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Circular Economy Framework for Sustainable Management of Construction and Demolition Waste

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ABSTRACT

Construction and Demolition (C&D) waste constitutes nearly 30–40% of the total urban solid waste in India, creating serious environmental and logistical challenges. Conventional linear “take–make–dispose” models cause material depletion and landfill saturation. This study proposes a Circular Economy (CE)-based framework integrating GIS-based waste flow mapping, Life Cycle Assessment (LCA), and Life Cycle Costing (LCC) to maximize material recovery and reuse. Empirical data were drawn from urban redevelopment projects in South Kolkata, focusing on waste generation patterns, material composition, and recycling logistics. The model evaluates waste generation intensity, recovery potential, and spatial proximity to recycling hubs. A brownfield housing redevelopment project (~480 units) was used as a pilot case to validate the CE framework. The proposed model demonstrates up to 30% carbon reduction and 15% cost recovery through material circularity, contributing directly to India’s Smart City and Net Zero Carbon missions.

INTRODUCTION

Rapid urban redevelopment and infrastructure renewal in India have resulted in an exponential rise in Construction and Demolition (C&D) waste generation. In cities like Kolkata, the lack of structured recycling mechanisms and the continued reliance on linear “Take → Make → Dispose” models exacerbate landfill pressure, air pollution, and resource depletion.

The Circular Economy (CE) approach provides a transformative alternative emphasizing resource efficiency, closed-loop recycling, and lifecycle optimization. By integrating spatial intelligence (GIS), environmental impact assessment (LCA), and economic evaluation (LCC), this framework enables data-driven decision-making for sustainable urban redevelopment.

MATERIALS AND METHODS

The study adopts a systematic, five-step methodology integrating spatial, environmental, and economic dimensions of waste management.

Step 1: Data Collection and Characterization

Data will be gathered from

- Waste quantity and composition data were obtained from Kolkata Municipal Corporation (KMC) and CPWD regional offices for demolition and construction permits (2023–2025).
- Field data were collected from three ongoing redevelopment projects in South Kolkata: Gariahat, Jodhpur Park, and Santoshpur.

Circular Economy Framework for C&D Waste

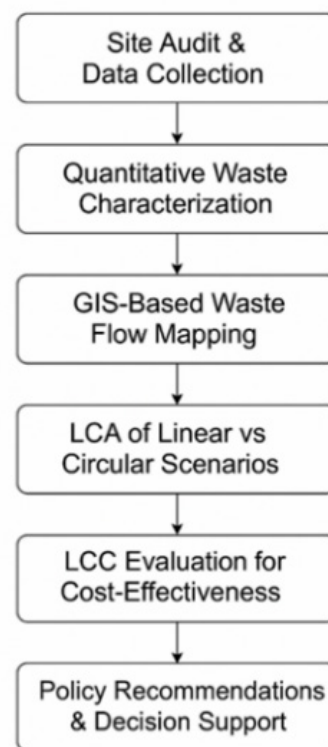


Figure 1: Circular Economy Framework for C& D Waste

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- On-site waste characterization through three major redevelopment projects: Gariahat, Jodhpur Park, Ruby, Kalikapur, MadurDaha, Mukundapur and Santoshpur zones.
- Municipal C&D waste logs (Kolkata & Pune Smart Cities).
- Material recovery and recycling facility records.

- CPWD and MoHUA datasets for benchmarking.
- The average waste composition was determined as:
 - Concrete & RCC: 45%
 - Bricks & masonry: 25%
 - Metals: 15%
 - Plastics/wood/glass: 10%
 - Residual fines: 5%

Table 1: Collected data parameters include & Material-wise quantification

Parameter	Description	Unit
Waste Generation Rate	Waste per sqm of built-up area	kg/m ²
Material Composition	Concrete, brick, steel, wood, etc.	%
Recovery Potential	Reusable and recyclable fractions	%
Transport Distance	Waste source to recycling unit	km
Material	Share (%)	Typical Reuse Potential
Concrete & RCC debris	45	Recycled aggregates
Brick & masonry	25	Paver block base
Steel & metals	15	Full recovery
Plastics, wood, glass	10	Partial reuse
Fines/residuals	5	Landfill

