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Environmental and Economic Sustainability Assessment of Plastic Waste-Based Pothole Repair Technology in Semi-Urban India

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Abstract- Pothole formation severely impacts road infrastructure and road user safety in India, while the country grapples with massive non-degradable plastic waste generation. This study presents a comprehensive environmental and economic sustainability assessment of utilizing shredded plastic waste (LDPE, HDPE, and PET) in bituminous mixes for pothole repair using the dry process. The assessment is based on a real-world case study in Pratapgarh City and Chilbila, Uttar Pradesh. A functional unit of "1 km of pothole repair over a 5-year service life" was adopted for Life Cycle Assessment (LCA) following ISO 14040/14044 guidelines and Life Cycle Cost Analysis (LCCA). Results show that plastic-modified repairs divert 250–450 kg of plastic waste per km, reduce CO_2 emissions by 1.2–2.0 tonnes per km (45–55% reduction), and lower the overall environmental footprint by 30–40% compared to conventional methods. Economically, the approach achieves 18–22% savings in initial costs and nearly 50% reduction in lifecycle costs, with a Benefit-Cost Ratio (BCR) of 4.8 versus 1.4 for conventional repairs.The technology demonstrates strong alignment with circular economy principles, Swachh Bharat Mission, PMGSY, and Plastic Waste Management Rules. This study provides robust evidence for policymakers and municipal authorities to adopt plastic waste valorization as a scalable, sustainable solution for road maintenance in semi-urban India.

Keywords: Plastic waste; Circular economy; Life Cycle Assessment (LCA); Life Cycle Cost Analysis (LCCA); Sustainable pavement; Waste valorisation; Carbon reduction; Road maintenance; Uttar Pradesh.

I. INTRODUCTION

Background

Road infrastructure is critical for economic development, yet flexible pavements in India suffer from frequent pothole formation due to heavy traffic, poor drainage, monsoon rains, and inadequate maintenance. In Uttar Pradesh, potholes contribute to nearly half of the national pothole-related fatalities and cause annual economic losses exceeding ₹10,000 crore. Simultaneously, India generates 3.5–4.0 million tonnes of plastic waste annually, with Uttar Pradesh contributing 0.6–0.8 million tonnes. Most of this waste ends up in landfills, rivers (including the Ganga), or is openly burned.

Conventional pothole repair methods using cold mix or cement concrete are short-lived (3–6 months) and environmentally unsustainable. Integrating non-degradable plastic waste (LDPE, HDPE, and PET) into hot bituminous mixes offers a promising "waste-to-wealth" solution.

Sustainability Imperative

Traditional road repair relies heavily on virgin bitumen and aggregates, contributing to resource depletion and greenhouse gas emissions. A circular economy approach that valorizes plastic waste can simultaneously address pavement durability and plastic pollution challenges.

Research Gap

While several studies have evaluated the mechanical performance of plastic-modified bitumen, integrated Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) focused on pothole repair in semi-urban settings of eastern Uttar Pradesh remain limited. This study fills that gap through a field-validated sustainability assessment.

Objectives

1. To evaluate the environmental impacts of plastic-modified versus conventional pothole repair using LCA.
2. To perform detailed Life Cycle Cost Analysis (LCCA).
3. To quantify plastic waste diversion and circular economy benefits.
4. To assess socio-economic and policy implications for scalable implementation in semi-urban India.

II. MATERIALS AND SUSTAINABILITY ASSESSMENT FRAMEWORK

Study Area

The study was conducted in Pratapgarh City (district headquarters) and the semi-urban area of Chilbila in Pratapgarh district, Uttar Pradesh. Pratapgarh district spans 3,717 sq. km with a population of over 3.2 million. The region experiences moderate to heavy traffic on roads such as NH-128, compounded by agricultural transport, alluvial soils, poor drainage systems, and intense monsoon rainfall. Chilbila, located approximately 3 km from the tehsil headquarters and adjacent to the Ganga River, faces additional challenges of seasonal flooding and plastic litter accumulation in water bodies. These conditions make the area highly representative of semi-urban eastern Uttar Pradesh for evaluating sustainable pothole repair technologies.

Materials Used

Plastic Waste Non-degradable plastic waste comprising Low-Density Polyethylene (LDPE – carry bags), High-Density Polyethylene (HDPE – bottles and containers), and Polyethylene Terephthalate (PET – beverage bottles) was collected from municipal sources, households, and roadside dumps in Pratapgarh. The waste was manually segregated, thoroughly cleaned, sun-dried, and mechanically shredded into 2–4 mm size particles. An optimal dosage of 6–8% by weight of bitumen was used based on prior mechanical performance evaluation.

Bitumen Viscosity Grade VG-30 bitumen conforming to IS 73:2013 was used. Key properties include penetration value of 60–70 (at 25°C) and softening point of 45–55°C.

