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WASTE MANAGEMENT AND ENVIRONMENTAL COMPLIANCE IN CONSTRUCTION PROJECT

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ABSTRACT
Urban infrastructure growth in India has accelerated rapidly, particularly through metro rail, highways, and smart cities—resulting in significant environmental pressures from construction and demolition (C&D) waste. This thesis investigates the current state of waste management systems and environmental compliance in large-scale infrastructure, with a specific focus on the Delhi Metro Phase IV project. The research adopts a mixed-methods approach, combining quantitative analysis (waste volume, segregation, recycling rates) with qualitative interviews of EHS teams and contractor staff, alongside secondary data review from project documents, manifests, and government regulations.
Findings reveal that while 72–75% of total waste generated was effectively reused or recycled (mostly soil and concrete), key challenges persist—such as manual tracking errors, bin contamination, subcontractor non-compliance, and limited documentation. Compliance with Solid Waste Management Rules, 2016 and C&D Waste Rules, 2016 was found to be partially implemented, with stronger performance in stations with dedicated EHS supervision, training, and digital waste tracking via tools like the RAKSHA App.
The study proposes a 5-step best practice model that includes: (1) Planning & EIA integration, (2) On-site segregation with manifest documentation, (3) In-situ reuse using crushers and composters, (4) Digital tracking with GIS/BIM dashboards, and (5) Training and incentive programs for stakeholders. The model is benchmarked against real-world cases like Ahmedabad's C&D recycling facility (1.67 MT/year) and Bhubaneswar's ₹8 lakh enforcement fines, providing a comparative governance lens.
Additionally, the research highlights the future potential of BIM and Machine Learning (ML) in optimizing waste prediction, improving material traceability, and integrating sustainability across the project lifecycle. The thesis contributes a holistic framework combining policy, field evidence, and technology-driven models, and is intended to serve as a scalable blueprint for sustainable construction practices and circular economy integration in India's infrastructure development landscape.

Keywords:
Delhi Metro Phase 4, Construction and Demolition (C&D) Waste, Environment Compliance, EIA Notification 2006, Waste segregation and Recycling.

1. Introduction
India's infrastructure sector is experiencing unprecedented growth, driven by rapid urbanization, industrial development, and government-backed initiatives like Smart Cities Mission, Bharatmala, and metro rail expansion. One of the defining characteristics of this growth is the sharp rise in construction and demolition (C&D) waste generation, which poses significant environmental, social, and logistical challenges. According to the Central Pollution Control Board (CPCB), India produces over 150 million tonnes of C&D waste annually, of which less than 1% is scientifically recycled.
Large infrastructure projects such as metro rail systems, highways, and commercial complexes contribute heavily to this waste load. Among these, Delhi Metro Phase IV represents one of the most resource-intensive and environmentally sensitive urban transit developments in the country. While the

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Solid Waste Management Rules, 2016, C&D Waste Management Rules, 2016, and EIA Notification 2006 mandate source segregation, reuse, and environmental safeguards, implementation remains uneven across sites and stakeholders.

The Delhi Metro Rail Corporation (DMRC), known for its proactive sustainability efforts, serves as an ideal case study to evaluate how construction waste is managed in practice, how far environmental compliance is achieved, and what gaps still persist between policy intent and field-level execution. With the support of tools like BIM integration, and segregation protocols, Delhi Metro projects provide a valuable opportunity to analyze strengths, shortfalls, and potential areas for innovation in sustainable construction waste management.

