Maneesha, P., Loganathan, S. and Mouli, D. 2026. Operationalising circular economy in mega infrastructure projects: A data-driven analysis. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1251-1264. DOI: https://doi.org/10.31705/WCS.2026.91. Available from: https://ciobwcs.com/papers/

OPERATIONALISING CIRCULAR ECONOMY IN MEGA INFRASTRUCTURE PROJECTS: A DATA-DRIVEN ANALYSIS

Paidi Maneesha[1], Santhosh Loganathan[2] and Durai Mouli[3]

ABSTRACT

The construction sector is among the most resource-intensive industries globally, with large-scale infrastructure projects generating substantial construction waste due to their scale, complexity, and execution uncertainties. While Circular Economy (CE) principles are increasingly promoted to address these challenges, their implementation at project sites remains largely disposal-oriented and insufficiently guided by data-driven prioritization approaches. The study presents a risk-based, site-centric assessment of construction waste streams to support practical CE implementation in large-scale infrastructure projects. Primary waste generation and material consumption data were collected from 58 infrastructure project sites, including metro, nuclear and hydel projects, over one year. The methodology integrates the Waste Generation Index (WGI) to normalize waste against issued material quantities, pareto analysis to identify dominant waste contributors, and Failure Mode and Effects Analysis (FMEA) to diagnose process-level failures based on severity, occurrence, and detectability. The study distinguishes between high-volume waste streams, including Construction and Demolition (C&D) waste and ferrous scrap, and high-inefficiency waste streams, including electrical waste, wood waste, and plastic waste. Results indicate that C&D waste exhibits the highest concentration of critical risk failure modes, driven by concreting losses and design-execution deviations. Although ferrous waste is largely recycled, the high-risk levels indicate upstream inefficiencies such as cutting losses and limited reuse of steel off cuts. Electrical waste emerges as a hidden high-risk hotspot, showing high waste intensity and risk even though its total quantity is relatively small. The findings demonstrate that effective CE interventions should consider both waste dominance and process risk, rather than waste quantity alone.

Keywords: *C&D waste; Circular economy;Llarge-scale infrastructure projects; Sustainable construction practices; Waste Generation Index (WGI).*

1. INTRODUCTION

The construction industry plays a pivotal role in economic growth and infrastructure development; however, it is also one of the most resource-intensive and waste-generating

[1] Post Graduate Student, Department of Civil Engineering, National Institute of Technology (NIT) Tiruchirappalli, Tamil Nadu, India; Senior Engineer, L&T Construction, Chennai, Tamil Nadu, India, maneeshapaidi198@gmail.com, orcid.org/0009-0005-8807-0533

[2] Assistant Professor, Department of Civil Engineering, National Institute of Technology (NIT) Tiruchirappalli, Tamil Nadu, India, lsanthosh@nitt.edu, orcid.org/0000-0003-2997-0599

[3] Head Environment, Heavy Civil Infrastructure IC, L&T Construction, Chennai, Tamil Nadu, India, mouli.durai1@lntecc.com

sectors globally (Hossain et al., 2024). Large quantities of materials such as cement, aggregates, steel, timber, and electrical components are consumed during construction activities, resulting in substantial generation of C&D waste, ferrous and electrical waste (Ginga et al., 2020). In rapidly urbanising countries such as India, the accelerated pace of infrastructure development has intensified concerns related to waste management, landfill dependency, and resource efficiency (CPCB, 2018). Indian infrastructure projects generate large volumes of mineral-based C&D waste, with concrete accounting for approximately 65% and bricks and masonry materials for nearly 25% of total C&D waste (Bhattacharyya et al., 2013). Despite this high material intensity, waste management practices in infrastructure projects remain largely disposal-oriented, relying heavily on landfilling or low-value recycling, leading to avoidable material losses and environmental impacts (Blumhardt, 2018).

The environmental implications of these practices are significant. Construction activities account for nearly 40% of global raw material consumption and generate approximately 25-35% of landfill waste worldwide (Munaro et al., 2023). Rising material costs, limited landfill capacity, and increasingly stringent regulatory mechanisms such as Extended Producer Responsibility (EPR) and updated C&D Waste Management Rules have increased compliance pressure on construction organizations (Badi & Murtagh, 2019; Ababio & Lu, 2022). However, fragmented project delivery systems, inadequate waste segregation, and poor data traceability continue to constrain effective waste management and resource recovery at the execution stage (Ezekwu, 2025).

In response to these challenges, the Circular Economy (CE) has emerged as a promising alternative to the traditional linear ‘take-make-dispose’ model, aiming to decouple economic growth from resource depletion and environmental degradation. In the construction sector, CE emphasises retaining material value through strategies such as reduction at source, reuse, recycling, repair, refurbishment, and recovery across extended life cycles (Hossain et al., 2024). Unlike conventional end-of-life waste management approaches, CE prioritises upstream interventions, including improved design coordination, procurement planning, process optimisation, and closed-loop material flows (Guerra et al., 2021; Amudjie et al., 2025). When effectively implemented, CE practices can reduce waste generation, lower project costs, and improve overall sustainability performance. Despite growing policy emphasis and industry awareness, implementation of CE principles in construction remains limited, particularly at the project execution stage. Existing research and practice show limited use of data-driven, site-level prioritisation approaches capable of identifying where CE interventions can deliver maximum impact. To address these gaps in research and practice, the present study adopts a quantitative, site-centric approach to evaluate CE applicability in large-scale infrastructure projects in India. Using primary data from multiple active project sites, the study integrates waste quantification, efficiency normalisation, and root cause analysis to support targeted and evidence-based CE implementation during project execution.

