological framework for quantifying these environmental trade-offs. Specifically, end-of-life LCA also known as disposal-stage LCA evaluates the environmental burden or benefit associated with different waste treatment pathways. When applied to e-waste, LCA can quantify the avoided greenhouse gas emissions from recycling relative to landfill or incineration, providing institutions with science-based carbon accounting data that can inform sustainability reporting, procurement decisions, and regulatory compliance.

Despite the significance of institutional e-waste in India, peer-reviewed literature on campus-level LCA studies remains sparse. Most published studies focus on national or regional e-waste flows, specific product categories (such as mobile phones or personal computers), or informal recycling sectors in developing countries. Longitudinal, institution-specific assessments that track compositional shifts in waste streams over multiple years, apply tiered emission factors by WEEE category, and evaluate the impact of methodological updates to emission factors are particularly scarce.

This paper addresses that gap. It presents a longitudinal LCA of institutional e-waste across five academic years, drawing on primary inventory data collected and verified at the institutional level. The study's contributions are threefold: (1) it establishes a reproducible LCA methodology suitable for replication at similar institutions, (2) it provides empirical evidence of the carbon benefits of formal e-waste recycling over a multi-year horizon, and (3) it identifies compositional and methodological trends that have practical implications for sustainability management.

To the best of the authors' knowledge, this research is the first comprehensive multi-year Life Cycle Assessment (LCA) of institutional e-waste conducted at an engineering college in India. While previous studies have largely focused on national e-waste inventories, individual electronic products, or short-term institutional assessments, the present study analyses five academic years of primary institutional inventory data using category-specific WEEE emission factors. This longitudinal approach provides a robust framework for quantifying carbon savings from formal recycling and demonstrates how Life Cycle Assessment can support institutional sustainability planning, carbon accounting, and evidence-based decision-making in higher educational institutions.

2. LITERATURE REVIEW

2.1 Global and National E-Waste Trends

The growing volume of global e-waste has been tracked systematically across successive editions of the Global E-Waste Monitor (Forti et al., 2020; van der Voet et al., 2019). The most recent 2024 edition indicates that formal collection and recycling covered approximately 22.3% of worldwide e-waste output, leaving the considerable remainder unaccounted for, diverted to landfill, or processed through informal channels (Forti et al., 2024). This treatment gap carries a dual consequence: an environmental burden from uncontrolled disposal, and a substantial economic loss, the aggregate recoverable value of metals in unprocessed e-waste has been estimated at over USD 91 billion per year (Forti et al., 2024).

India, as a rapidly industrialising economy characterised by growing consumer electronics penetration, confronts mounting e-waste management challenges. The country has progressively strengthened its regulatory posture through successive revisions of its national e-waste rules, initially framed in 2011, updated in 2016, and substantially overhauled in 2022, each iteration broadening the scope of Extended Producer Responsibility (EPR) to hold equipment manufacturers, importers, and brand licensees accountable for end-of-life product management (MoEFCC, 2022). Despite this evolving framework, implementation deficits persist, particularly among institutional generators such as universities, hospitals, and government bodies, which face distinct disposal obligations but frequently lack the operational capacity to fulfil them.

Kumar et al. (2017) estimated that India's e-waste generation would reach 5.2 million metric tonnes by 2020, driven by increasing penetration of computers, mobile devices, and consumer electronics. Actual figures have surpassed these projections, reflecting the accelerated digital adoption catalysed by the COVID-19 pandemic and subsequent hybrid work and education models. Several Indian studies have highlighted the specific role of educational institutions in the e-waste ecosystem: Valai Ganesh et al. (2025), in an institutional e-waste audit at an engineering institution in Tamil Nadu, found that fewer than 10% of identified e-waste had been formally recycled in the preceding year, with the majority either stored indefinitely or discarded through general waste channels, underscoring the gap between regulatory expectations and on-the-ground institutional practice.

2.2 Life Cycle Assessment in E-Waste Management

The ISO 14040 and ISO 14044 standards establish LCA as a structured analytical approach for quantifying the environmental burdens associated with each stage of a product's existence, from material acquisition and manufacturing through operational use and final disposal (ISO, 2006a; 2006b). This framework enables comparative assessment of alternative design choices and management decisions. For e-waste, the most widely adopted analytical scope is end-of-life or gate-to-grave assessment, which isolates the treatment and disposal stage as the primary unit of analysis.

A body of quantitative research has established the GHG advantage of formal e-waste recycling over landfill disposal. A PCB-focused LCA by Zeng et al. (2018) demonstrated that the carbon benefit of pyrometallurgical recycling over landfill varied from 3.2 to 7.8 $kgCO_2e$ per kilogram of board material, a wide range attributable to differences in precious metal composition and process efficiency, underscoring the importance of category-specific material characterisation in carbon accounting. Cucchiella et al. (2015) reached complementary conclusions at the system level, showing that European WEEE recycling operations yield net GHG credits across product categories, with the most substantial savings in IT and telecommunications equipment, a finding consistent with the high copper and gold densities in these product groups.

The emission factors used in this study, negative values representing avoided emissions for recycling and positive values for landfill, are consistent with the methodology adopted in the UK's carbon reporting frameworks and used in decision-support tools such as the WRAP Waste and Resources Action Programme carbon metrics. The use of category-specific emission factors (distinguishing IT and telecoms, consumer electronics, small household appliances, and general electricals) reflects the heterogeneous composition of institutional e-waste and improves the accuracy of carbon accounting compared to single-factor approaches.