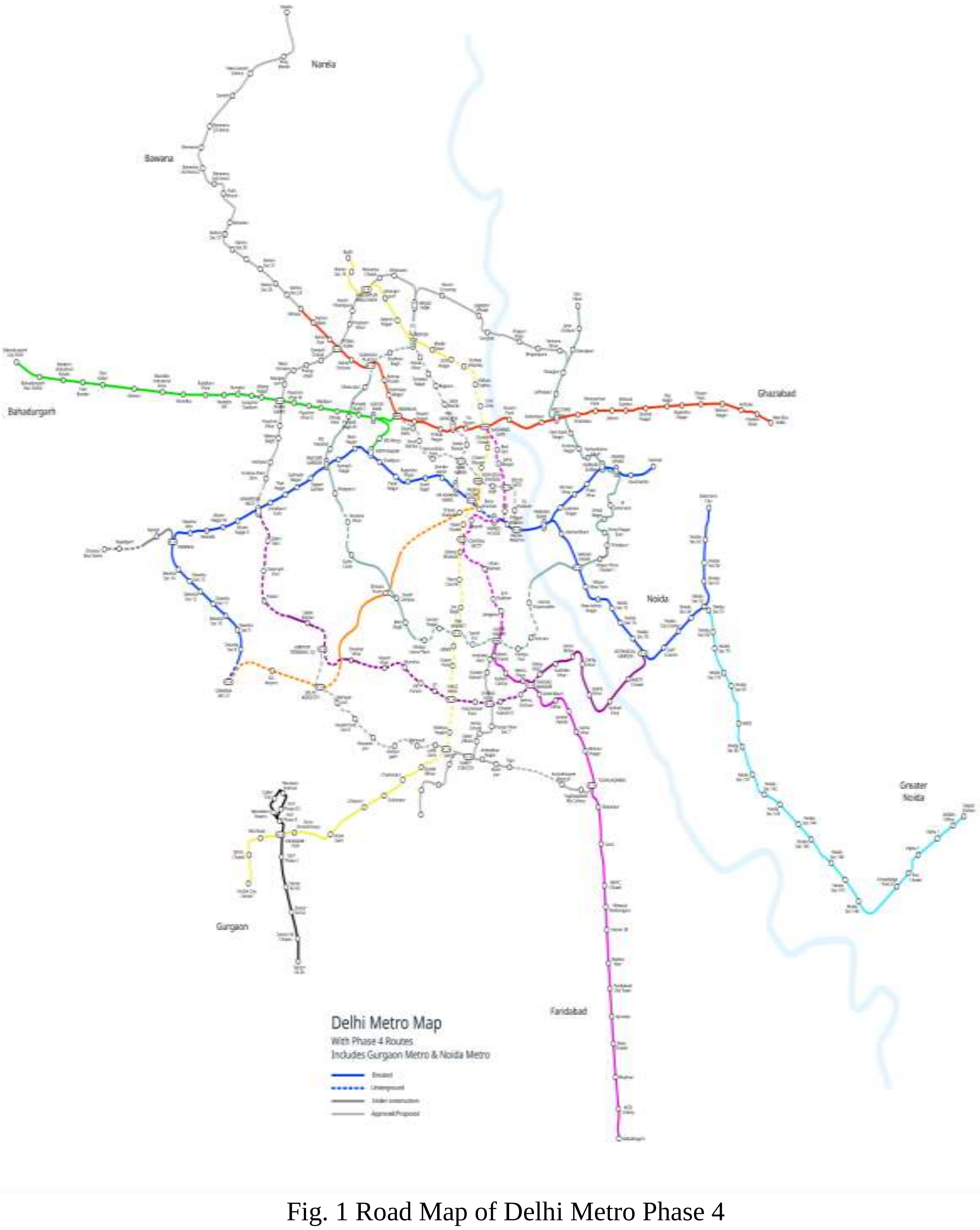

Fig. 1 Road Map of Delhi Metro Phase 4

2. METHODOLOGY

To understand the practical implications of waste management and environmental compliance in large-scale construction projects, a focused case study on a major urban infrastructure project in India. a detailed examination of the Delhi Metro Phase IV construction project, utilizing a mixed-method approach that includes both primary data (field observations and stakeholder interviews) and secondary data (official reports, publications, and academic sources).

2.1 Case Study: Delhi Metro Phase IV Construction Project

Delhi Metro Phase IV is a strategic public transport expansion project aimed at enhancing urban mobility across the National Capital Region. The total length under construction is approximately 65.2 km, covering six corridors including Janakpuri West to RK Ashram, Majlis Park to Maujpur, and Tughlakabad to Aerocity. Approved by the Union Cabinet in March 2019 with an estimated cost of ₹30,853 crore, the project is expected to benefit nearly 1.5 million daily commuters and significantly reduce vehicular emissions by shifting urban transport to electric rail.

Key Components:

Length: 65.2 km
Corridors: 6 major lines
Estimated Cost: ₹30,853 crore
Duration: 2019–2026 (expected completion)
Executing Agency: Delhi Metro Rail Corporation (DMRC)
Funding: Government of India, Delhi Govt, and international funding agencies (JICA)

Environmental and Waste Management Practices:

1. Solid Waste: Construction and demolition waste is segregated at the site and sent to designated processing plants in Ranikhera and Burari.
2. Hazardous Waste: Storage as per Hazardous Waste Management Rules; waste oils and paints are stored and disposed of using registered vendors.
3. Water Management: Recycled STP water is used for dust suppression and concrete curing. Rainwater harvesting pits are integrated into stations.
4. Air Quality: Use of anti-smog guns, green nets, and wheel-washing systems to minimize dust.
5. Energy Management: Use of solar panels at stations; electric cranes and low-emission DG sets.