2. LITERATURE REVIEW

In construction, the principles of a CE revolve around the reduction of materials at the source, the reuse of components, the recycling of C&D waste, the repair and refurbishment of assets, and the design for building adaptability and disassembly. Most of the research consistently highlights their effectiveness in waste prevention, environmental impact mitigation, and resource efficiency increase.

2.1 CE Strategies and Practical Limitations

A wide range of CE strategies applicable to construction projects has been proposed in the literature, including sustainable design, modular construction, prefabrication, reuse of materials, and recycling of C&D waste (Hossain et al., 2024). However, despite the growing volume of CE related research in construction, much of the literature remains conceptual and strategic, focusing on frameworks, principles, and policy-level recommendations rather than operational implementation (Guerra et al., 2021; Munaro & Tavares, 2023). In practice, CE implementation in construction remains heavily dominated by recycling-based approaches. Higher-order strategies such as reuse, repair, refurbishment, and industrial symbiosis are comparatively underdeveloped, particularly in large infrastructure projects. This indicates that circularity in construction is often addressed through downstream waste management rather than upstream interventions targeting design coordination, procurement planning, and execution-stage process optimization (Guerra et al., 2021).

Several studies have identified the integration of lean construction principles as a complementary pathway for improving CE performance. Lean practices such as waste minimisation, just-in-time material delivery, and prefabrication reduce material losses and improve process efficiency, thereby supporting circular objectives at the site level. Execution-stage strategies, including source segregation, workforce training, and recycling incentives, have been reported as beneficial, especially in developing country contexts (Benachio et al., 2021; Wu et al., 2024). Nevertheless, these studies often rely on qualitative assessments or isolated case examples, limiting their generalisability. Few comprehensive quantitative analyses across multiple construction sites make it difficult to validate CE strategies at scale.

Recent studies have increasingly examined CE implementation in large-scale infrastructure projects, highlighting challenges associated with high material intensity, complex supply chains, and extended execution periods. Infrastructure projects such as transportation systems and energy facilities generate significant volumes of mineral-based waste and require coordinated planning for effective material recovery and reuse (Hasselsteen et al., 2025). Recent research emphasises the importance of circular material flows, including reuse of materials, adoption of recycled aggregates, and integration of secondary resources in construction processes; however, practical implementation remains limited due to operational and supply chain constraints (Krajewska et al., 2025). Furthermore, existing studies indicate that despite increasing interest in circular construction, most applications remain project-specific and lack standardised, data-driven evaluation across multiple sites, limiting scalability and broader adoption of CE practices (Mohandes et al., 2026).

2.2 Project-Level Constraints for CE implementation

Despite the availability of CE strategies, their adoption within the construction sectors, particularly at the project level, is constrained by multiple systemic and operational barriers. Fragmented supply chains, stakeholder misalignment, and weak coordination between design, procurement, and execution stages are repeatedly identified as major obstacles to effective CE implementation at project level (Badi & Murtagh, 2019). While policy instruments such as landfill taxes, Extended Producer Responsibility (EPR) schemes, and sustainability regulations act as important drivers, their translation into consistent site-level practices remains limited (Ababio & Lu, 2022; Munaro et al., 2023).

Operational constraints at the site-level further restrict circular implementation. Inadequate waste segregation, material contamination, insufficient on-site storage facilities, and the absence of structured waste handling plans reduce the recoverability and reuse potential of construction materials. These challenges are particularly pronounced in large-scale infrastructure projects, where complex workflows, multiple subcontractors, and schedule pressures often result in reactive, disposal-oriented waste management practices (Nunes et al., 2012; Akinade et al., 2015; Galvez et al., 2018).

2.3 CIRCULAR ECONOMY ASSESSMENT APPROACHES

Assessment of CE performance in construction has predominantly relied on environmental evaluation tools, particularly Life Cycle Assessment (LCA). While LCA provides valuable insights into environmental impacts, it often lacks operational resolution and offers limited guidance for decision-making during project execution. Economic feasibility and process-level inefficiencies are frequently underrepresented in LCA studies, reducing the usefulness of existing frameworks for stakeholders responsible for site operations (Pomponi & Moncaster, 2017).

Although Material Flow Analysis (MFA) is commonly used to quantify construction waste streams, many studies focus on absolute waste quantities without relating them to total material consumption or project scale (Hasselsteen et al., 2025). This limits meaningful comparison across projects of different sizes. Without indicators such as waste intensity per unit area or material input, it becomes difficult to separate waste driven by project magnitude from waste caused by process inefficiencies. As a result, high-volume waste streams may be prioritized simply due to their size, while proportionally inefficient streams are overlooked, potentially diverting CE efforts away from areas with greater optimization potential. Few studies integrate waste quantification with risk-based prioritization approaches, limiting the ability to translate material flow insights into actionable site-level interventions.

2.4 EMPIRICAL RESEARCH GAPS AND THE INDIAN CONTEXT

Existing research shows real-world limited availability of empirical, project-level studies examining CE implementation in active construction projects. This gap is even more pronounced in the Indian context, where existing studies largely focus on policy analysis, regulatory frameworks, or generalised waste management practices, with minimal emphasis on quantitative assessment and execution-stage diagnosis in infrastructure projects (Hill et al., 2023). Although government initiatives such as the Construction and Demolition Waste Management Rules (2016), resource efficiency strategies proposed by NITI Aayog, and related policy reforms have strengthened regulatory direction, and corporate ESG initiatives have increased sustainability reporting, anecdotal evidence indicates that these efforts largely remain compliance or disclosure oriented.