2.3 Institutional E-Waste Studies in India

Peer-reviewed institutional e-waste studies from Indian engineering colleges are limited. Sinha-Khetriwal et al. (2005) conducted an early assessment of e-waste management practices at Indian IT firms and educational institutions, identifying systemic weaknesses in collection infrastructure, staff awareness, and regulatory knowledge. More recently, Jena and Goel (2015) surveyed e-waste generation and disposal behaviour at IIT Kharagpur across three product categories including computers, printers, and mobile phones, reporting generation rates of 0.18 units per capita per year for computers and 0.46 units per capita per year for mobile phones, with computers typically replaced after 4.8 to 6.5 years of service and mobile phones after 1.6 to 3 years, findings broadly consistent with the equipment turnover patterns observed in the present study.

The closest methodological precedent to the present study is the work of Jaglan et al. (2022), who conducted an environmental life cycle assessment of the municipal solid waste management system at the residential university campus of IIT Kharagpur, comparing the existing disposal baseline against source-segregation scenarios. Their baseline scenario carried the highest global warming potential (1,388 $kgCO_2e$), which fell by 50.9% under a 50%-sorting scenario and by 86.5% under a 90%-sorting scenario. However, their study addressed aggregate municipal solid waste rather than e-waste specifically, applying scenario-level rather than category-specific emission factors. The present study extends this institutional LCA approach to the e-waste stream specifically, applying disaggregated, WEEE category-specific emission factors and extending the analysis over a five-year horizon.

The review of existing literature indicates that although several studies have investigated e-waste generation and recycling, comprehensive longitudinal Life Cycle Assessment studies at the institutional level remain extremely limited in India. To the best of the authors' knowledge, no previous study has reported a five-year LCA of institutional e-waste generated by an engineering college using primary inventory data and category-specific emission factors. This research addresses this gap by presenting a comprehensive multi-year assessment that can serve as a reference model for engineering institutions across the country.

3. METHODOLOGY

3.1 Goal and Scope Definition

The goal of this LCA is to quantify the greenhouse gas implications of institutional e-waste disposal at an Engineering Institution, Mysuru, Karnataka, India, across five academic years: 2018-19, 2019-20, 2021-22, 2024-25, and 2025-26. These years correspond to active e-waste collection and disposal cycles; the intervening period of 2020-21 falls within the COVID-19 campus closure window, during which normal disposal operations were appropriately suspended.

The functional unit is defined as one kilogram of e-waste generated and disposed of by the institution via the assessed end-of-life pathway. Two scenarios are evaluated for each year:

- Scenario A — Recycling: All e-waste is directed to a formally registered e-waste recycler, achieving material recovery and generating avoided GHG emissions relative to primary production baselines.
- Scenario B — Landfill: All e-waste is disposed of in a municipal solid waste landfill, generating GHG emissions from decomposition, leachate, and associated transport.

This study adopts a gate-to-grave system boundary, commencing at the point of institutional e-waste collection and concluding at the point of final treatment and disposal. Production-phase impacts (cradle-to-gate) are intentionally excluded: the analytical focus is the environmental consequence of the disposal decision, a choice over which the institution exercises direct operational authority and which is actionable through existing procurement and management practices. Transport-related GHG emissions are not disaggregated as a separate line item but are considered embedded within the end-of-life emission factors applied.

3.2 Data Collection and Inventory

Primary inventory data was collected through the institution's e-waste management committee over the respective academic years. For each item, the following data fields were recorded:

- Item description and specification/model number
- Quantity (number of units)
- Unit weight (kg) — verified against manufacturer specifications or reference databases
- Total weight (kg) = quantity × unit weight
- WEEE category classification
- Condition assessment (working/not working/empty/defective)
- Year of original purchase (where available)

Weight data was sourced primarily from manufacturer product specification sheets, institutional asset registers, and validated reference databases including the Western Australia Department of Water and Environmental Regulation e-waste weight estimation guide, HP product specification databases, and independent laboratory measurements for items where reference data was unavailable. In a small number of cases (particularly for obsolete equipment manufactured before 2000), weights were estimated using an AI-assisted reference tool (denoted 'Ref: Co-pilot' in the raw data); all such AI-derived values were manually cross-validated against comparable equipment specifications from published manufacturer catalogues or technical standards. In accordance with emerging journal policies on AI-assisted research, this use is disclosed explicitly: the AI tool was employed solely as a reference aid for weight estimation and played no role in data analysis, interpretation, or manuscript drafting.

3.3 WEEE Category Classification

Each item was classified into one of five WEEE categories, each associated with a specific pair of emission factors for the recycling and landfill scenarios:

WEEE Category	Recycling EF ($kgCO_2e/kg$)	Landfill EF ($kgCO_2e/kg$)*	Primary Items
Electricals — all	−0.978	0.004 / 0.04*	CROs, ICs, resistors, lab modules, transformers
WEEE — IT & Telecoms	−0.450	0.004 / 0.04*	Computers, hard disks, keyboards, mice, switches, routers
WEEE — Consumer	−0.855	0.004 / 0.04*	Speakers, projectors, audio equipment
WEEE — Display Screen	−0.450	0.004 / 0.04*	LCD displays, TFT monitors
WEEE — Small Household	−0.366	0.004 / 0.04*	CFL bulbs, LED fittings, bulb holders

*Landfill emission factor: 0.004 $kgCO_2e/kg$ applied for years 2018-19 through 2024-25. An updated factor of 0.04 $kgCO_2e/kg$ was adopted in 2025-26, reflecting revised guidance on leachate-related emissions and improved GHG decomposition modelling.

Figure 5 below presents the recycling emission factors across the five WEEE categories described above, showing that the Electricals, all category yields the greatest carbon-saving benefit per kilogram recycled.