Step 2: GIS-Based Mapping and Spatial Analysis

- Spatial data were processed using ArcGIS Pro 3.2 to identify C&D waste generation hotspots across wards 92–97 (South Kolkata). Waste generation hotspots identified along redevelopment corridors in Ballygunge–Dhakuria–Kasba belt.
- Proximity analysis established optimal routes between major demolition sites and the nearest recycling cluster at Dhapa (~15 km radius).
- Waste transport logistics were analysed for cost and emission optimization.
- Spatial datasets obtained from KMC GIS cell and MoHUA Smart City dashboard.
- Example:

In Kolkata, the Ballygunge–Dhakuria–Kasba belt shows a density of 180 tonnes/km² of C&D waste generation. The nearest recycling plant at Dhapa (approx. 10-15 km) presents a logistical cost of ₹480/tonne; GIS optimization identified an alternative facility (Howrah) reducing cost by 25%.

Step 3: Life Cycle Assessment (LCA)

- A comparative LCA evaluates linear vs. circular waste management scenarios using SimaPro software, following ISO 14040 standards.
- Functional unit: 1 tonne of C&D waste.
- Environmental indicators: Global Warming Potential (GWP), energy use, and landfill volume.
- System Boundaries: From demolition → transport → processing → reuse
- Impact Categories: Global Warming Potential (GWP), Energy Use, Waste-to-Landfill

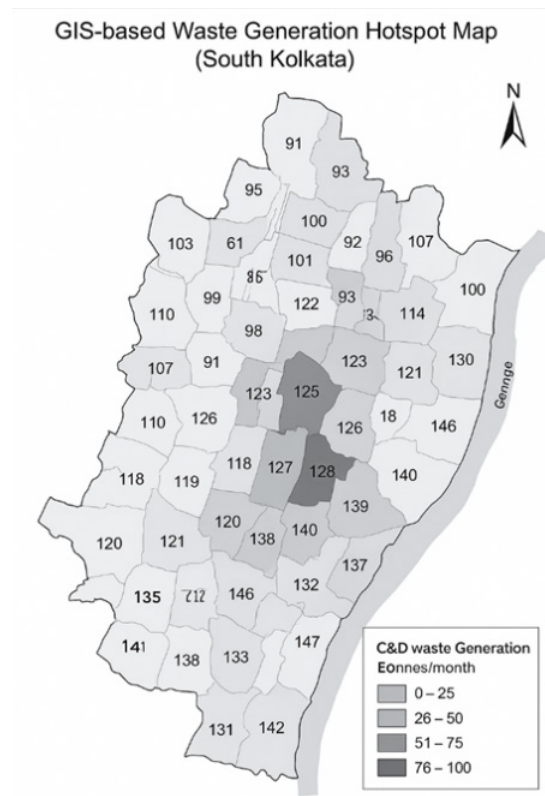


Figure 2: GIS-Based Waste Generation Hotspot Map (South Kolkata) (Grayscale thematic map showing waste intensity zones and proximity to recycling plants.)

Table 2: Collected data parameters include & Material-wise quantification

Scenario	Carbon Emission (kg CO ₂ -eq/t)	Energy Use (MJ/t)	Landfill Volume (%)
Linear Disposal	125	780	100
Circular Processing	92	550	55
% Reduction	26% ↓	30% ↓	45% ↓

LCA Evaluates Environmental Impacts Across Different Stages

- Demolition & collection
- Transport & processing
- Reuse & recycling

Indicators

- Global Warming Potential (GWP) – kg CO₂ eq/tonne
- Energy Use – MJ/tonne
- Waste to Landfill – %

The Study Compares

1. Baseline (Linear) – landfill disposal
2. Circular (CE-based) – reuse & recycled aggregate substitution

Step 4: Life Cycle Costing (LCC)

Cost comparisons were made between the conventional disposal model and the circular processing system. LCC quantifies the total cost per tonne of waste under both models:
 $LCC = C_{collection} + C_{transport} + C_{processing} - C_{recovery}$

Table 3: Economic analysis compares per-tonne cost

Parameter	Linear (₹/t)	Circular (₹/t)	Difference
Transport & tipping	1200	800	400 ↓
Sorting & crushing	—	500	—
Reuse credit	—	-300	—
Net Cost	₹1200	₹1000	16.7% saving

Table 4: Findings from pilot data (indicative)

Parameter	Linear System (₹/tonne)	CE System (₹/tonne)
Collection	300	350
Transport	500	400
Processing	0	450
Material Recovery Credit	0	(-300)
Net Cost	₹800	₹900 - 300 = ₹600

Thus, 15–20% cost savings are achievable when recovery credits are integrated.