Furthermore, only a few studies systematically link waste quantification to structured root cause analysis. Without identifying the process-level failures contributing to waste generation, CE strategies risk remaining generic and difficult to operationalize both at the project level and organisational level. The limited integration of waste quantification, efficiency normalisation, and risk-based prioritisation represents a key limitation in current research. Addressing these gaps with empirical evidence from Indian infrastructure projects during the project execution stage forms the basis of the present study.

3. METHODOLOGY

The present study adopts a project-level, mixed-method research approach to evaluate the applicability of CE principles in large-scale infrastructure projects. The methodology integrates quantitative waste assessment and performance-based indicators with qualitative validation through site observations and expert interviews in the investigated projects. The methodological framework is designed to address two core objectives:

i. Quantify major construction waste streams and assess material efficiency using normalised performance indicators

ii. Identify and prioritise the root causes of waste generation through structured, risk-based analysis

A bottom-up, project-centric approach is employed to ensure that findings reflect actual construction practices.

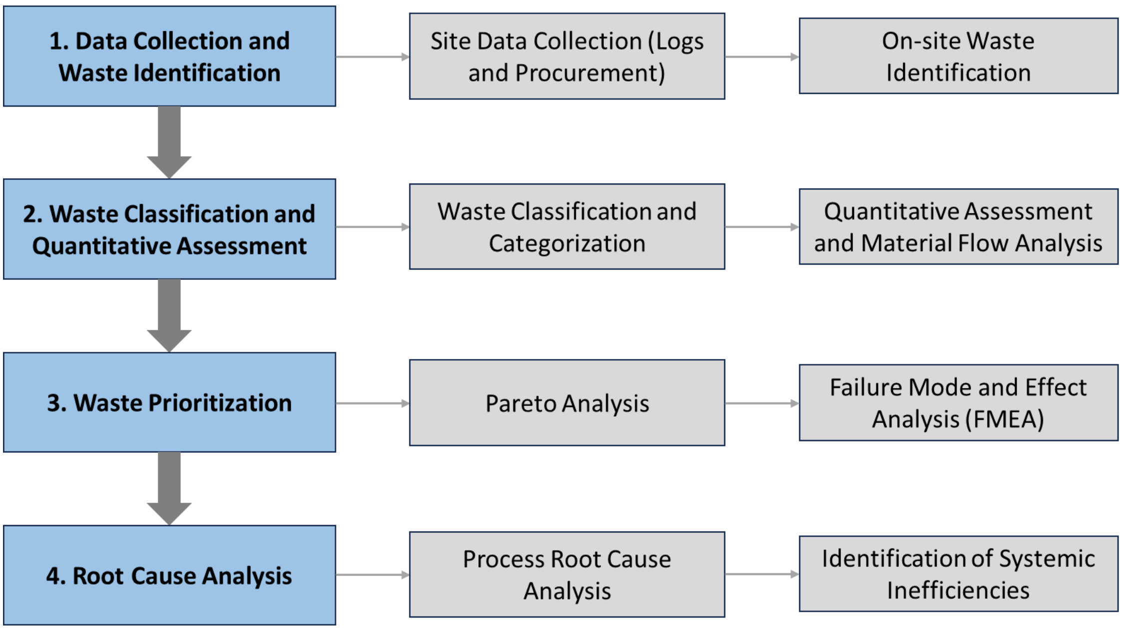

Figure 1: Methodology framework

The overall methodology is illustrated in Figure. 1.

3.1 DATA COLLECTION AND WASTE IDENTIFICATION

The study is based on primary waste management data collected from 58 large-scale infrastructure project sites over a period of one year (2024-25), covering civil, mechanical, and electromechanical works. The projects included nuclear, metro, and hydel infrastructure works characterised by high material intensity, repetitive construction operations, and extended execution periods, making them suitable for large-scale waste and circular economy assessment.

The dataset comprised site waste registers, monthly environmental reports, material movement logs, and procurement and issue records documenting waste generation, reuse, recycling, sale, and disposal pathways. All waste quantities were standardised to tons to enable aggregation and cross-project comparison. Waste streams were classified into hazardous and non-hazardous categories in accordance with hazardous waste rules, contractual Environmental Management Plans (EMP), and prevailing site practices. Waste output data were analysed alongside material input baselines derived from procurement and issue records to support quantitative assessment and material flow analysis across project types. Site observations were conducted to validate reported data and document on-ground waste handling, segregation, and storage practices. Examples of waste segregation and on-site waste handling practices observed during field visits are illustrated in Figure 2.

Figure 2: Waste segregation at project sites

For data validation and interpretation, expert interviews were conducted with seven project engineers, six environmental personnel and site management teams from the respective project sites. Each interview lasted approximately 25-30 minutes with project engineers and around 40 minutes with environmental personnel, focusing on execution-stage constraints influencing waste generation and management practices. Secondary data, including applicable codes and policy documents, were used to provide regulatory context and methodological support.

3.2 WASTE CLASSIFICATION AND QUANTIFICATION

Waste streams generated during construction activities were identified across multiple work fronts, including concrete and masonry waste, ferrous and reinforcement scrap, timber and formwork waste, electrical and MEP scrap, packaging waste, and miscellaneous site waste. Identified waste streams were categorised into hazardous and non-hazardous waste in accordance with applicable regulatory definitions.