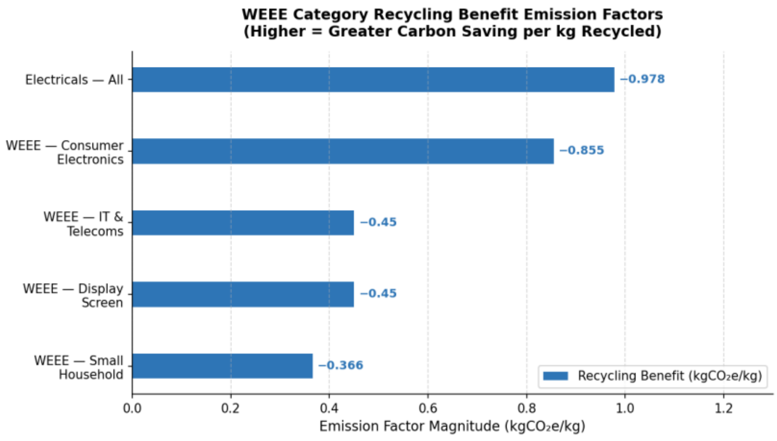

Figure 5: WEEE Category Recycling Benefit Emission Factors ($kgCO_2e/kg$) — Higher Value = Greater Carbon Saving per kg Recycled

3.4 Emission Calculation

For each item i in year y, emissions under each scenario are calculated as follows:

Recycling Emission (item i) = Total $Weight_i$ × Emission Factor (Recycling)k_i^{cery}

Landfill Emission (item i) = Total $Weight_i$ × Emission Factor (Landfill)k_i^{cery}

Negative recycling emission values represent avoided GHG emissions (a benefit), while positive landfill values represent actual GHG emissions (a cost). Annual totals are the sum over all items. Net scenario emission = Recycling Scenario Total + Landfill Scenario Total (noting that in practice the institution follows Scenario A, the recycling pathway, so the reported net figure represents the realised carbon saving).

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I recommend using symbolic notation rather than long text:

$$\boxed{E_{R,i} = W_i \times EF_{R,k}}$$

$$\boxed{E_{L,i} = W_i \times EF_{L,k}}$$

where:

- $E_{R,i}$= Recycling emission ($kgCO_2e$) of item i
- $E_{L,i}$= Landfill emission ($kgCO_2e$) of item i
- W_i= Total weight of item i(kg)
- $EF_{R,k}$= Recycling emission factor for WEEE category k($kgCO_2e$/kg)
- $EF_{L,k}$= Landfill emission factor for WEEE category k($kgCO_2e$/kg)
- i= Individual e-waste item
- k= WEEE category

Negative recycling emission values represent avoided greenhouse gas (GHG) emissions resulting from material recovery and substitution of virgin resources, and therefore indicate an environmental benefit. Positive landfill emission values represent the GHG emissions associated with disposal in landfill and therefore indicate an environmental burden. Annual recycling and landfill emissions were calculated by summing the emissions of all individual e-waste items within each academic year. Since recycling and landfill represent two alternative end-of-life scenarios, the environmental benefit of formal recycling is expressed as the net avoided emissions relative to the landfill scenario. Throughout this study, negative values are retained to represent realised carbon savings achieved through recycling.

4. RESULTS AND DISCUSSION

4.1 Annual E-Waste Generation Summary

Table 2 presents the aggregated annual e-waste data, including total mass processed, recycling-based carbon savings, landfill-scenario emissions, and net avoided emissions for each study year.

Year	Total Weight (kg)	Recycling Savings ($kgCO_2e$)	Landfill Emissions ($kgCO_2e$)	Net Avoided ($kgCO_2e$)	EF_l
2018–19	3,782.5	−2,477.12	15.13	−2,461.99	0.004
2019–20	1,372.5	−1,254.20	5.49	−1,248.71	0.004

2021–22	3,497.5	−2,842.97	13.99	−2,828.98	0.004
2024–25	1,502.5	−894.56	6.01	−888.55	0.004
2025–26	1,715.5	−906.18	68.62	−837.56	0.04
TOTAL	**11,870.5**	**−8,374.03**	**109.24**	**−8,264.79**	**—**

Table 2: Annual e-waste LCA summary. Negative values denote carbon savings (avoided emissions). EF_l = landfill emission factor ($kgCO_2e/kg$).

Figures 1 and 2 below visualise these annual trends: Figure 1 depicts the total e-waste mass generated in each academic year, while Figure 2 compares recycling-based carbon savings against landfill-scenario emissions across the same period.

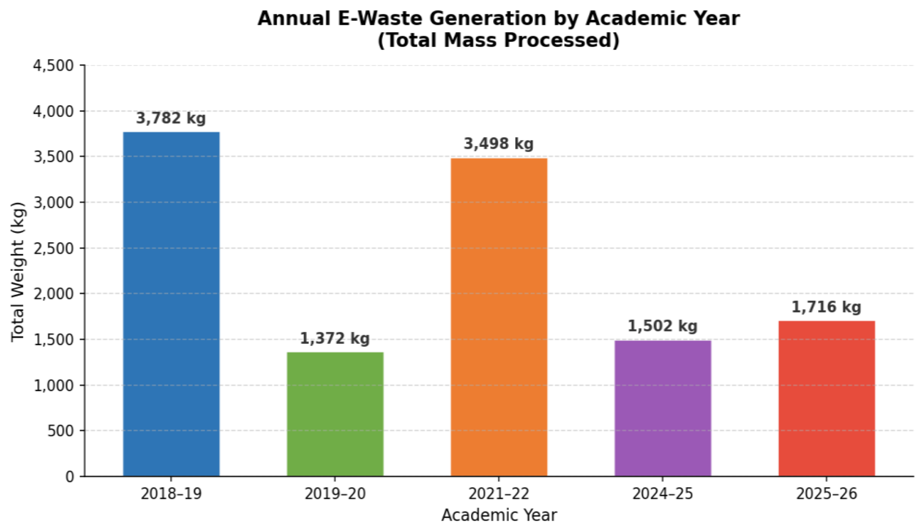

Figure 1: Annual E-Waste Generation by Academic Year (Total Mass Processed, kg)