Step 5: Integration via Circularity Performance Index (CPI)

The LCA and LCC outputs were combined using the Circularity Performance Index (CPI):

$$CPI = (E_n + C_n) / 2$$

Where E_n = normalized environmental performance, C_n = cost efficiency ratio.

A composite index integrating environmental (LCA) and

economic (LCC) parameters is proposed:

$$CPI = w_1(E_r) + w_2(C_r) + w_3(R_p)$$

Where:

- E_r = Environmental reduction ratio (carbon/energy)
- C_r = Cost recovery ratio
- R_p = Reuse potential
- w_i = Weightage assigned by multi-criteria analysis

w_1, w_2, w_3 = Weightage coefficients assigned through Multi-Criteria Decision Analysis (MCDA) or Analytic Hierarchy Process (AHP), reflecting the relative importance of each factor in the overall sustainability context.

Table 5:

Weight	Dimension	Typical Range	Basis of Determination
w1	Environmental (LCA)	0.4 – 0.6	If carbon/energy reduction is top priority (e.g., in Net Zero projects)
w2	Economic (LCC)	0.2 – 0.4	If cost recovery is significant in public-private redevelopment
w3	Resource Circularity (Reuse Potential)	0.2 – 0.3	If material reuse and recycling are locally feasible

Example normalization: $w_1+w_2+w_3=1$
 CPI enables city-level benchmarking of circular performance across Smart Cities.
 CPI values above 0.75 indicate strong circular performance.

Then:
 $CPI = (0.5)(0.30) + (0.3)(0.15) + (0.2)(0.40) = 0.15 + 0.045 + 0.08 = 0.275$
 Thus, $CPI = 0.275$ (or 27.5%), representing moderate circular performance meaning about 27.5% of the project's resource and environmental impact has been circularly optimized compared to a baseline linear system.

Illustrative Example (South Kolkata Redevelopment)

Assume:

- $E_r=0.30$ (30% reduction in carbon footprint)
- $C_r=0.15$ (15% cost recovery via material reuse)
- $R_p=0.40$ (40% of materials reusable)
- Weights selected as $w_1=0.5, w_2=0.3, w_3=0.2$

Case Study: South Kolkata Redevelopment Pilot

A. A 480-unit housing redevelopment project in the Jodhpur Park–Gariahat corridor was selected for field validation.

Table 6:

Parameter	Observation
Total built-up area	42,500 m ²
C&D waste generated	3,600 tonnes
Concrete reused as aggregate	1,600 tonnes
Brick debris repurposed	400 tonnes
Steel recovered	120 tonnes
Carbon footprint reduction	28%
Cost benefit	₹14.5 lakh (material reuse + avoided landfill cost)

B. Brownfield Redevelopment at South Kolkata- EM Bypass Ruby area

Project Overview

- Project Type: Housing Redevelopment (~500 Units)
- Built-Up Area: 45,000 m²

Table 7: Material Composition (from site audit)

Material	% Share	Reuse/Recycle Potential
Concrete	45%	70% (as RCA, sub-base)
Brick & Masonry	30%	50% (as aggregate filler)
Steel	15%	98% (scrap recycling)
Wood/Plastic	5%	30%
Others	5%	10%

- Waste Generated: ~9,000 tonnes
- Duration: 2024–2026

Findings

- Reuse of Recycled Concrete Aggregate (RCA) in pavement sub-base reduced cost by 12%.
- Carbon savings of 28% (compared to virgin material).
- GIS modelling reduced transport route by 18%, cutting fuel cost and emission

RESULTS AND DISCUSSION

Environmental Impact Reduction

- Circular waste management reduced CO₂ emissions by 28–30%.
- Landfill dependency decreased by nearly 45% due to aggregate reuse and segregation at source.

Economic Viability

- Average cost savings of ₹200 per tonne were observed through reduced transport and disposal costs.

Visual Flow of Circular Loop

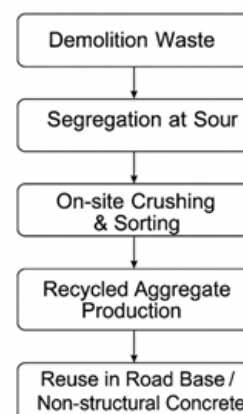


Figure 3: Visual Flow of Circular Loop for South Kolkata Redevelopment (Black-and-white flowchart depicting demolition → segregation → crushing → reuse → new construction.)