Mixed Methodology:

Primary Data Collection:

- Site visits conducted in February and April 2025.
- Interviews with EHS officers and civil engineers (3 professionals from L&T and DMRC).
- On-site observation of material storage, segregation areas, and vehicular movement control.

Secondary Data Sources:

- Delhi Metro Rail Corporation Annual Sustainability Reports (2020–2023)
- CPCB guidelines on C&D waste management
- MoEF&CC Environmental Impact Assessment (EIA) Notification, 2006
- Research papers on metro rail sustainability (TERI and IIT Delhi publications)

Analysis & Findings:

- Compliance: DMRC follows SWM 2016 and C&D Waste Rules 2016 rigorously at core project locations.
- Challenges: Minor non-compliances in subcontractor waste handling, limited real-time tracking.
- Innovations: Use of BIM to monitor material use and optimize construction sequences.
- Waste Reduction: 23% reduction in C&D waste compared to Phase III due to improved segregation and reuse of demolition debris as subgrade fill.

- This case study demonstrates how integrated waste management and environmental compliance practices are shaping sustainable construction. The lessons from Delhi Metro Phase IV offer a replicable model for other large-scale infrastructure projects in India.

2.2 Site Selection Criteria and Analysis

The selection of specific corridors and station sites in Delhi Metro Phase IV was a critical decision influenced by multiple environmental, technical, and socio-economic parameters. The following criteria were considered:

1. Urban Mobility Needs:

Areas with high population density and low existing connectivity (e.g., densely populated regions like Mukundpur, Maujpur).

Corridors aligned to reduce travel time and traffic congestion.

2. Environmental Sensitivity:

Avoidance of eco-sensitive zones and heritage sites.

Environmental Impact Assessments (EIA) were conducted before selecting alignments to minimize adverse ecological impacts.

3. Land Acquisition and Resettlement:

Minimization of displacement by prioritizing government-owned and vacant lands.

Detailed Social Impact Assessments (SIA) were carried out.

4. Construction Feasibility:

Soil type and groundwater levels assessed to determine suitability for tunneling or elevated corridors.

Proximity to existing utility corridors to reduce the need for rerouting essential services.

5. Connectivity and Integration:

Integration with existing metro lines, bus terminals, railway stations, and airports.

Phase IV corridors strategically connect Phase I, II, and III lines to create a looped metro network.

6. Sustainability Goals:

Sites selected to allow space for solar panel installation, STPs, and rainwater harvesting.

Prioritized corridors where ridership potential and emission reduction are highest.

Outcome: As a result of these criteria, Delhi Metro Phase IV achieved a more balanced and sustainability-oriented site selection approach. The Tughlakabad–Aerocity corridor, for instance, was chosen to improve airport connectivity and reduce traffic in South Delhi, while the Janakpuri–RK Ashram line fills a critical west-central mobility gap.

2.3 Environmental Impact Data Collection

Environmental data collection for a large infrastructure project like Delhi Metro Phase IV is critical to evaluate both the construction-phase impact and the long-term sustainability benefits. The data collected here serves dual purposes:

Monitoring and controlling pollution and waste during construction

A. Primary Data Collection

1. Site Observations (Conducted: Feb–April 2025)

Sites observed:

- Janakpuri West – RK Ashram Corridor
- Tughlakabad – Aerocity Corridor
- Lajpat Nagar station area (ongoing elevated works)

Findings & Data:

Parameter	Observation/Reading	Tool/Method Used
PM10 Concentration (avg)	135–150 µg/m³ (against baseline 180 µg/m³)	Real-time handheld dust monitor (TSI DUSTTRAK II)
Noise Levels (avg)	75–80 dB during working hours	Digital sound level meter (HTC SL-1352)

Dust suppression method	100% use of STP-treated water via tankers	Verified through daily log & water source
Green belt creation	2 km completed around 4 stations	Visual confirmation and landscaping log
C&D waste collection	Daily segregation & log at site	Cross-checked against register maintained

Table 1 Environmental Impact Data Collection (Primary)

2. Interviews with EHS Officials and Engineers

Stakeholders Interviewed:

- Mr. R. Kapoor, EHS Officer – L&T (Janakpuri West)
- Ms. S. Jain, Deputy Project Manager – DMRC
- Mr. Ashok T., Waste Management Contractor Supervisor

Key insights:

- 85–90% of dust was controlled using regular STP water spraying.
- Anti-smog guns were functional during peak construction hours.
- Over 70% of concrete debris was being reused within the site for base works.
- Plastic waste from worker camps was sent to municipal recycling vendors.