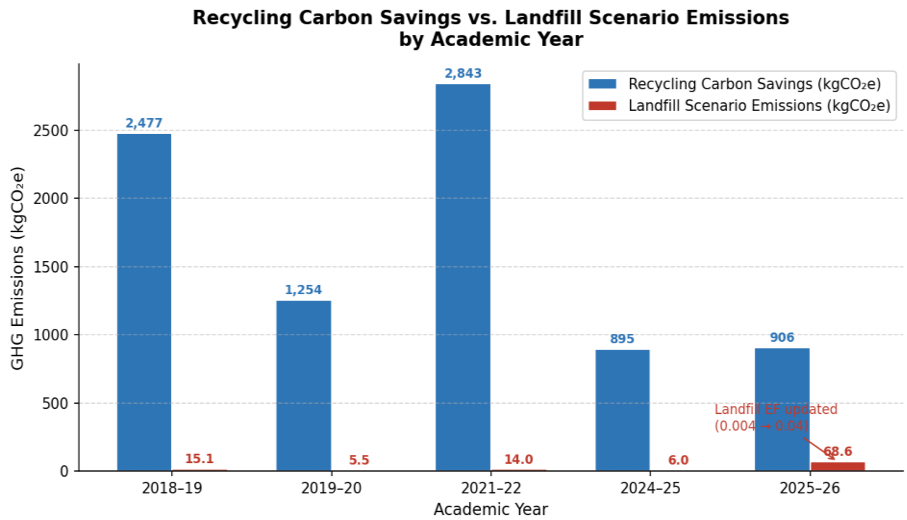

Figure 2: Recycling Carbon Savings vs. Landfill Scenario Emissions by Academic Year ($kgCO_2e$)

Figure 3 below depicts the estimated compositional shift in e-waste categories, by percentage of total weight, across the five study years.

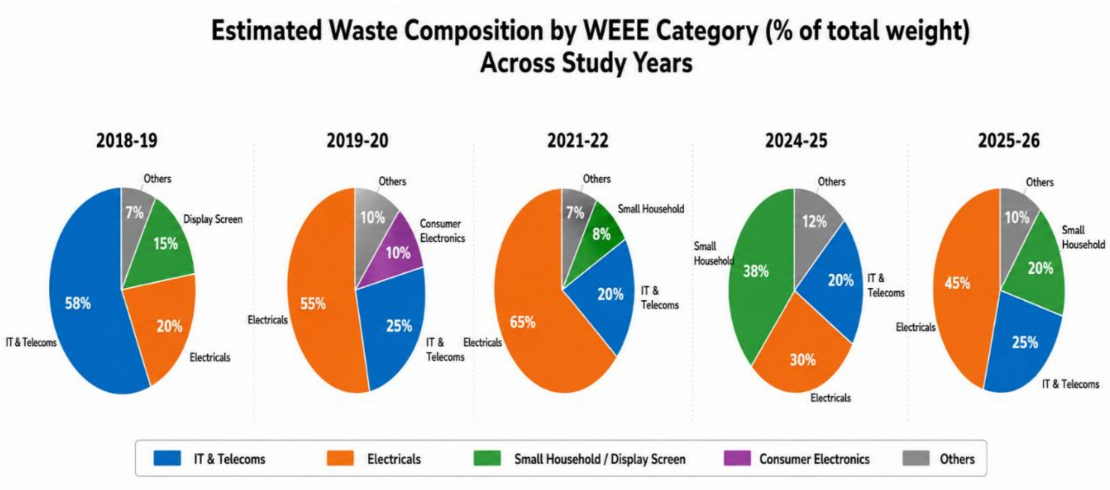

Figure 3: Estimated E-Waste Composition by WEEE Category (% Total Weight) Across Study Years

4.2 Year-by-Year Analysis

4.2.1 Academic Year 2018-19: The Great Hardware Decommissioning

The 2018-19 academic year recorded the second highest e-waste volume (3,782.5 kg) and the second highest carbon saving (2,477.12 kgCO_2e) of any year in the study. This year was characterised overwhelmingly by the mass decommissioning of legacy IT infrastructure that had reached the end of its operational life after approximately 12 to 15 years of service.

The inventory reveals the full scale of the hardware refresh: 44 assembled Intel P-IV desktop systems (weighing approximately 8.77 kg each, totalling 385.9 kg), 28 Acer Power Series Intel P-IV systems (245.6 kg), 17 AMD Acer systems (149.1 kg), 25 TFT monitors (137.5 kg), 56 CRT monitors, the single largest item category by weight at 1,232 kg, given each CRT weighed 22 kg, 92 PS/2 keyboards (36.8 kg), and 91 PS/2 mice (36.4 kg). In total, legacy IT equipment accounted for an estimated 2,200 kg, or 58% of total e-waste weight in this year.

The presence of 56 CRT monitors is particularly significant from an LCA perspective. CRT monitors contain between 1.5 and 3 kg of lead per unit (primarily in the cathode ray tube glass) and are classified as hazardous waste under India's Hazardous Waste Management Rules. Their formal recycling prevents lead contamination of soil and groundwater while recovering glass, copper, and aluminium. The large batch decommissioning in 2018-19 likely reflects a decade or more of accumulated obsolescence, as CRT technology was commercially superseded by LCD panels by the mid-2000s.