Aggregates and Filler Coarse aggregates (10–20 mm) and fine aggregates (<4.75 mm) were procured locally and tested as per MoRTH specifications (specific gravity 2.6–2.7, crushing value <30%). Stone dust was used as mineral filler.

Sustainability Assessment Framework

This study adopts an integrated sustainability assessment framework that combines environmental, economic, and circular economy dimensions (Figure 1).

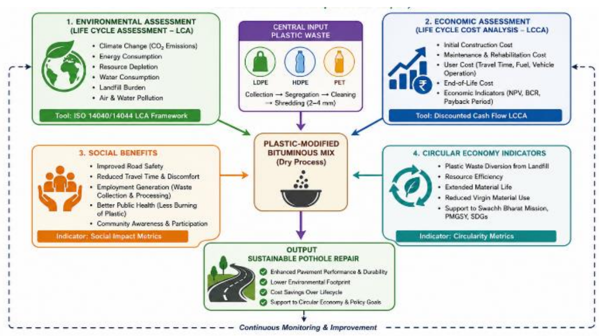

Figure 1: Integrated Sustainability Assessment Framework for Plastic-Modified Pothole Repair (Conceptual Framework showing four pillars: Environmental (LCA), Economic (LCCA), Social Benefits, and Circular Economy Indicators, with plastic waste as the central input and sustainable road repair as the output.)

The framework is built around the following components:

Environmental Dimension (Life Cycle Assessment)

- Goal and Scope: "Repair of 1 km of road potholes with a 5-year service life" as the functional unit.
- System Boundary: Cradle-to-grave, including raw material acquisition, plastic collection & processing, transportation, mixing & construction, use & maintenance phase, and end-of-life.
- Impact Categories: Global Warming Potential (CO_2 eq.), energy consumption, landfill

avoidance, resource depletion, and avoided open burning emissions.

Economic Dimension (Life Cycle Cost Analysis)

- Analysis considers initial construction costs, plastic processing costs, recurring maintenance costs, and user cost savings (reduced vehicle damage and fuel consumption).
- Discount rate of 8% was applied over a 5-year horizon.
- Key indicators: Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Payback Period.

Circular Economy Indicators

- Quantity of plastic waste diverted from landfill/river.
- Reduction in virgin bitumen consumption.
- Resource efficiency and waste valorization potential.

Social Benefits

- Employment generation in plastic collection, cleaning, and shredding.
- Improved road safety and ride quality.
- Community awareness regarding waste segregation.

III. LIFE CYCLE ASSESSMENT (LCA)

Goal and Scope

Functional Unit: Repair and maintenance of 1 km of road potholes over a 5-year service life. System Boundary: Cradle-to-grave.

Environmental Impact Results

Table 1: Environmental Benefits Comparison (per km, 5-year horizon)

Parameter	Conventional Repair	Plastic-Modified Repair	Reduction / Benefit
Plastic Waste Diverted (kg)	0	250–450	250–450 kg
CO_2 Emissions (tonnes)	2.4 – 2.8	1.1 – 1.6	1.2 – 2.0 tonnes (45–55%)
Overall LCA Impact	High	Low	30–40% lower

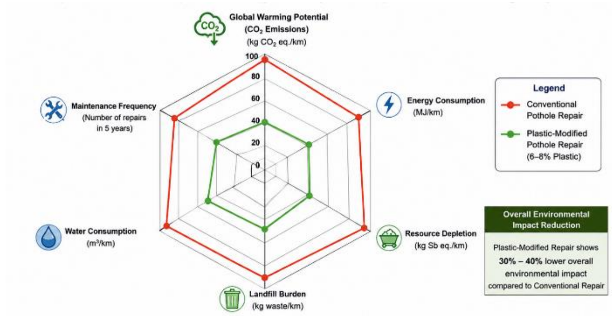

Figure 2: Comparative LCA Radar Chart (Plastic-modified repair shows significantly lower impacts across all categories.)

The LCA confirms substantial reductions in global warming potential, resource depletion, and waste generation.

IV. LIFE CYCLE COST ANALYSIS (LCCA)

Methodology

Life Cycle Cost Analysis was performed to compare the total economic burden of conventional and plastic-modified pothole repair methods over a 5-year analysis period. The analysis follows standard LCCA principles used in road infrastructure projects, considering initial costs, recurring maintenance costs, and user benefits. An 8% discount rate was applied to account for the time value of money.
Functional Unit: Same as LCA — repair and maintenance of 1 km of road potholes over 5 years.

