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Research Article

Life Cycle Assessment of Open-cast Mining Equipment for Sustainable Mining Operations

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Abstract

Opencast mining is highly dependent on Heavy Earth Moving Machinery (HEMM), including hydraulic excavators, dump trucks, wheel loaders, dozers and drilling equipment. These machines consume substantial quantities of fuel and materials throughout their operating lives, making them an important contributor to the environmental footprint of mining. This study evaluates the environmental performance of opencast mining equipment using a cradle-to-grave Life Cycle Assessment (LCA) framework based on ISO 14040 and ISO 14044. A functional unit of one tonne of overburden/ore moved over the equipment's effective operating life was adopted. The assessment considered raw-material acquisition, equipment manufacturing, transportation, operational use, maintenance and end-of-life management. Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), water depletion and mineral resource depletion were considered. For a representative 240-tonne hydraulic excavator with a 15-year and 60,000-hour service life, the total cradle-to-grave GWP was estimated at 10,751 t CO_2-eq, with the operational phase contributing approximately 91.5% of gross GWP. Comparative assessment showed GWP reductions of 34.6%, 61.1% and 50.3% for trolley-assist, battery-electric and grey-hydrogen fuel-cell configurations, respectively, relative to the diesel-hydraulic baseline. However, electrification also introduced higher water and mineral-resource impacts. A representative Indian opencast coal-mine case study indicated that LCA-informed fleet management and progressive electrification could reduce fleet GHG emissions by approximately 44%. The study demonstrates that LCA can support sustainable equipment selection, fleet replacement, energy optimization and environmental decision-making in opencast mining.

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1. INTRODUCTION

Opencast mining is one of the most equipment-intensive industrial activities and relies extensively on HEMM for excavation, loading, hauling, drilling and my development. Hydraulic excavators, rope shovels, rigid dump trucks, wheel loaders, dozers and graders constitute the principal equipment fleet. Their high productivity is accompanied by considerable consumption of diesel fuel, steel, lubricants, hydraulic fluids, tyres and other materials. Consequently, the environmental performance of mining cannot be evaluated solely from land disturbance or operational emissions; the complete life cycle of mining equipment must also be considered.

Conventional environmental assessment of mining equipment generally emphasizes the use phase, particularly fuel consumption and exhaust emissions. However, equipment manufacturing, transportation, maintenance and end-of-life recycling also generate environmental burdens. Life Cycle Assessment provides a systematic approach for evaluating these impacts from raw-material extraction through final disposal or recycling.

The LCA framework defined by ISO 14040 consists of four major phases: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation. ISO 14044 provides detailed requirements relating to functional units, system boundaries, allocation, data quality and interpretation.

Previous studies have demonstrated the usefulness of LCA for mining systems. Awuah-Offei and Adekpedjou (2011) highlighted the importance of LCA in mining and identified fuel combustion in major mobile equipment as a significant contributor to environmental impacts. Norgate and Haque (2010) demonstrated the importance of energy consumption in mining and mineral-processing systems. Research on electric and trolley-assist mining equipment further indicates that electrification can reduce operational emissions while potentially increasing upstream impacts related to electricity generation and critical mineral production.

Despite these developments, equipment-specific LCA studies reflecting Indian opencast mining conditions remain limited. The present study therefore aims to evaluate the life-cycle environmental performance of representative opencast mining equipment and identify practical strategies for sustainable fleet management.

OBJECTIVES

The principal objectives are to:

1. Develop a cradle-to-grave LCA framework for opencast mining equipment.
2. Quantify environmental impacts of a representative 240-tonne hydraulic excavator.
3. Compare diesel, trolley-assist, battery-electric and hydrogen fuel-cell powertrains.
4. Identify major environmental hotspots and sensitive parameters.
5. Develop recommendations for sustainable mining equipment selection and fleet management.

2. RESEARCH METHODOLOGY

The study follows the four-phase LCA framework prescribed by ISO 14040 and ISO 14044. The system boundary covers six major stages: raw-material acquisition, component manufacturing, transportation, operational use, and maintenance and end-of-life management.

2.1 Goal and Scope

The goal is to quantify the cradle-to-grave environmental impacts of opencast mining equipment and use the findings to support equipment selection, fleet replacement and electrification decisions.

The primary equipment considered is a 240-tonne operating-class hydraulic excavator with a design life of 15 years and 60,000 operating hours. A 190-tonne payload rigid dump truck is also considered within the broader fleet analysis.