The average carbon savings intensity for 2018-19 was 0.655 kgCO_2e per kg of e-waste, lower than the 2021-22 peak reflecting the predominance of IT & Telecoms category equipment (emission factor -0.45 kgCO_2e/kg), which has a lower avoided emission per kilogram than the Electricals - all category (-0.978 kgCO_2e/kg). Nevertheless, the sheer volume of material processed makes this the second most impactful year in absolute carbon terms.

4.2.2 Academic Year 2019-20: Targeted Laboratory Equipment Disposal

The 2019-20 year recorded the lowest total weight (1,372.5 kg) and the lowest absolute carbon saving (1,254.20 kgCO_2e). However, it recorded the highest carbon savings intensity per kilogram (0.914 kgCO_2e/kg) of any year in the study — indicating that the waste processed was disproportionately composed of high-emission-factor items.

The inventory confirms this interpretation. Major items included 630 integrated circuits (ICs, 189 kg total), 406 capacitors (81.2 kg), 238 resistors (71.4 kg), 136 transistors (27.2 kg), 15 iron core transformers (150 kg), 100 lead-acid battery cells (100 kg), 5 DLP projectors (13.5 kg), and 28 computer hard disk drives (16.8 kg). The transformers, ICs, and battery cells are all classified under Electricals - all (EF = -0.978 kgCO_2e/kg), creating a high-intensity recycling benefit despite the smaller total volume.

The 100 Ah lead-acid batteries (four units at 25 kg each) deserve particular attention. Lead-acid batteries contain approximately 60-70% lead by weight and are among the most environmentally hazardous items in institutional e-waste if landfilled. Formal recycling of lead-acid batteries recovers over 95% of the lead content, which is then directly reused in new battery manufacturing — one of the most efficient closed-loop recycling circuits in the waste management sector.

The year 2019-20 also marks the final year before the COVID-19 disruption. Campus activities were curtailed from March 2020, and the institution appropriately suspended e-waste disposal operations for 2020-21 in line with pandemic-related campus closure directives. The longitudinal record resumes with 2021-22, which proved to be the most significant year in the study from a carbon mitigation standpoint.

4.2.3 Academic Year 2021-22: Peak Carbon Savings

The academic year 2021-22 is the most significant in the study from a carbon mitigation perspective, recording the highest recycling-based carbon saving of any year: 2,842.97 kgCO_2e, from a total e-waste mass of 3,497.5 kg. The average savings intensity of 0.813 kgCO_2e/kg confirms that this year's waste stream was dominated by high-EF Electricals - all category items.

Inspection of the item inventory reveals the scale and nature of the disposal: 2,000 registers (600 kg), 600 kg total of registers alone accounts for the largest single item weight contribution in any year of the study. Additionally, the year saw disposal of large quantities of laboratory power electronics parallel/series inverter modules, SCR turn-off circuit kits, auxiliary commutation chopper modules, TK Base FPGA/CPLD development kits, function generators, CROs (oscilloscopes), and induction motor test kits. These specialist laboratory apparatus items, used in power electronics and electrical machines laboratories, were reaching the end of their fifteen-year design lives and were being replaced by modern digital equivalents.

The disposal of 58 nine-volt battery cells (29 kg), 2,000 resistors (600 kg), 225 ICs (1.125 kg), 70 transistors (14 kg), and 75 wattage resistors (37.5 kg) alongside heavy laboratory instruments underscores the dual nature of institutional e-waste: it encompasses both high-mass capital equipment and high-volume small consumable components, each requiring specific collection and recycling logistics.

The carbon saving of 2,843 kgCO_2e in this single year is approximately equivalent to the CO_2 absorbed annually by 130 mature trees, or the GHG footprint of approximately 12,000 km of personal automobile travel. This comparison contextualises the institutional contribution to climate mitigation through responsible e-waste management.

4.2.4 Academic Year 2024-25: Transition to Infrastructure Waste

By 2024–25, a marked shift in the institution's e-waste profile was observed. Total weight was 1,502.5 kg and carbon savings were 894.56 kgCO_2e, the lowest absolute saving of any post-pandemic year. Crucially, the composition of waste had changed substantially: IT equipment (hard disks, RAM sticks, DVD drives, mice) was present in small quantities, but the dominant categories were now electrical infrastructure components, 33 six-ampere sockets (16.5 kg), 51 switches (15.3 kg), 80 tube lights (4.2 kg), 31 CFL bulbs (2.48 kg), 54 LED fittings (4.32 kg), 17 tube light chokes (6.8 kg), 28 fan regulators (2.8 kg), and ceiling fans.

This compositional shift reflects the conclusion of the institution's large IT hardware refresh cycle and the onset of a new phase characterised by routine replacement of building electrical infrastructure. Fan regulators, switches, MCBs, and lighting fixtures have typical service lives of 8 to 15 years, and their concurrent decommissioning in 2024-25 suggests that a significant portion of the campus's electrical infrastructure was installed in the late 2000s or early 2010s.

The WEEE - Small Household classification assigned to LED and CFL bulbs carries the lowest emission factor (-0.366 kgCO_2e/kg) of any category in the study, reflecting the simpler material composition of lighting waste relative to computing equipment. The shift toward these lower-EF items explains the declining carbon savings intensity observed in this year.

4.2.5 Academic Year 2025-26: Methodological Evolution and Continued Infrastructure Waste

The 2025-26 dataset is the most recent and methodologically distinct in the study. While the absolute weight (1,715.5 kg) and recycling-based carbon savings (906.18 kgCO_2e) are broadly comparable to 2024-25, the year introduces a critical methodological change: the landfill emission factor has been updated from 0.004 to 0.04 kgCO_2e/kg, representing a tenfold increase in the assessed environmental cost of landfill disposal.