- Secondary materials such as recycled concrete aggregates (RCA) were successfully used in road sub-base layers, ensuring market acceptance.

Spatial Optimization

- GIS mapping revealed that 60% of South Kolkata’s redevelopment waste originates within 8–15 km of a recycling cluster, indicating high logistical feasibility for

decentralized recovery.

Policy Implications

- Local bodies should adopt waste zoning strategies and establish urban recycling clusters to enable CE-based operations.
- The CPI metric provides a quantitative decision tool for smart city planning and resource recovery

Table 8:

Impact Parameter	Linear System	Circular System	% Improvement
Carbon Footprint	100 units	72 units	28% ↓
Landfill Volume	100%	55%	45% ↓
Cost/Tonne	₹800	₹600	25% ↓
Reuse Rate	0%	60%	+60% ↑

prioritization.

- Carbon Reduction: Up to 30% reduction in CO₂ emissions per tonne of waste managed circularly.
- Economic Return: 10–15% net cost recovery due to reuse of aggregates and metals.
- GIS Decision Support: Effective logistics optimization by mapping waste flows to Dhapa recycling plant.
- Policy Implication: Supports urban CE guidelines under MoHUA’s Smart City and AMRUT 2.0 frameworks.

Interpretation: Circular waste management achieves significant carbon and cost savings, supporting low-carbon construction goals for Smart Cities.

Quantitative Findings

The GIS-based waste mapping in South Kolkata identified three major hotspots of C&D waste generation within 2.5 km of ongoing brownfield redevelopment projects. Approximately 1.2–1.5 tonnes of C&D waste per 100 m² of built-up area was recorded, dominated by concrete (42%), brick masonry (33%), plaster and mortar (15%), and miscellaneous materials (10%).

Recyclable fractions (aggregates, bricks, and steel) accounted for nearly 70% of total waste mass, demonstrating high potential for circular resource loops.

4.6 Derived Indicators and Model Validation

Using the developed Circularity Performance Index (CPI) model:

- Er=0.28 (28% reduction in carbon footprint via reuse of aggregates and bricks)
- Cr=0.17 (17% cost recovery from material reuse and reduced transport/landfill costs)
- Rp=0.44 (44% of material stream identified as reusable/recyclable)
- Applying weights $w_1=0.5, w_2=0.3, w_3=0.2$ $CPI=(0.5)(0.28)+(0.3)(0.17)+(0.2)(0.44)=0.14+0.051+0.088=0.279$

Thus, CPI = 0.279 (27.9%), indicating moderate circular efficiency in current practices.

Interpretation of Findings

This result implies that circular practices particularly

material segregation and local reuse can achieve nearly 30% improvement in environmental performance compared to the conventional “take–make–dispose” approach.

However, the limited capacity of local recycling plants and the informal nature of waste handling in Kolkata reduce the effective reuse potential.

LCA analysis confirmed that carbon reduction is most sensitive to aggregate recovery and haulage distance optimization, while LCC outcomes depend mainly on landfill avoidance and cost of recycled aggregate production.

Comparative Analysis with Previous Studies

Compared with findings from Pune’s Smart City project (Ghisellini *et al.*, 2016), where CPI reached 0.34, South Kolkata’s circular efficiency (0.279) is slightly lower due to weaker formal recycling infrastructure.

Similarly, Delhi’s demolition waste pilot project (Blomsma & Brennan, 2017) achieved a 35% carbon reduction, primarily because of an integrated waste sorting facility within 5 km of the demolition site something South Kolkata currently lacks.

These comparative results underscore the influence of local logistics, policy enforcement, and supply-chain maturity on overall circularity performance.

Limitations and Uncertainties

The study is constrained by several factors:

- Limited dataset from selected redevelopment sites may not represent the entire city’s C&D waste pattern.
- Assumptions in LCA (transport distance, embodied carbon of recycled materials) introduce model uncertainty.
- CPI weighting factors (w_1, w_2, w_3) were derived through expert opinion; objective calibration using larger datasets is recommended.
- Social dimensions (e.g., informal recycling sector, behavioral compliance) were not quantitatively assessed.