An overview of the study design, including project classification, waste categorization, and data collection sources, is illustrated in Figure 3. Quantitative assessment was carried out to determine the volume and proportion of each waste stream over the study period.

All quantities were standardized to a common unit to enable aggregation and comparison across project types.

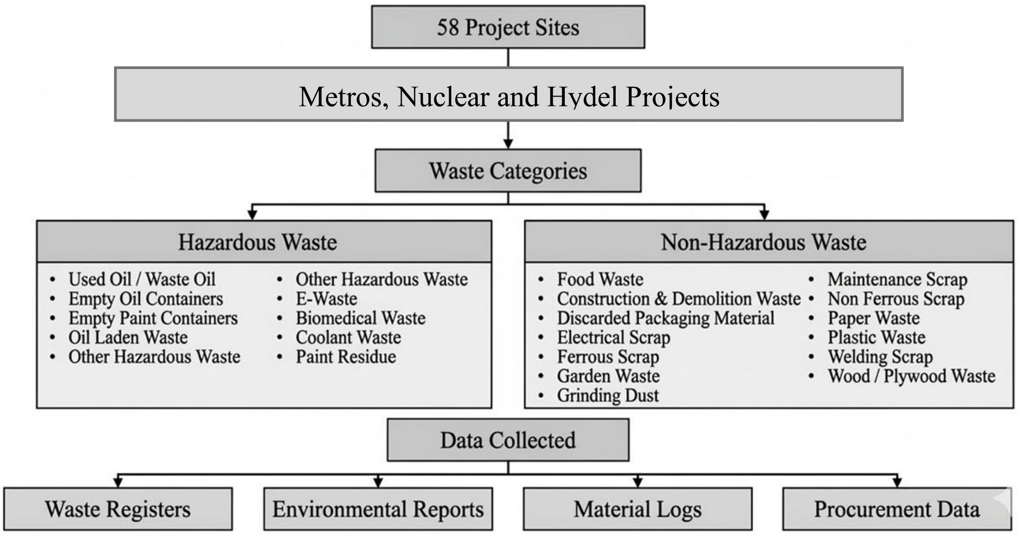

Figure 3: Study overview of infrastructure project waste assessment

To evaluate material efficiency, waste quantities were normalized against corresponding material issue quantities using the Waste Generation Index (WGI), defined as the ratio of waste generated to material issued for construction activities.

3.3 WASTE PRIORITISATION AND ROOT CAUSE ANALYSIS

To prioritise waste streams for detailed analysis, pareto analysis, an 80/20-based method for identifying the few (20%) contributors responsible for the majority of outcomes (80%) - was applied to identify dominant contributors to overall waste generation at the organizational level. This enabled distinction between high-volume waste streams and those requiring focused intervention. For prioritised waste streams, Failure Mode and Effects Analysis (FMEA) was employed as a structured root-cause analysis tool. Potential failure modes contributing to waste generation were identified across design, procurement, material handling, storage, execution, and supervision stages. Each failure mode was evaluated based on severity, occurrence, and detectability, and corresponding Risk Priority Numbers (RPNs) were calculated. This risk-based approach facilitated systematic prioritization of process failures contributing to waste generation and provided a quantitative basis for identifying CE intervention points.

4. PROJECT SITE-LEVEL WASTE ASSESSMENT

This section presents a structured assessment of waste generation and management practices at the project site level. The analysis focuses on quantifying waste streams, classifying material categories into hazardous and non-hazardous waste, and examining disposal and recovery pathways across different infrastructure project types. By integrating waste output data with material input records, the assessment enables evaluation of material efficiency, identification of high-impact waste streams, and benchmarking of circular economy performance across sites.

4.1 QUANTITATIVE ASSESSMENT OF HAZARDOUS WASTE STREAMS

Hazardous waste generation across the studied projects was dominated by oil-related waste streams, reflecting the intensive use of heavy machinery and equipment.

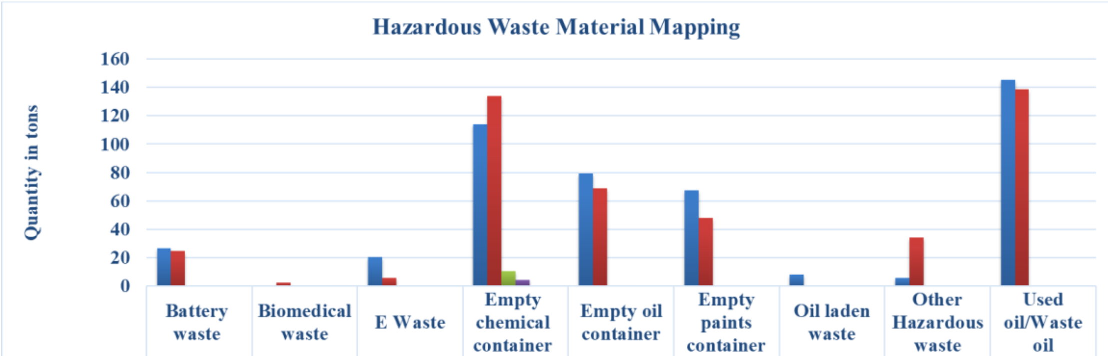

Figure 4: Hazardous waste material mapping

Used oil accounted for approximately 51% of total hazardous waste, followed by empty oil containers (25%) and empty paint containers (19%). Lower-volume hazardous streams such as e-waste, biomedical waste, and oil-laden waste contribute less than 5% of the total quantity.