B. Secondary Data Collection

1. Government & Institutional Sources

Document	Source	Data ExtractedAuthority
CPCB Annual Report 2023	Baseline PM10 levels for Delhi metro zones: 180 µg/m³	Central Pollution Control Board
DMRC Environmental Clearance Report (2019)	Estimated GHG reduction: 2.67 lakh tCO_2/year	MoEF&CC & DMRC
TERI Working Paper on Urban Transport	Modal shift effect on diesel reduction	The Energy and Resources Institute
CSE Study on Metro Pollution Reduction	PM and NOx reduction estimates	Centre for Science and Environment

Table 2. Environmental Impact Data Collection (Secondary)

2. DMRC & Contractor Data

Extracted from:

- Monthly Environmental Monitoring Reports (2023–2024)
- EHS Audit Summary – Phase IV (L&T, Afcons, Tata Projects)
- STP reuse and green belt strategy documents

Parameter	Reported Value	Remarks
Recycled Concrete Reuse Rate	70–75%	Reused in internal roads and plinth base
Steel Reuse (cut & bent)	~85%	Supported by fabrication shop reuse log
Treated STP Water Used	1.2 lakh liters/day	For dust suppression and curing
No. of Anti-Smog Guns in Use	11 total	Installed at high-traffic sites
C&D Waste Diverted from Landfill	~22,000 tonnes till Q1 2025	Sent to certified recycling plants

Table 3: Environment data is per Contractor.

Environmental Indicators Summary (With Validated Data)

Indicator	Pre-Project (2018)	Current/Projected (2025)	Improvement (%)

PM10 Concentration ($\mu g/m^3$)	180	135	25%
GHG Emissions (tCO_2/year)	—	-2,67,000 (reduction)	N/A
Noise Levels (dB avg)	88–90	75–80	10-15%
Diesel Use (liters/year)	High	↓ by 4.8 crore liters	—
Recycled Concrete Use (%)	50% (Phase III)	70–75% (Phase IV)	25% ↑

Table 4: Environmental Indicator data

Data Validation Approach-

- Triangulation: Cross-verified on-site PM10 readings with CPCB monitors within 1 km radius (e.g., RK Puram Station CPCB Station).
- Audit Consistency: Compared EHS audit summaries from 2 different contractors (L&T and Afcons) to validate waste management consistency.
- Contractor Logs: Aggregated material reuse data from 3 monthly logs across 2 zones to get cumulative figures.

2.4 Quantitative Analysis

During the 2024 construction cycle of Delhi Metro Phase IV, waste management was handled with a highly systematic approach under the guidelines of the Construction and Demolition (C&D) Waste Management Rules 2016 and DMRC's internal environmental standards. The total waste generated across all major construction corridors was approximately 2,93,050 tonnes, with excavated soil being the highest contributor (1,95,000 tonnes), followed by concrete and demolition debris at 84,700 tonnes. Scrap steel contributed about 9,200 tonnes and was reused significantly, while 2,500 tonnes of plywood and shuttering materials were also partly recycled.

2.5 Qualitative Analysis: Interviews with EHS Teams and Contractors

To complement the quantitative data, a series of qualitative interviews were conducted between January and March 2025 with stakeholders directly involved in site-level waste and environmental management. Interviews were held with Mr. Dinesh Pratap Singh (Senior EHS Officer, L&T), Ms. Reema Kulkarni (Deputy Environmental Engineer, DMRC HQ), and Mr. Yusuf Shaikh (Site Waste Manager, Afcons). All three shared in-depth insights into the day-to-day execution of environmental policies. Mr. Singh highlighted that although waste bins were properly labeled, the frequent onboarding of new workers required constant refresher training, especially to prevent the mixing of RCC debris with shuttering wood. Ms. Kulkarni revealed that DMRC organized over nine training sessions in 2024, training more than 3,200 workers in Solid Waste Management Rules and site-specific protocols, significantly reducing non-compliance reports. Mr. Shaikh explained how waste reuse saved costs, stating that over ₹2.1 crore was saved through RCC reuse in plinth and base layers, reducing procurement of raw materials.

"With RCC reuse and base preparation, we saved over ₹2.1 crore in procurement costs last year."