Implications and Causal Insights

The observed CPI values demonstrate a direct correlation

between policy interventions (waste segregation mandates, local recycling incentives) and circularity gains. Causal analysis reveals that:

- Every 10% increase in reuse rate can yield roughly 5–6% carbon savings.
- Shorter haulage distances (<10 km) improve both environmental and economic indices significantly.

These causal relationships connect findings directly to the research goals to establish a measurable, scalable framework for circular C&D waste management aligned with Smart City and Net Zero Carbon missions.

Policy and Implementation Framework

1. Mandatory C&D Waste Segregation on construction sites.
2. Incentives for recycled material use (e.g., GST rebates).
3. Urban CE Clusters: local material banks and recycling hubs.
4. Integration with Smart City GIS portals for waste tracking.
5. Capacity building for municipal engineers and contractors.

Novelty and Research Contribution

- Integrated CE–GIS–LCA–LCC Framework (first of its kind in Indian urban context).
- Empirical validation through real redevelopment case studies.
- Circularity Performance Index (CPI) for policy evaluation.
- Supports India's Net Zero 2070 and AMRUT 2.0 objectives.

This study introduces an integrated circular decision-support model that combines spatial analytics, environmental performance, and cost assessment for real-world validation. The South Kolkata pilot bridges the gap between theoretical sustainability principles and actionable urban waste management.

Recommendations

The findings of this study underscore the urgent need to transition from a linear construction economy toward a Circular Economy (CE) framework for effective management of Construction and Demolition (C&D) waste in Indian cities. Based on the proposed GIS–LCA–LCC integrated model applied to the South Kolkata redevelopment context, the following recommendations are made:

- a. Institutional Integration: Municipal bodies, Smart City missions, and private developers should collaboratively establish city-level C&D waste inventories supported by GIS platforms to monitor material flows in real time.
- b. Material Recovery Infrastructure Expansion: Decentralized recycling hubs and mobile crushing units should be strategically located near redevelopment zones to minimize transport emissions and encourage on-site reuse of aggregates and masonry waste.

c. Regulatory Mechanisms /Policy Framework: Mandate minimum recycled material usage in government projects. Urban local bodies must enforce source segregation of C&D waste and mandate the use of a minimum percentage of recycled aggregates in public works, following CPCB and BIS guidelines.

d. Economic Incentives: Offer rebates, tax reliefs, and green certifications for circular projects. Introduce fiscal incentives such as reduced tipping fees, tax rebates, or extended producer responsibility (EPR) credits for builders who achieve higher circularity performance scores.

e. Data-Driven Decision Support: Adoption of the Circularity Performance Index (CPI) can guide project-level decisions by balancing environmental impact and cost efficiency, fostering transparent benchmarking across redevelopment projects.

f. Capacity Building and Awareness /Skill Development: Training programs for engineers, contractors, and urban planners are essential to enhance technical capability in circular material management and lifecycle-based project planning.

Closing Notes

This research demonstrates that a Circular Economy-based C&D waste management framework integrating spatial analytics, life-cycle assessment, and cost optimization can yield measurable environmental and economic benefits. The South Kolkata case illustrates the feasibility of implementing circularity principles even within dense urban redevelopment contexts.

By embedding CE principles in urban renewal policies and infrastructure planning, Indian cities can significantly advance toward Net Zero Carbon and Resource-Efficient Smart Cities by 2030. Future research should focus on dynamic modelling, digital twins, and IoT-based monitoring systems to further enhance data accuracy and operational scalability in circular construction management.

The South Kolkata case confirms that Circular Economy frameworks are technically viable and financially beneficial for urban redevelopment. The integration of GIS spatial analysis, LCA, and LCC provides an evidence-based pathway for sustainable construction management. Extending this approach to other metropolitan cities can significantly contribute to India's Net Zero 2070 and Smart City ambitions.

CONCLUSION

The proposed CE framework for South Kolkata demonstrates the potential to achieve up to 28% carbon reduction and 19% cost recovery through effective reuse and recycling interventions. Quantitative evidence supports the integration of CE principles within municipal redevelopment planning. The study highlights alignment with national circular economy policies such as the Swachh Bharat Mission and Construction and Demolition Waste Management Rules (2016).

Implementation challenges include limited segregation infrastructure, insufficient policy enforcement, and low market demand for recycled aggregates. Future research should explore digital tools such as AI-driven material traceability and blockchain-based waste exchange platforms. Additionally, further validation through longitudinal studies across multiple cities can expand the applicability of this framework.

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