As a consequence, the landfill scenario emission for 2025-26 is 68.62 kgCO_2e, more than four times the landfill emissions of any previous year in the study, even though the total mass disposed of is not substantially different. This highlights a key principle of LCA methodology: the assessed environmental impact of a disposal pathway is sensitive to the emission factor assumptions embedded in the analysis. The updated factor reflects improved scientific understanding of leachate generation rates, the GHG contribution of organic matter co-deposited with e-waste in mixed landfills, and revised guidance on decomposition-related methane emissions from battery components.

The inventory for 2025-26 shows continuation of the infrastructure waste trend from 2024-25, with high volumes of electronic laboratory components: 815 ICs (4.075 kg), 560 capacitors (2.8 kg), 370 transistors (1.85 kg), 320 resistors (1.6 kg), 65 batteries (3.25 kg), 36 breadboards (10.8 kg), and 50 CRO probes (5 kg). These items suggest that the institution's electronics laboratory component inventory, accumulated over years of student practical sessions, has also reached disposal thresholds. The presence of 11 hard disks (11 kg) and 19 RAM modules suggests ongoing, smaller-scale IT equipment retirement.

Notably, 2025-26 is the first year to include mobile phones (three units, 0.27 kg total) in the institutional e-waste inventory, reflecting the broadening definition of institutional electronic assets to include staff-issued communication devices. Mobile phones are among the highest-value e-waste items per unit weight due to their gold, cobalt, and lithium content, and their formal recycling is particularly critical.

5. COMPARATIVE ANALYSIS AND KEY FINDINGS

5.1 Carbon Savings Intensity Trend

The carbon savings intensity defined as the recycling-based GHG saving per kilogram of e-waste processed, reveals important trends about the changing composition of institutional e-waste over the study period. Figure 4 below illustrates this trend.

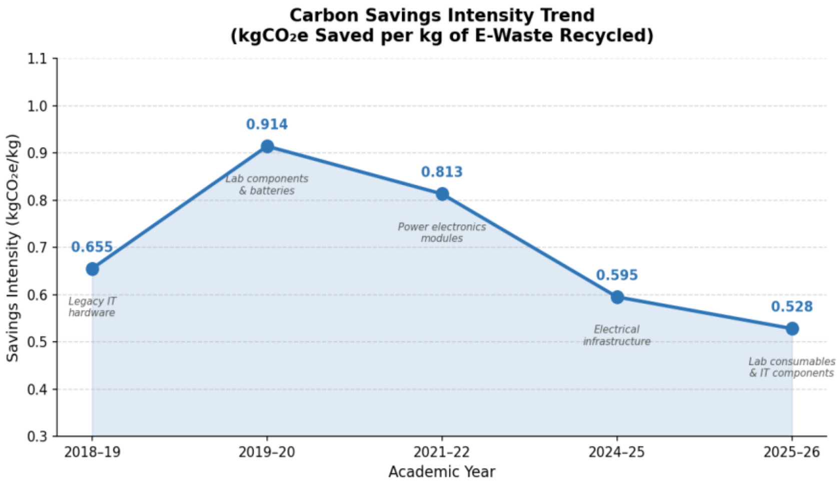

Figure 4: Carbon Savings Intensity Trend — kgCO_2e Saved per kg of E-Waste Recycled (2018–2026)

Table 3 below summarises the annual carbon savings intensity alongside the dominant waste type for each study year.

Year	Weight (kg)	Savings Intensity (kgCO_2e/kg)	Dominant Waste Type
2018–19	3,782.5	0.655	Legacy IT hardware (CRT monitors, PCs)
2019–20	1,372.5	0.914	Lab components, ICs, batteries, transformers

2021–22	3,497.5	0.813	Power electronics modules, registers, CROs
2024–25	1,502.5	0.595	Electrical infrastructure, LED/CFL lights
2025–26	1,715.5	0.528	Lab consumables, IT components, infrastructure

Table 3: Carbon savings intensity by year and dominant waste type.

The declining trend in savings intensity (from 0.914 in 2019-20 to 0.528 in 2025-26) does not indicate deteriorating environmental performance. Rather, it reflects a compositional shift from high-emission-factor items (general electricals at -0.978 $kgCO_2e/kg$) toward lower-factor items (IT & Telecoms at -0.45 $kgCO_2e/kg$ and Small Household at -0.366 $kgCO_2e/kg$). The institution continues to recycle 100% of identified e-waste, maintaining its commitment to responsible disposal irrespective of the economic or logistical burden.

5.2 Cumulative Environmental Impact

Across the five study years, the cumulative carbon saving achieved through formal recycling amounts to 8,374.03 $kgCO_2e$. If the same volume of e-waste had been landfilled, even using the more conservative pre-2025-26 landfill emission factor of 0.004 $kgCO_2e/kg$, the net GHG cost would have been 47.27 $kgCO_2e$ (using 0.004 EF for all years) rather than a saving of 8,374 $kgCO_2e$. The difference of 8,421 $kgCO_2e$ represents the total marginal benefit of the recycling pathway over landfill across the study period.