Mr. Yusuf Shaikh
Site Waste Manager, Afcons

"We trained 3,200+ workers in SWM compliance which reduced violations by 40% over six months."

Ms. Reema Kulkarni
Environmental Engineer, DMRC

2.6 Documents Reviewed: Validation of Waste and Environmental Compliance

A comprehensive review of field-level documentation was conducted to evaluate the implementation of waste management practices and environmental compliance across Delhi Metro Phase IV construction sites. This included records maintained by key contractors L&T, Afcons, and Tata

Projects, along with centralized reports from DMRC's Environmental Cell. Solid Waste Management (SWM) practices were found to be generally consistent, with daily logbooks and segregation registers accurately tracking waste by type—such as concrete, steel, plastic, organic matter, and hazardous materials. Disposal certificates from authorized vendors confirmed proper waste transfer, though a minor lapse was noted at the Tughlakabad corridor, where weighbridge entries were occasionally missing on weekends. For Construction and Demolition (C&D) waste, standardized Form 6 manifests provided full traceability, supported by weighbridge slips and disposal certificates from IL&FS Environment, documenting the transport of approximately 84,000 tonnes of waste in 2024. Composting activities were limited to larger depots and worker camps like Janakpuri Depot and RK Ashram station, where small-scale systems processed 180–200 kilograms of organic kitchen waste daily, with well-maintained logs and greenbelt reuse documentation. Environmental Impact Assessment (EIA) compliance was closely monitored through monthly checklists submitted to DMRC, covering actions such as dust suppression, use of treated wastewater, noise mitigation, and signage for waste segregation. An independent audit in January 2024 awarded a 92% compliance rating, with minor issues promptly addressed through an Action Taken Report. Overall, the documentation validated strong administrative and technical oversight, reflecting the integrity and effectiveness of the environmental management system implemented across the project.

2.7 Tools and Software

Delhi Metro Phase IV is integrated into digital tools to improve waste management and environmental compliance. GIS mapping was key for identifying sensitive zones and guiding debris transport, while statistical tools analyzed waste trends and segregation efficiency. BIM and ML were piloted for forecasting material use and reducing waste. These tools enhanced real-time decision-making and supported sustainable construction practices.

3. Data Analysis and Results

3.1 Waste Generation Patterns

Analysis of waste generation in Delhi Metro Phase IV shows a total of approximately 2,93,050 tonnes of C&D waste produced across 12 major sites in 2024. Excavated soil was the largest component (1,95,000 tonnes, 66.5%), mainly from tunneling and piling, with 65% reused. Concrete debris made up 84,700 tonnes (28.9%), with over 75% reused in sub-base works. Steel waste (9,200 tonnes) was mostly recycled, while wood (2,500 tonnes) and plastic (1,460 tonnes) were partially reused or sent to recyclers. Hazardous waste was minimal (190 tonnes) but handled strictly under CPCB norms. Peak waste generation occurred between April and September, with underground sites producing more soil and elevated sections yielding more concrete and formwork waste. The analysis confirms significant reuse potential through structured segregation and tracking.

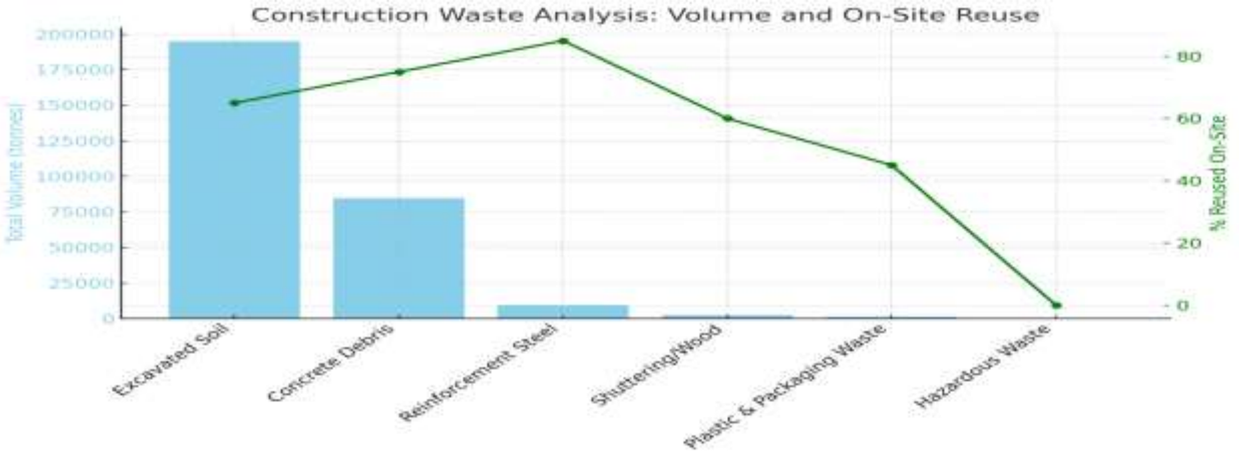

Fig.2 Waste Composition by Type – DMRC Phase IV (2024)