Material flow analysis as represented in Figure.4, revealed that over 85% of hazardous waste was sold to authorised recyclers, indicating strong regulatory compliance and a mature external disposal ecosystem. Internal reuse or recycling was minimal (≈3%), largely restricted by safety considerations and statutory controls. A small but significant fraction of hazardous waste (≈11%) was recorded as generated but not yet disposed, indicating temporary storage inventories or reporting lags. Overall, hazardous waste management was found to be compliance-driven and externally dependent, leaving limited scope for discretionary CE interventions at the site level.

4.2 QUANTITATIVE ASSESSMENT OF NON-HAZARDOUS WASTE STREAMS

Non-hazardous waste constituted the largest share of total waste generation and exhibited substantial variability across project types.

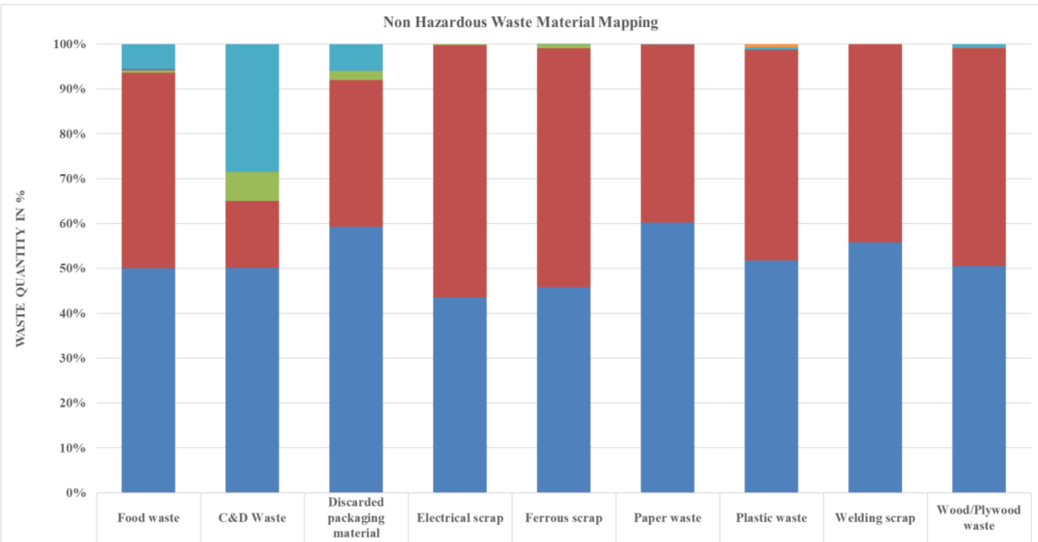

Figure 5: Non-Hazardous waste material mapping

C&D waste emerged as the dominant stream, accounting for approximately 17.5% of total non-hazardous waste, followed by ferrous scrap (13.4%). Other streams included wood/plywood waste, plastic waste, packaging waste, and biodegradable waste. Material flow analysis, as represented in Figure.5, showed that nearly 50% of non-hazardous waste was sold to external recyclers, driven primarily by ferrous and non-ferrous scrap markets. However, internal reuse and recycling accounted for only 2.4%, indicating significant untapped circular potential, particularly for C&D waste, packaging materials, and temporary works. Approximately 10% of non-hazardous waste was sent to landfill, while 37.6% remained categorised as generated but not yet disposed, highlighting inventory accumulation and documentation gaps. These findings establish non-hazardous waste streams, especially C&D waste and ferrous scrap as priority areas for CE analysis.

4.3 PROJECT-TYPE-WISE WASTE GENERATION CHARACTERISTICS

Waste generation patterns varied significantly across project types. Metro projects generated the highest absolute waste quantities, dominated by C&D waste arising from excavation, mass concrete, rework, and interface coordination issues. Nuclear projects were primarily characterised by high ferrous scrap generation linked to reinforcement cutting and fabrication activities. Hydel projects, although smaller in total waste volume, exhibited higher on-site reuse of excavation material due to logistical and geographical constraints. These variations underline the need for project-specific waste management strategies, rather than a uniform approach across infrastructure typologies.

4.4 WASTE GENERATION INDEX (WGI) ANALYSIS

To evaluate material efficiency, waste quantities were normalised against material issue quantities using the WGI (refer Table 1).

Table 1: WGI Range

WGI Range	Category
< 0.01 (1%)	Very Low
0.01 - 0.03 (1-3%)	Low
0.03 - 0.06 (3-6%)	Moderate
0.06 - 0.10 (6-10%)	High
> 0.10 (10%)	Very High

The analysis revealed that while concrete and welding consumables consistently exhibited very low WGI values across project types, electrical materials recorded the highest WGI values (>0.10), identifying them as a recurring inefficiency hotspot. Ferrous and wood waste exhibited moderate WGI values, suggesting opportunities for improved planning, detailing, and reuse cycles. The WGI analysis provided a quantitative basis for distinguishing high-volume waste streams from high-inefficiency waste streams, informing subsequent prioritisation.

5. WASTE PRIORITISATION

Following the site-level waste assessment, a structured prioritisation approach was adopted to identify high-impact waste streams requiring targeted intervention. Since waste quantity alone does not fully reflect operational risk or inefficiency, both volume-based and risk-based analytical methods were applied. The prioritisation process integrates Pareto analysis to identify dominant waste contributors and FMEA to evaluate process-level risk intensity, enabling data-driven selection of waste streams for circular economy interventions.