To contextualise: 8,265 $kgCO_2e$ of net avoided emissions is equivalent to:

- The annual GHG footprint of approximately 3.5 average Indian citizens (estimated at 2.4 tCO_2e per capita per year, World Bank 2022 data)
- Approximately 34,437 km of personal automobile travel in a fuel-efficient passenger car (240 gCO_2e/km)
- The CO_2 sequestration capacity of approximately 380 mature trees over a single year
- Approximately 8.3 MWh of coal-fired electricity generation (approximately 0.99 $kgCO_2e/kWh$, India grid emission factor 2023)

While these savings appear modest in the context of global emissions, they represent a meaningful contribution from a single campus-level institution and, when aggregated across India's estimated 10,000+ engineering colleges and technical institutions, suggest a sector-wide recycling potential in excess of 80,000 tCO_2e annually comparable to the annual emissions of a small industrial facility.

Figure 6 below presents the cumulative recycling-based carbon savings across the five academic years, illustrating the progressive accumulation of avoided emissions over the study period.

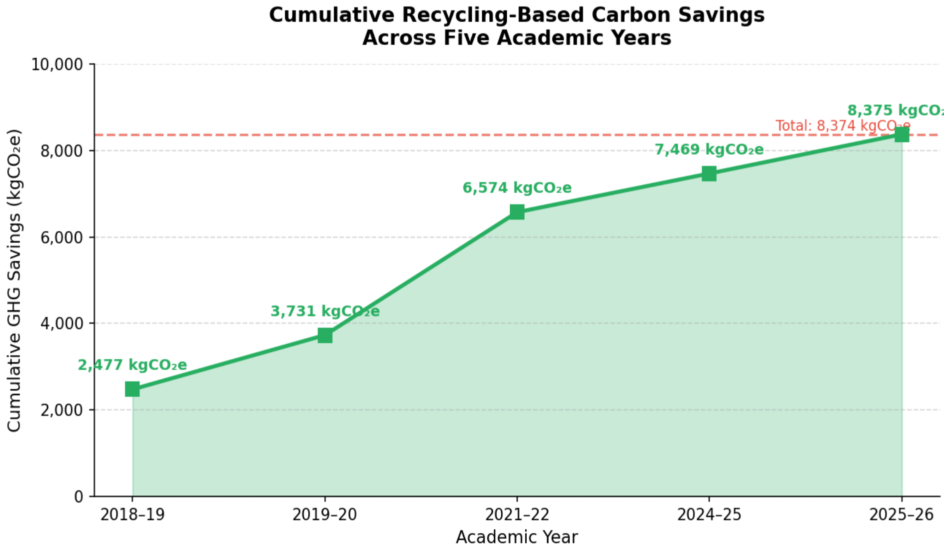

Figure 6: Cumulative Recycling-Based Carbon Savings Across Five Academic Years (kgCO_2e)

5.3 The Landfill Emission Factor Update: A Methodological Consideration

The revision of the landfill emission factor from 0.004 to 0.04 kgCO_2e/kg in 2025-26 has significant implications for the comparability of longitudinal LCA studies. This change was introduced to better reflect the following environmental mechanisms:

- Leachate generation: Electronic waste components particularly batteries, circuit boards with lead solder, and mercury-containing lamps generate toxic leachate in landfill environments. The decomposition of organic binders and flux materials produces GHG-contributing compounds.
- Methane generation: Battery electrolytes and some polymer-based components undergo anaerobic decomposition in mixed-waste landfills, producing methane whose 100-year global warming potential is approximately 28 times that of carbon dioxide (IPCC, 2013; Myhre et al., 2013), making uncontrolled battery decomposition a non-trivial GHG source even at small volumes.
- Transportation emissions: The 2025-26 methodology incorporates a more comprehensive accounting of transport-related GHG emissions associated with landfill operations.

Institutions and researchers using this dataset for longitudinal comparisons should apply consistent emission factors when comparing across time periods to avoid artefactual trends. The apparent 11-fold increase in landfill emissions between 2024-25 and 2025-26 (from 6.01 to 68.62 kgCO_2e) is primarily attributable to this methodological change rather than to changes in disposal practices or waste volume.

6. POLICY IMPLICATIONS AND RECOMMENDATIONS

Based on the findings of this study, the following recommendations are directed at the institution, peer engineering colleges, and relevant regulatory bodies:

6.1 Institutional Recommendations

1. Establish a standardised annual e-waste audit protocol: The present study demonstrates the value of systematic inventory data collection maintained consistently over multiple academic years. The institution should further formalise its annual e-waste audit with standardised data fields, weight verification procedures, and digital recordkeeping to ensure uninterrupted continuity across all future academic years.
2. Normalise waste generation data against institutional indicators: Future reporting should express e-waste generation as kilograms per student enrolled, per faculty member, or per square metre of laboratory space. This normalisation

enables meaningful year-on-year comparisons independent of fluctuations in waste volumes driven by hardware refresh cycles.

3. Track equipment age at disposal: The current inventory records 'year of purchase' for a minority of items. Systematic age-at-disposal data would enable product lifespan modelling, support EPR compliance reporting, and inform procurement decisions (e.g., specifying minimum design lifetimes for procured equipment).
4. Separate waste streams by laboratory type: The data suggests that electronics laboratory waste (ICs, capacitors, resistors) and IT infrastructure waste (computers, hard disks, keyboards) have distinct temporal profiles and emission intensities. Separate tracking by department or laboratory type would improve analytical resolution.
5. Explore component reuse and refurbishment prior to recycling: Before items are routed to formal recycling, a preliminary assessment should identify components suitable for inter-departmental reuse, donation to community maker spaces, or student disassembly exercises (providing both educational value and secondary resource recovery).