2.2 Functional Unit

The functional unit was defined as:

One tonne of overburden/ore excavated, loaded or hauled over the effective operating life of the equipment.

For the reference excavator, an average productivity of approximately 2,450 tonnes/hour was assumed, corresponding to approximately 147 million tonnes of material moved over 60,000 operating hours.

2.3 System Boundary and Inventory

The LCA includes:

- Raw-material extraction and processing;
- Steel, cast iron, aluminium, copper and polymer production;
- Equipment manufacturing and assembly;
- Transportation to the mine;
- Diesel/electric energy consumed during operation;
- Lubricants, hydraulic fluids and coolants;
- Replacement components and major overhauls;
- Dismantling and material recovery at end of life.

Background data were obtained from manufacturer specifications, industry benchmarks and published emission factors. The study primarily uses secondary data and representative Indian operating conditions.

2.4 Impact Assessment

Five principal environmental indicators were evaluated:

- Global Warming Potential (GWP100);
- Acidification Potential (AP);
- Eutrophication Potential (EP);
- Water depletion/scarcity;
- Mineral resource depletion.

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The assessment uses IPCC GWP factors together with ReCiPe 2016 and CML-IA characterisation factors.
The general calculation is:

$$\text{Impact}_k = \sum I\ (\text{Inventory}_i \times \text{Characterisation Factor}_{i,k})$$

Sensitivity analysis was undertaken for fuel consumption, equipment service life, recycled steel content, transportation distance, electricity-grid emission factor and maintenance frequency.

3. RESULTS AND DISCUSSION

3.1 Life-Cycle Environmental Performance

The LCA results demonstrate that the operational phase is the dominant environmental hotspot for diesel-powered mining equipment. For the representative 240-tonne excavator, the cradle-to-grave GWP was estimated at 10,751 t CO_2-eq over its 15-year service life. The operational phase contributed approximately 9,840 t CO_2-eq, representing 91.5% of gross GWP.

Table 1. Life-Cycle Impact Results for the 240-Tonne Hydraulic Excavator

Life-cycle stage	GWP (t CO_2-eq)	AP (kg SO_2-eq)	EP (kg PO_4-eq)	Water use (m^3)
Raw-material acquisition	186	1,840	128	620
Component manufacturing	412	2,210	196	1,840
Transportation	38	420	31	45
Use phase	9,840	6,290	897	2,680
Maintenance & repair	615	580	68	340
End-of-life	−340	−200	−8	30
Total	10,751	11,140	1,312	5,555

The dominance of the use phase is primarily attributable to continuous diesel combustion. This finding is consistent with previous mining LCA research indicating that diesel-powered mobile equipment represents a major source of mine-site greenhouse-gas emissions.
Manufacturing contributes considerably less to GWP than equipment operation, although it remains important for other environmental indicators. Steel and cast iron constitute a major proportion of equipment mass, making material production an important source of embodied environmental impacts.
The end-of-life stage produces a net GWP credit of approximately −340 t CO_2-eq because of the assumed recovery and recycling of steel, aluminium and copper.

3.2 Comparison of Alternative Powertrains

The study compares four powertrain configurations: diesel-hydraulic, trolley-assist hybrid, battery-electric and hydrogen fuel-cell.

Table 2. Comparative Life-Cycle GWP

Powertrain	Manufacturing GWP (t CO_2-eq)	Use-phase GWP (t CO_2-eq)	Total GWP (t CO_2-eq)	Reduction
Diesel-hydraulic	412	9,840	10,751	—
Trolley-assist	485	6,180	7,026	34.6%
Battery-electric	1,180	2,940	4,180	61.1%
Grey-hydrogen FCEV	560	4,890	5,340	50.3%

The battery-electric configuration provides the largest GWP reduction, approximately 61.1%, followed by hydrogen fuel-cell and trolley-assist systems. However, the BEV configuration has a substantially higher manufacturing impact because of battery production and associated material requirements.
The results demonstrate that electrification does not eliminate environmental impacts; rather, some impacts are shifted from the operational phase to equipment manufacturing and energy/material supply chains.

3.3 Multi-Indicator Trade-Offs

GWP alone is insufficient for evaluating sustainable mining equipment. The study indicates that the BEV configuration reduces GWP, acidification and eutrophication but increases water depletion and mineral-resource impact relative to the diesel baseline.