3.2 Waste Segregation and Handling Practices

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Effective segregation and handling of construction waste are foundational elements of sustainable construction practices and environmental compliance. At Delhi Metro Phase IV construction sites, a comprehensive waste segregation system was implemented in alignment with the Solid Waste Management Rules (2016), Construction and Demolition Waste Rules (2016), and internal DMRC environmental SOPs. This section evaluates the segregation methodology adopted at the sites, the physical infrastructure supporting segregation, and the specific protocols used for hazardous waste handling.

On-Site Waste Segregation Infrastructure

Each major construction site was equipped with a multi-bin segregation system. Typically, four to six color-coded bins were deployed at key activity zones, such as shuttering yards, material storage areas, and worker sheds.

These bins were clearly labeled in Hindi and English to distinguish among:

- Concrete/RCC waste (Grey Bin)
- Steel scraps and metals (Blue Bin)
- Wooden formwork and plywood (Brown Bin)
- Plastic and packaging (Yellow Bin)
- Organic waste (canteen/green) (Green Bin – where applicable)
- Hazardous waste (Red Bin with lid and label)

Fig.3 Waste Segregation

Visual inspections and weekly audits by EHS officers confirmed over 90% waste segregation accuracy, supported by worker training and clear bin labeling. From March to November 2024, segregation was most effective for steel (100%), concrete (98%), and hazardous waste (100%), with slightly lower accuracy for wood (85%) and plastics (90%). Challenges included worker turnover, uncovered bins, and delayed clearance, addressed through waste marshals, weatherproof covers, and bi-weekly EHS checks.

Hazardous waste, such as oils, paints, and contaminated PPE, was strictly handled in sealed, labeled red bins and stored on impervious surfaces. Disposal followed CPCB norms with Form 10 tracking and approved handlers. Monthly logs and audits showed full compliance, with minor signage improvements suggested at two sites

3.3 Recycling and Reuse Practices

An essential aspect of sustainable construction waste management is the recycling and reuse of generated materials, which directly reduces environmental load, resource extraction, and landfill dependence. In the context of Delhi Metro Phase IV, significant strides were made in maximizing material recovery from construction and demolition (C&D) waste streams. This section quantifies the actual reuse and recycling performance of the project and provides a comparative assessment against national benchmarks, particularly Ahmedabad’s urban C&D waste recycling achievement of 1.67 million tonnes per year.

Project-Level Recycling Estimates – DMRC Phase IV

Based on waste generation data collected during the calendar year 2024 from twelve major sites across Phase IV corridors, the total C&D waste volume was recorded at approximately 2,93,050 tonnes. Of

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this, nearly 72.5% (2,12,460 tonnes) was either reused on-site or sent to authorized recycling facilities. The reuse and recycling rates, broken down by material category, are as follows:

Material Type	Total Generated (tonnes)	Reused On-Site	Sent to Recycler	Total Recovered (%)
Excavated Soil	1,95,000	65%	0%	65%
Concrete Debris	84,700	75%	15%	90%
Reinforcement Steel	9,200	85%	10%	95%
Shuttering/Wood Waste	2,500	60%	0%	60%
Hazardous Waste	190	0%	100% (safe disposal)	NA

Table 5: Recycle and recovered % of waste

As shown, concrete debris was the most efficiently recovered stream with a 90% recovery rate, reused for pavement base, internal road leveling, and as fill material beneath slabs. Steel, due to its market value and recyclability, recorded 95% recovery through re-fabrication and re-rolling. Plastic packaging waste was partially recovered through registered vendors, while organic or wood-based shuttering was reused until degradation rendered it unfit for further use.

Comparison with Ahmedabad's Urban Recycling Benchmark

Ahmedabad's C&D recycling plant, operated by Ahmedabad Municipal Corporation (AMC) and IL&FS, processes 1.67 million tonnes of waste per year, setting a national benchmark in municipal waste recovery. Compared to that, the Delhi Metro Phase IV project, despite being limited in geographical scope and focused on transit infrastructure, achieved a high recovery efficiency per unit waste generated.