5.1 PARETO-BASED WASTE PRIORITISATION

Pareto analysis revealed a pronounced concentration of waste generation across a limited number of streams, as illustrated in the Pareto chart in Figure.6. C&D waste from Metro projects alone contributed approximately 63% of total organisational waste, while ferrous waste from Metro and Nuclear projects contributed an additional ~26%.

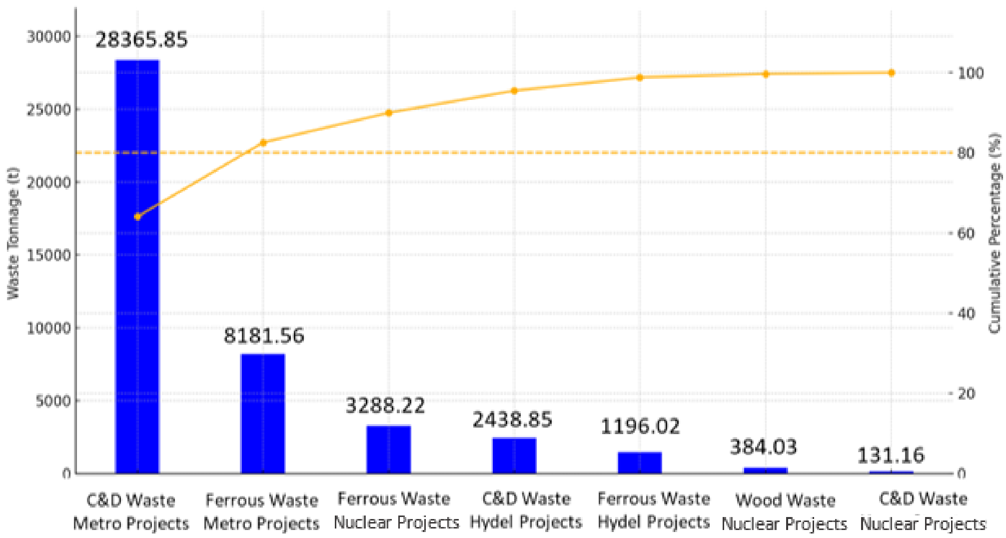

Figure 6: Pareto chart

Together, these streams accounted for nearly 84% of total waste generation, validating the applicability of the Pareto principle for targeted intervention. In contrast, wood and plastic wastes formed a Pareto 'long tail', lower in absolute quantity but exhibiting disproportionately high WGI values, indicating inefficiencies that may be overlooked when prioritisation is based solely on volume.

5.2 FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

To move beyond quantity-based prioritization, FMEA was employed to systematically identify process-level failures contributing to waste generation. Severity (S), Occurrence (O), and Detection (D) scores were assigned based on site observations, expert inputs, WGI values, and Pareto results. Risk Priority Numbers (RPNs) were calculated to rank failure modes according to risk criticality. The formulated RPN bands are:

- RPN ≥ 250 → Critical (Immediate intervention required)
- RPN 200-250 → High (Process optimization needed)
- RPN 100-200 → Moderate
- RPN < 100 → Low

The calculated RPN values form the basis for prioritizing waste streams for corrective action and development of CE strategies in subsequent analysis. The FMEA focused on major waste streams, including C&D waste, ferrous waste, electrical waste, wood waste, and plastic waste. The results revealed substantial variation in risk intensity across streams, highlighting that waste-related risk is governed not only by quantity, yet by severity of impact, frequency of occurrence, and detectability of failures.

6. ROOT CAUSE ANALYSIS

A root cause analysis was conducted to identify the underlying process-level drivers contributing to waste generation and elevated risk levels. The objective was to move beyond surface-level metrics and examine operational, planning, and coordination failures influencing each major waste category. By linking Risk Priority Numbers (RPNs) with specific construction practices, the analysis provides actionable insights for targeted circular economy interventions.

Risk Category		Priority Bands		
		RPN Range	≥ 250	200 — 249
RPN	**Critical** • Immediate intervention required	≥ 250	• **C&D Waste** (majority of failure modes)	• **C&D Waste** (majority of failure modes) • **Electrical Waste** (key failure modes)
High	**High** • Process optimization essential	200 – 249	• **Ferrous Waste** • Select Wood Waste modes	
RPN	**Moderate** • Improvement desirable	100 – 199	• **Plastic Waste** • Secondary Wood Waste modes	
Low	**Low**	<100	–	

Figure 7: Risk priority matrix

The resulting risk intensity across waste streams is visualised using a risk matrix as represented in Figure.7, which categorises failure modes based on severity and occurrence levels to highlight critical intervention areas.

6.1 CONSTRUCTION AND DEMOLITION WASTE: DOMINANT CRITICAL RISK STREAM

C&D waste exhibited the highest concentration of critical RPN values (240–288), establishing it as the most risk-intensive stream. Key failure modes included over-excavation beyond design depth, handling and pouring losses during concrete, absence of planned reuse for excavated material, and rework arising from design-execution mismatches. These failures are primarily driven by planning deficiencies, conservative assumptions, and weak process control rather than material behavior alone. This finding aligns with existing studies that identify C&D waste as the dominant waste stream in infrastructure projects, driven by rework, over-excavation, and material handling losses (Hossain et al., 2024; Wu et al., 2024). However, the present study further shows that these streams also exhibit high process-level risk, highlighting the need for risk-based prioritisation.