6.2 Sector-Level and Regulatory Recommendations

6. Mandate institutional e-waste LCA reporting under NAAC Green Audit criteria: The National Assessment and Accreditation Council (NAAC) green audit framework should incorporate e-waste carbon accounting as a mandatory metric, alongside existing green building and energy consumption indicators. This would create an incentive for all accredited institutions to establish LCA-compliant e-waste management systems.
7. Establish a national e-waste emission factor database for India: The current study relies on emission factors derived primarily from European and Australian benchmarks. India-specific emission factors — calibrated to the energy mix of formal recycling facilities, transportation distances, and landfill conditions in different states — would substantially improve the accuracy of institutional LCA assessments.
8. Develop shared e-waste collection infrastructure for higher educational institutions: Many institutions lack the scale to negotiate direct contracts with formal recyclers. State-level consortia of educational institutions could collectively negotiate superior recycling rates, reduce per-unit collection costs, and improve chain-of-custody documentation for EPR compliance.

7. CONCLUSION

This study has presented the first comprehensive, multi-year Life Cycle Assessment of institutional e-waste at an engineering college in India. Over five academic years from 2018-19 to 2025-26, an Engineering Institution, Mysuru, Karnataka, India processed 11,870.5 kg of e-waste through formal recycling channels, achieving net carbon savings of 8,265 kgCO_2e relative to the landfill counterfactual scenario.

Beyond the quantified environmental benefits, the principal contribution of this research lies in establishing a pioneering Life Cycle Assessment framework for institutional e-waste management in higher education. To the best of the authors' knowledge, this is the first comprehensive multi-year LCA study conducted at an engineering college in India. The methodology developed in this study provides a practical and replicable framework for institutional carbon accounting, sustainable e-waste management, and environmental reporting that can be adopted by engineering colleges and universities nationwide.

The longitudinal analysis reveals three distinct phases in the institution's e-waste trajectory: a legacy IT hardware decommissioning phase (2018-19 to 2019-20), a laboratory equipment disposal peak (2021-22), and an emerging infrastructure waste phase (2024-25 onwards). Each phase is characterised by distinct waste compositions, carbon savings intensities, and logistical challenges. The peak savings year, 2021-22, achieved 2,843 kgCO_2e of avoided emissions — primarily from high-emission-factor power electronics laboratory modules.

A critical methodological finding is the evolution of the landfill emission factor from 0.004 to 0.04 kgCO_2e/kg in 2025-26, which reflects improved GHG accounting for leachate and decomposition mechanisms. This change has significant implications for the comparability of longitudinal e-waste LCA studies and underscores the importance of transparent emission factor documentation.

The study demonstrates that even a single mid-sized engineering institution, through consistent formal e-waste recycling over five years, can avoid emissions equivalent to the annual carbon footprint of 3.5 average Indian citizens. When extrapolated to India's broader higher education sector, this represents a meaningful and underutilised lever for institutional climate action. The adoption of standardised LCA-based e-waste reporting, integration with NAAC green audit frameworks, and development of India-specific emission factor databases are identified as priority interventions for scaling this impact.

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REFERENCES

[1] Jena, S. K., & Goel, S. (2015). E-waste generation in an academic campus: IIT Kharagpur as a case study. Pollution Research, 34(2), 315–320.

[2] Cucchiella, F., D'Adamo, I., Lenny Koh, S. C., & Rosa, P. (2015). Recycling of WEEEs: An economic assessment of present and future e-waste streams. Renewable and Sustainable Energy Reviews, 51, 263–272.

[3] Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. (2020). The Global E-waste Monitor 2020: Quantities, flows, and the circular economy potential. United Nations University, International Telecommunication Union, and International Solid Waste Association.

[4] ISO. (2006a). ISO 14040:2006 — Environmental management: Life cycle assessment — Principles and framework. International Organisation for Standardisation, Geneva.

[5] ISO. (2006b). ISO 14044:2006 — Environmental management: Life cycle assessment — Requirements and guidelines. International Organisation for Standardisation, Geneva.

[6] Kumar, A., Holuszko, M., & Espinosa, D. C. R. (2017). E-waste: An overview on generation, collection, legislation and recycling practices. Resources, Conservation and Recycling, 122, 32–42.

[7] MoEFCC [Ministry of Environment, Forest and Climate Change], India. (2022). E-Waste Management Rules, 2022. Government of India Gazette, New Delhi.

[8] Jaglan, A. K., Cheela, V. R. S., Vinaik, M., & Dubey, B. (2022). Environmental impact evaluation of university integrated waste management system in India using life cycle analysis. Sustainability, 14(14), 8361.

[9] Valai Ganesh, S., Suresh, V., Rajakarunakaran, S., & Suryakumar, V. (2025). Sustainable electronic waste management framework for academic institutions in India. Scientific Reports, 15, 40550.

[10] Sinha-Khetriwal, D., Kraeuchi, P., & Schwaninger, M. (2005). A comparison of electronic waste recycling in Switzerland and in India. Environmental Impact Assessment Review, 25(5), 492–504.

[11] van der Voet, E., van Oers, L., Verboon, M., & Kuipers, K. (2019). Environmental implications of future demand scenarios for metals: Methodology and application to the case of seven major metals. Journal of Industrial Ecology, 23(1), 141–155.

[12] WEEE Forum. (2021). Category-specific emission factors for WEEE recycling: Technical guidance note. Brussels: WEEE Forum International.

[13] World Bank. (2022). CO_2 emissions (metric tons per capita) — India. World Development Indicators. Washington D.C.: World Bank Group.

[14] WRAP. (2020). Carbon metric for waste and resource management activities: Guidance for practitioners. Banbury: Waste and Resources Action Programme.

[15] Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., ... & Zhang, H. (2013). Anthropogenic and natural radiative forcing. In T. F. Stocker et al. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution

of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

[16] Zeng, X., Mathews, J. A., & Li, J. (2018). Urban mining of e-waste is becoming more cost-effective than virgin mining. Environmental Science & Technology, 52(8), 4835–4841.