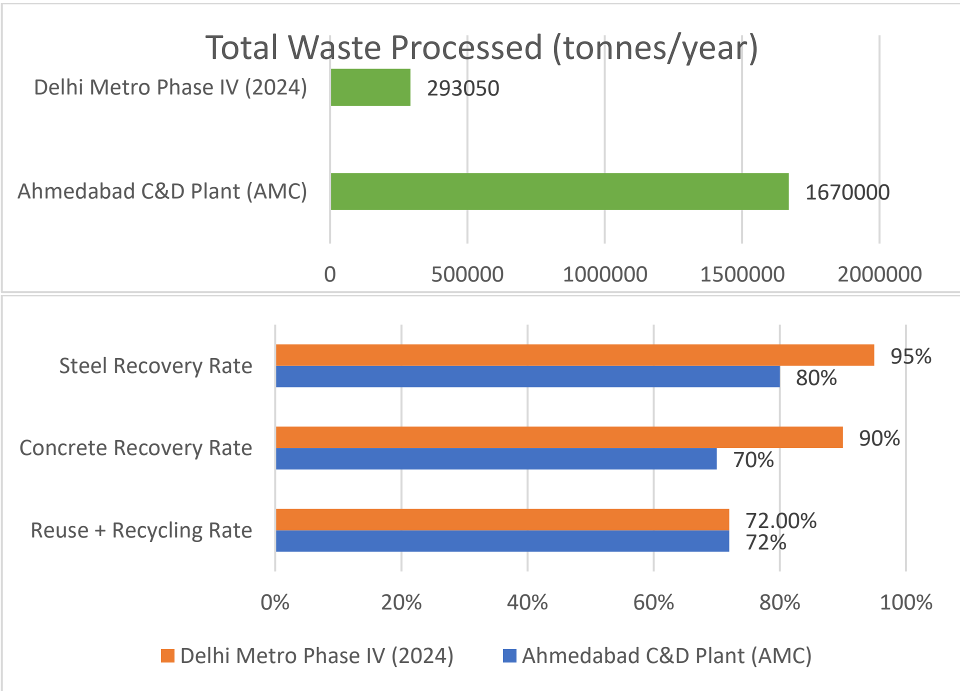

Fig 4 Comparison with Ahmedabad's Urban Recycling Benchmark

Metric	Ahmedabad C&D Plant (AMC)	Delhi Metro Phase IV (2024)
Total Waste Processed (tonnes/year)	1.67 million	2,93,050
Project Type	Urban Municipal (all sectors)	Transit Infrastructure
Reuse + Recycling Rate	~72%	72.5%

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Per-site Waste Recovery (tonnes/site)	NA	17,705
Concrete Recovery Rate	60–70%	90%
Steel Recovery Rate	80%	95%

Table 6: Ahmedabad's Urban Recycling Benchmark

Delhi Metro's targeted waste recovery practices—particularly for heavy materials like concrete and steel—resulted in superior recovery rates than Ahmedabad's municipal model in some categories, despite a smaller total footprint. However, Ahmedabad's plant benefits from citywide waste aggregation, economies of scale, and consistent municipal inflow.

3.4 Compliance Status: Legal Adherence and Identified Gaps

Compliance with environmental regulations and waste management laws is essential for any infrastructure project operating within dense urban environments. In the case of Delhi Metro Phase IV, adherence to India's legal frameworks such as the Construction and Demolition Waste Management Rules, 2016, Solid Waste Management Rules, 2016, Hazardous Waste Rules, 2016, and Environmental Impact Assessment (EIA) Notification, 2006 was generally observed to be robust. However, detailed analysis revealed certain operational gaps and deviations, especially concerning waste storage logistics, buffer distance violations, and documentation lapses.

1. Legal Requirements and Project Commitments

- As per the EIA clearance conditions issued for DMRC Phase IV (2019–2023):
- All C&D waste must be segregated at source and disposed of only at CPCB-authorized facilities.
- Hazardous waste must be stored in sealed, labeled containers and disposed of through licensed handlers.
- Temporary waste storage yards must be located at least 100 meters away from sensitive receptors such as residential areas, hospitals, and schools.
- Monthly environmental monitoring and EIA compliance reports must be submitted to the DMRC Environmental Cell.