6.2 FERROUS WASTE: HIGH RISK WITH EFFECTIVE DIVERSION

Ferrous waste failure modes recorded high yet non-critical RPN values (≈190–224). While near-complete diversion through recycling mitigates disposal impacts, elevated RPNs highlight upstream inefficiencies related to cutting losses, congested detailing, and limited internal reuse of off-cuts. This indicates a reliance on downstream recycling rather than preventive material optimisation. This is consistent with literature reporting high recycling rates for ferrous waste in construction projects (Benachio et al., 2021; Munaro et al., 2023). However, the findings highlight persistent upstream inefficiencies, indicating that recycling alone does not address material losses.

6.3 ELECTRICAL WASTE: HIGH-INTENSITY HIDDEN HOTSPOT

Electrical waste emerged as a high-risk efficiency hotspot, despite low absolute quantities. Failure modes such as cable length miscalculation and scrapping due to late design changes recorded RPN values up to 280, explaining the consistently high WGI values observed earlier. This stream demonstrates how low-volume waste can translate into significant cost and risk due to high severity and poor detectability.

6.4 WOOD AND PLASTIC WASTE: LONG-TAIL INEFFICIENCY ZONE

Wood and plastic wastes occupied the moderate-risk band (RPN 140–210). Although their quantities are small, inefficiencies related to handling, storage, moisture exposure, and lack of reuse mechanisms reduce reuse cycles and increase replacement demand. These streams represent low-cost, high-return intervention opportunities through procedural and planning improvements.

By integrating WGI, Pareto analysis, and FMEA, the study demonstrates a structured, risk-based approach to identifying priority waste streams for CE implementation in large-scale infrastructure projects. The findings confirm that effective circular interventions must target both dominant waste streams and hidden inefficiency hotspots, rather than focusing on waste quantity alone. The study addresses the lack of empirical, site-level evidence on CE implementation in Indian infrastructure projects and demonstrates the value of integrating waste quantification, efficiency normalisation, and risk-based analysis. The combined use of WGI, Pareto analysis, and FMEA advances methodological rigor beyond conceptual CE frameworks. From a practical standpoint, the findings provide contractors and project managers with a replicable decision-support framework for prioritising waste streams and targeting execution-stage circular interventions. The results emphasise that effective CE implementation requires moving beyond disposal efficiency toward quantification-driven diagnosis and process-level optimisation.

Existing studies mainly focus on high-volume waste streams and recycling-based approaches for CE implementation (Guerra et al., 2021; Munaro et al., 2023). However, this study shows that volume-based prioritisation can overlook high-inefficiency waste streams with significant operational risk. Unlike prior work based on qualitative or single-project studies, this research provides multi-site, data-driven evidence linking waste quantification with risk-based prioritization and root cause analysis, offering a more differentiated understanding of CE implementation in large-scale infrastructure projects.

7. CONCLUSIONS

The study presented a data-driven, site-centric evaluation of construction waste streams in large-scale infrastructure projects to support practical CE implementation at the project execution stage. Using primary data from 58 infrastructure projects in India, the study integrated the WGI, Pareto analysis, and FMEA to move beyond conventional volume-based waste assessment toward efficiency- and risk-based prioritisation. The findings reveal that C&D waste from metro projects constitutes the dominant waste hotspot, contributing nearly two-thirds of total organisational waste and exhibiting the highest concentration of critical risk failure modes. These risks are primarily driven by planning deficiencies, design-execution mismatches, conservative excavation practices, and the absence of structured reuse planning, rather than material-related constraints. As a result, C&D waste represents the most impactful leverage point for CE interventions in large-scale infrastructure projects.

Although ferrous waste achieves near-complete diversion through external recycling, elevated RPN highlight persistent upstream inefficiencies related to cutting losses, congested reinforcement detailing, and limited internal reuse of off-cuts. This underscores a key limitation of recycling-dominated CE practices and emphasises the need to shift focus from disposal efficiency toward preventive material optimisation. The study identifies electrical waste as a high-intensity hidden inefficiency hotspot. Despite low absolute quantities, electrical waste consistently exhibited very high WGI and RPN values due to cable length miscalculations, late design changes, and poor detectability of losses. These findings demonstrate the value of integrating normalised efficiency metrics with risk-based analysis to uncover inefficiencies that may otherwise remain overlooked. Wood and plastic wastes form a Pareto long tail, reflecting moderate risk driven by handling, storage, and planning deficiencies, and offering low-cost opportunities for procedural improvement.

Overall, the study demonstrates that effective CE implementation in infrastructure projects requires prioritisation based on both waste dominance and process risk, rather than waste quantity alone. It provides a replicable decision-support tool for practitioners to identify and target high-impact CE interventions. Future research should focus on evaluating the technical and economic feasibility of prioritised CE strategies to translate diagnostic insights into actionable implementation pathways.