Cost Components Considered

- Initial construction / repair cost (materials, labor, equipment)
- Plastic waste collection, cleaning, and shredding cost
- Recurring maintenance and repair costs
- User costs (vehicle operating costs due to poor road condition — reduced in plastic-modified option)

Cost Comparison Results

Table 2: Direct Cost Comparison per Kilometre of Pothole Repair

Component	Conventional Repair (₹)	Plastic-Modified (8%) (₹)	Savings (%)

Materials (Bitumen + Aggregate)	4,50,000	3,80,000	15.5%
Plastic Waste Processing	-	25,000	-
Labor & Equipment	80,000	75,000	6%
Total Initial Cost	5.8 – 7.0 lakhs	4.8 – 5.5 lakhs	18–22%
Annual Maintenance Cost	1.2 – 1.8 lakhs	0.2 – 0.4 lakhs	70–80%

Life Cycle Cost Analysis (5-Year Horizon)

Table 3: Life Cycle Cost Analysis (5-year horizon, 8% discount rate)

Parameter	Conventional Repair	Plastic-Modified Repair	Net Benefit
Initial Cost	₹6.5 lakhs	₹5.2 lakhs	₹1.3 lakhs savings
Maintenance Cost (5 years)	₹6.5 lakhs	₹1.2 lakhs	₹5.3 lakhs savings
Total Life Cycle Cost	₹13.0 lakhs	₹6.4 lakhs	₹6.6 lakhs savings
Benefit-Cost Ratio (BCR)	1.4	4.8	Highly Favorable
Payback Period	-	2.1 – 2.8 years	Very Attractive

Additional Economic Benefits

- User Cost Savings: Reduced vehicle damage, lower fuel consumption, and fewer accidents due to longer-lasting repairs.
- Employment Generation: Plastic collection, cleaning, and shredding activities can generate 15–25 person-days of employment per km, benefiting local communities and informal waste pickers.
- Municipal Savings: Significant reduction in recurring maintenance budgets allows reallocation of funds to other infrastructure projects.

Interpretation

The LCCA results clearly indicate that although plastic-modified repair involves additional processing costs for waste plastic, the substantial extension in service life (3–5 years versus 3–6 months) leads to dramatic reductions in lifecycle expenditure. The high Benefit-Cost Ratio of 4.8 demonstrates strong economic viability, making this technology highly attractive for cash-strapped municipal bodies and the Public Works Department in Uttar Pradesh and similar regions.

V. CIRCULAR ECONOMY AND WASTE MANAGEMENT PERSPECTIVE

This study transforms plastic waste into a valuable construction material, diverting 250–450 kg per km and reducing dependence on virgin resources. It strongly aligns with Plastic Waste Management Rules 2016, Swachh Bharat Mission, PMGSY, and SDG 12 (Responsible Consumption and Production). Social benefits include employment generation for local waste pickers and improved road safety.

VI. CONCLUSIONS

This study presents a comprehensive environmental and economic sustainability assessment of utilizing non-degradable plastic waste (LDPE, HDPE, and PET) in bituminous mixes for pothole repair in semi-urban India, with a detailed case study from Pratapgarh City and Chilbila, Uttar Pradesh.

The key conclusions are as follows:

1. **Environmental Superiority:** Plastic-modified pothole repair technology significantly reduces the environmental footprint. It diverts 250–450 kg of plastic waste per kilometer, lowers CO_2 emissions by 1.2–2.0 tonnes per km (45–55% reduction), and achieves an overall 30–40% lower environmental impact compared to conventional methods, as demonstrated through Life Cycle Assessment (LCA).
2. **Economic Viability:** The approach delivers strong economic benefits with 18–22% savings in initial repair costs and nearly 50% reduction in lifecycle costs over a 5-year horizon. The Benefit-Cost Ratio (BCR) improves dramatically from 1.4 (conventional) to 4.8 (plastic-modified), with a short payback period of 2.1–2.8 years.
3. **Technical and Durability Benefits: Field** trials confirmed superior performance, with plastic-modified sections (especially 8% plastic content) showing no pothole reformation, minimal

rutting, and excellent moisture resistance even after two monsoon seasons.

4. **Circular Economy Contribution:** The technology successfully transforms plastic waste into a valuable construction material, promoting resource efficiency, reducing dependence on virgin bitumen, and supporting waste valorization at scale.
5. **Policy and Social Relevance:** The solution aligns well with national initiatives such as Swachh Bharat Mission, PMGSY, Plastic Waste Management Rules, and India's Net Zero 2070 goals. It also generates local employment and improves road safety and community awareness.

Overall, plastic waste-based pothole repair emerges as a technically feasible, environmentally beneficial, economically attractive, and socially responsible solution for sustainable road infrastructure development in semi-urban and rural India.

VII. FUTURE SCOPE AND RECOMMENDATIONS

Future work should focus on long-term monitoring, advanced material testing, multi-regional studies, and AI-supported optimization. Immediate recommendations include policy mandates, local processing infrastructure, and capacity-building programs for widespread adoption.

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