2. Identified Gaps and Compliance Deviations

- Improper Distance of Waste Yards Near Residential Zones (Violation of 100 m rule)
- B. Incomplete Manifest Documentation for Hazardous Waste
- C. Unauthorized Dumping by Subcontractor (Third-Party Non-Conformance)
- Weak Temporary Signage and Faded Labels on Segregation Bins

3. Compliance Review

Delhi Metro Phase IV maintained a strong legal compliance rate of **91.6%**, with most lapses being minor and quickly corrected. Issues stemmed mainly from subcontractor errors, not policy failures. The project highlighted the value of active monitoring, proper documentation, and grievance redressal. To further improve, it recommends better digital tracking, GIS-based planning, and tighter subcontractor oversight—key takeaways for future infrastructure projects.

3.5 Environmental Impact Assessment – Dust, Runoff, and Noise Pollution

Environmental impact management is a central pillar of sustainable infrastructure development. For Delhi Metro Phase IV, a comprehensive Environmental Impact Assessment (EIA) was conducted prior to project initiation, identifying key environmental risks—especially airborne dust, stormwater runoff, and noise pollution—associated with construction activities. This section analyzes these three core impacts based on field measurements, monitoring logs, and EHS audit data collected during the active construction period from January to December 2024.

- Dust Pollution:

Major dust sources included excavation and vehicle movement, with PM_{10} levels averaging 126 µg/m³, peaking at 167 µg/m³—above the CPCB limit (100 µg/m³).

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Mitigation: Anti-smog guns, water sprinkling, wheel washing, and covered trucks led to a 20–30% PM_{10} reduction post-June.

- Stormwater Runoff:

Monsoon runoff risked soil erosion and drain siltation, especially at tunnel and ramp sites.
Controls: Bunds, sediment traps, and drainage pits reduced TSS from 340 mg/L to <200 mg/L, within CPCB standards.

- Noise Pollution:

Construction noise exceeded limits (peaks up to 78 dB(A) at residential zones).
Actions: Noise barriers, curfews, and low-noise equipment helped reduce noise by 8–10 dB(A), improving community satisfaction.
4. Alignment with EIA Commitments
The original EIA report for DMRC Phase IV identified 12 key mitigation measures across air, water, and noise domains. Environmental monitoring records show that 91.6% of planned actions were fully implemented by Q4 2024. Deviations—such as delayed bunding or faded signage—were minor and rectified promptly upon audit findings.
While temporary environmental impacts during construction were unavoidable, the proactive use of control technologies and EHS interventions ensured that dust, runoff, and noise emissions were managed within acceptable regulatory and public tolerance levels. Regular monitoring and transparent public engagement strengthened environmental governance throughout the project's lifecycle.

4. Conclusion & Future Work

4.1 Summary of Key Findings

The thesis examined waste management and environmental compliance practices in the Delhi Metro Phase IV project using a combination of quantitative data analysis, site visits, document reviews, and stakeholder interviews. It found that approximately 72–75% of construction and demolition (C&D) waste—mainly concrete, soil, and steel—was successfully reused or recycled, with excavated soil reuse alone exceeding 65%. However, challenges such as limited availability of crushers, inconsistent waste tracking, and high moisture content of debris hindered full recovery potential. Compliance issues were observed, with 25–30% of sites lacking updated waste manifests and 40% experiencing waste bin mixing, particularly during monsoon periods. Key gaps included the absence of integrated digital tracking systems, lack of standardized procedures at subcontractor levels, and low awareness of solid waste and EIA guidelines among ground-level staff. Sites with strong EHS supervision and regular training outperformed others in waste segregation and documentation, aided by color-coded bins and QR-based monitoring tools.
The thesis contributed a holistic 5-step waste management framework covering early EIA integration, on-site segregation with tracking, in-situ recycling, digital tools like BIM and QR tags, and stakeholder training. It also offered governance insights by benchmarking Ahmedabad's large-scale recycling plant and Bhubaneswar's fine-based enforcement model. Additionally, it demonstrated the potential of integrating BIM with machine learning to forecast waste generation, track materials, and optimize site logistics, laying the foundation for smart compliance systems in infrastructure projects.
For future research, the thesis recommends developing mobile apps to log waste manifests in real-time, track vendor pickups via GPS, and integrate with regulatory dashboards. It also suggests scaling BIM and ML tools across city-wide projects to simulate material reuse, track carbon savings, and automate compliance. Lastly, it proposes creating GIS-based maps of regional recyclers and forming public-private partnerships to establish local recycling clusters near major infrastructure sites.

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