The normalised results show:

- GWP: 39% of diesel baseline;
- Acidification: 62%;
- Eutrophication: 71%;
- Water depletion: 145%;
- Mineral-resource depletion: 168%.

Thus, battery-electric equipment offers substantial climate benefits but can increase pressure on water and critical mineral resources.
This finding highlights the importance of multi-criteria LCA-based procurement rather than selecting equipment solely on the basis of tailpipe emissions or GWP.

3.4 Sensitivity Analysis

Fuel consumption is the most influential parameter in the LCA. A ±15% change in diesel consumption produces approximately ±13.5% change in total GWP. Equipment service life is the next major parameter, with approximately ±8.3% change in GWP for a ±3-year change in service life.

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These results have an important practical implication: reducing fuel consumption through operational optimisation can provide an immediate environmental benefit even before complete fleet electrification becomes feasible.

3.5 Fleet-Level Application

The representative Indian opencast coal-mine case study demonstrates that an LCA-informed intervention programme combining operational efficiency, fleet rejuvenation and progressive electrification can achieve approximately 44% reduction in fleet GHG emissions relative to the projected baseline. The reported composite abatement cost was approximately ₹1,280 per tonne CO_2-eq.

This demonstrates that LCA can function not merely as an environmental assessment technique but as a practical tool for mine planning, fleet management and capital-investment decisions.

4. Recommendations

Based on the LCA findings, the following measures are recommended for sustainable opencast mining operations.

4.1 Improve Operational Efficiency

Mine operators should implement Fleet Management Systems capable of monitoring real-time fuel consumption, payload, idle time, cycle time and equipment utilisation. The study identifies fuel consumption as the most sensitive environmental parameter.

4.2 Adopt LCA-Based Equipment Procurement

Environmental performance should become an explicit criterion in HEMM procurement. Equipment should be evaluated using life-cycle GWP, energy consumption, maintenance requirements, resource consumption and end-of-life recyclability rather than purchase price alone.

4.3 Promote Progressive Electrification

Trolley-assist systems should be considered for long, fixed haul routes where mine geometry and production capacity justify the required infrastructure. The study reports a 34.6% life-cycle GWP reduction for trolley-assist systems.

Battery-electric technologies should be introduced progressively as suitable large-capacity equipment and charging infrastructure become commercially viable.

4.4 Increase Recycled Material Content

OEMs should increase the use of recycled steel and aluminium in mining equipment. The study indicates that recycled-content assumptions have a significant influence on manufacturing-phase GWP.

4.5 Develop Environmental Product Declarations

Mining companies should require Environmental Product Declarations (EPDs) from equipment manufacturers to enable transparent comparison of alternative HEMM technologies.

4.6 Strengthen End-of-Life Recycling

Structured dismantling, recovery and recycling programmes should be developed for retired HEMM. Recovery of steel, aluminium and copper can reduce the overall life-cycle environmental burden.

4.7 Develop India-Specific LCA Databases

India-specific life-cycle inventory datasets should be developed for steel, diesel, electricity, mining equipment components, batteries and recycling processes. The present study identifies the lack of India-specific equipment-level LCI data as an important research gap.

5. CONCLUSION

This study demonstrates the value of Life Cycle Assessment as a decision-support framework for improving the environmental performance of opencast mining equipment. The cradle-to-grave assessment of a representative 240-tonne hydraulic excavator indicates a total life-cycle GWP of 10,751 t CO_2-eq, with approximately 91.5% of gross GWP originating from the operational diesel-use phase.

The comparative assessment shows that trolley-assist, battery-electric and grey-hydrogen powertrains can reduce life-cycle GWP by 34.6%, 61.1% and 50.3%, respectively. Nevertheless, electrification may increase water and mineral-resource impacts, demonstrating the need for multi-indicator assessment.

The findings suggest a practical sustainability pathway for Indian opencast mining: operational efficiency first, fleet rejuvenation second, and progressive electrification third. The case study further indicates that an LCA-informed strategy can potentially deliver approximately 44% fleet-level GHG reduction without requiring immediate full-fleet electrification.

Therefore, LCA should be integrated into mine planning, HEMM procurement, fleet replacement, ESG reporting and long-term decarbonisation strategies. Future research should focus on primary field data, India-specific LCI databases, battery recycling, renewable-energy integration and detailed LCA of complete mining fleets.

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