8. REFERENCES

Ababio, B. K., & Lu, W. (2023). Barriers and enablers of circular economy in construction: A multi-system perspective towards the development of a practical framework. *Construction Management and Economics*, *41*(1), 3–21. https://doi.org/10.1080/01446193.2022.2135750

Akinade, O. O., Oyedele, L. O., Ajayi, S. O., Bilal, M., Alaka, H. A., Owolabi, H. A., & Arawomo, O. O. (2018). Designing out construction waste using BIM technology: Stakeholders' expectations for industry deployment. *Journal of Cleaner Production*, *180*, 375–385. https://doi.org/10.1016/j.jclepro.2018.01.022

Amudjie, J., Agyekum, K., Adinyira, E., Amos-Abanyie, S., & Botchway, E. A. (2025). Implementing the principles of circular economy in the construction industry: Exploratory and confirmatory factor analyses of strategies. *Construction Innovation*, *25*(3), 761–786. https://doi.org/10.1108/CI-10-2022-0270

Badi, S., & Murtagh, N. (2019). Green supply chain management in construction: A systematic literature review and future research agenda. *Journal of Cleaner Production*, *223*, 312–322. https://doi.org/10.1016/j.jclepro.2019.03.132

Benachio, G. L. F., Freitas, M. D. C. D., & Tavares, S. F. (2021). Interactions between lean construction principles and circular economy practices for the construction industry. *Journal of Construction Engineering and Management*, *147*(7), 04021068. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002082

Bhattacharyya, S. K., Minocha, A. K., Garg, M., Singh, J., Jain, N., Maiti, S., & Singh, S. K. (2013). Demolition wastes as raw materials for sustainable construction products. *CSIR-CBRI Newsletter*, *33*(2), 1–2. https://cbri.res.in/pdf/newsletter_apr_jun_2013.pdf

Blumhardt, H. (2018). Trashing waste: Unlocking the wasted potential of New Zealand's Waste Minimisation Act. *Policy Quarterly*, *14*(4). https://doi.org/10.26686/pq.v14i4.6545

Central Pollution Control Board (CPCB). (2017/2018). *Guidelines on environmental management of construction and demolition (C&D) waste in India*. Ministry of Environment, Forest and Climate Change, Government of India. https://prana.cpcb.gov.in/assets/pdf/c_and_d_guidelines_1.pdf

Ezekwu, E. (2025). Sustainable supply chain practices: Driving efficiency, reducing waste, and promoting circular economy models. *International Journal of Science and Research Archive*, *14*(1), 1167–1181. https://doi.org/10.30574/ijsra.2025.14.1.0206

Gálvez-Martos, J. L., Styles, D., Schoenberger, H., & Zeschmar-Lahl, B. (2018). Construction and demolition waste best management practice in Europe. *Resources, Conservation and Recycling*, *136*, 166–178. https://doi.org/10.1016/j.resconrec.2018.04.016

Ginga, C. P., Ongpeng, J. M. C., & Daly, M. K. M. (2020). Circular economy on construction and demolition waste: A literature review on material recovery and production. *Materials*, *13*(13), 2970. https://doi.org/10.3390/ma13132970

Guerra, B. C., Shahi, S., Mollaei, A., Skaf, N., Weber, O., Leite, F., & Haas, C. (2021). Circular economy applications in the construction industry: A global scan of trends and opportunities. *Journal of Cleaner Production*, *324*, 129125. https://doi.org/10.1016/j.jclepro.2021.129125

Hasselsteen, L., Damgaard, A., Otovic, A. P., Birgisdóttir, H., & Kanafani, K. (2025). Tracing resource flows and reducing environmental impacts during construction: Assessment framework for on-site waste efficiency. *Journal of Cleaner Production*, *521*, 146243. https://doi.org/10.1016/j.jclepro.2025.146243

Hill, W., Jalloul, H., Movahedi, M., & Choi, J. (2023). Sustainable management of the built environment from the life cycle perspective. *Journal of Management in Engineering*, *39*(2), 03123001. https://doi.org/10.1061/JMENEA.MEENG-4759

Hossain, M. S., Lopa, N. Z., Khatun, M., & Rahim, S. T. (2024). Enablers of circular economy implementation in built environment sector of developing countries: Evidence from Bangladesh. *Circular Economy and Sustainability*, *4*(3), 2287–2311. https://doi.org/10.1007/s43615-024-00392-4

Krajewska, A., & Siewczyńska, M. (2025). Circular economy in the construction sector in materials, processes, and case studies: Research review. *Sustainability*, *17*(15), 7029. https://doi.org/10.3390/su17157029

Mohandes, S. R., Fan, A., Zou, J., Taiwo, R., Shakor, P., & Banihashemi, S. (2026). Advancing circular economy adoption through investigating RFID technology in construction. *Engineering, Construction and Architectural Management*, 1–34. https://doi.org/10.1108/ECAM-05-2025-0851

Munaro, M. R., & Tavares, S. F. (2023). A review on barriers, drivers, and stakeholders towards the circular economy: The construction sector perspective. *Cleaner and Responsible Consumption*, *8*, 100107. https://doi.org/10.1016/j.clrc.2023.100107

Nunes, K. R. A., & Mahler, C. F. (2020). Comparison of construction and demolition waste management between Brazil, European Union and USA. *Waste Management & Research*, *38*(4), 415–422. https://doi.org/10.1177/0734242X20902814

Oshilalu, A. Z. (2024). Sustainability meets scalability: Transforming energy infrastructure projects into economic catalysts through supply chain innovation. *International Journal of Research Publication and Reviews*, *5*(12), 762–779. https://doi.org/10.55248/gengpi.5.1224.3417

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Wu, H., Weng, X., Li, Y., Liu, S., Ma, J., Chen, R., & Bao, Z. (2025). Critical construction waste minimization strategies for a circular economy in developing countries: A contractor's perspective in China. *International Journal of Environmental Science and Technology*, *22*(12), 11211–11228. https://doi.org/10.1007/s13762-024-06150-1