



# AI-Driven Life Cycle Assessment (LCA) Tool for Advancing Circularity and Sustainability in Metallurgy and Mining

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KEYWORDS	ABSTRACT
AI-driven LCA, Circularity, Sustainability, Metallurgy, Mining, Machine Learning, Environmental Impact, Carbon Footprint, Life Cycle Assessment	The metallurgical and mining sectors are pivotal to global infrastructure but are also among the largest contributors to environmental degradation. Traditional Life Cycle Assessment (LCA) methods are often manual, static, and retrospective, lacking the agility and precision required for real-time sustainability optimization. This paper presents an AI-Driven Life Cycle Assessment (LCA) Tool designed to automate and optimize sustainability assessments in metallurgy and mining. The tool calculates environmental impacts such as carbon footprint, energy consumption, and water usage, while also quantifying circularity through innovative metrics. Leveraging machine learning models, including Random Forest and Decision Tree algorithms, the system predicts emission factors and recommends optimal process routes. The platform integrates a self-learning loop, enhancing model accuracy over time. This paper outlines the methodology, system architecture, implementation, and performance metrics, demonstrating the tool's potential to significantly reduce industrial environmental footprints and support the transition to a circular economy.

## 1. INTRODUCTION

The metallurgical and mining industries are foundational to modern infrastructure, supplying essential materials such as aluminum, copper, and critical minerals. However, these sectors are also

significant contributors to global greenhouse gas emissions and environmental degradation. As the world shifts toward a green economy, the demand for sustainable practices in resource extraction and processing has intensified. Life Cycle Assessment (LCA)

has emerged as a critical methodology for evaluating the environmental impacts of products and processes across their life cycles.

Despite its importance, traditional LCA approaches are often manual, time-consuming, and lack integration with real-time operational data. These limitations hinder the ability of industries to make timely, data-driven decisions that could enhance sustainability and circularity. Moreover, existing tools are frequently cost-prohibitive, complex, and not tailored to the specific needs of the metallurgy and mining sectors. This project addresses these challenges by introducing an AI-driven LCA tool that automates environmental impact assessments and provides actionable insights for process optimization.

## 2. RELATED WORK

Conventional LCA tools such as GaBi and SimaPro are widely used in industry due to their extensive databases and compliance with international standards. However, these tools are often expensive, require specialized training, and lack predictive capabilities. Excel-based calculators offer a more accessible alternative but are prone to human error, lack scalability, and do not support real-time analytics.

Recent research has explored the application of machine learning in sustainability assessments. Mousavi et al. (2022) demonstrated the use of Random Forest and Neural Networks to estimate environmental impacts in industrial ecology. These approaches offer the potential to fill data gaps and improve the accuracy of LCA predictions. Additionally, the Ellen MacArthur Foundation's Material Circularity Indicator (MCI) provides a standardized framework for assessing circularity, which this project adapts into a simplified scoring model to evaluate recycled content and reuse efficiency.

## 3. PROPOSED WORK

The proposed AI-Driven LCA Tool integrates environmental impact assessment and circularity scoring into a single, web-based platform. The system is developed using FastAPI for the backend, MySQL/SQLite for data storage, and a responsive frontend built with HTML5, CSS3, and JavaScript. It supports multiple user roles, including Sustainability

Managers, Process Engineers, and Administrators, each with tailored dashboards and functionalities.

The core of the system is a hybrid machine learning engine that employs Random Forest and Decision Tree algorithms to predict emission factors and energy intensity based on user-provided inputs. The tool also features a feedback loop where validated user assessments are incorporated into the training dataset, enabling continuous improvement of the model's predictive accuracy. This approach ensures that the system evolves over time, adapting to new data and refining its recommendations for optimal process routes and sustainability strategies.

### System Architecture

The system is designed using a three-tier architecture comprising the presentation, application, and data layers. The presentation layer includes a responsive web interface developed with HTML5, CSS3, and JavaScript, providing interactive dashboards for different user roles. Users can input data, visualize results, and download reports through an intuitive interface.

The application layer is powered by FastAPI, a high-performance Python web framework that handles business logic, API routing, authentication, and machine learning inference. It uses SQLAlchemy ORM for seamless interaction with the database and integrates serialized machine learning models using Joblib for efficient prediction.

The data layer utilizes MySQL for production environments and SQLite for local development. The database schema is normalized to the third normal form (3NF) to ensure data integrity and efficient querying. It stores user credentials, input records, LCA results, and training data. The system workflow involves user data submission, backend validation, ML-based prediction of missing parameters, LCA metric computation, and result visualization on the frontend.

### System Workflow:

The system flow of the AI-Driven Life Cycle Assessment (LCA) Tool begins with users submitting input data, including material type, energy usage, and emission parameters, through a web-based interface. This data undergoes validation and preprocessing to ensure accuracy and completeness. Once validated, the information is passed to a machine learning engine that employs Random Forest or Decision Tree algorithms to

predict any missing emission factors or energy intensities. If the prediction is successful, the system proceeds to calculate comprehensive LCA metrics such as carbon footprint, energy consumption, and water usage, along with a circularity score based on recycled content and process efficiency. The computed results are then stored in a structured database for future reference and model training. Finally, the results are visualized on an interactive dashboard, enabling users to analyze environmental impacts and compare different production scenarios in real time.

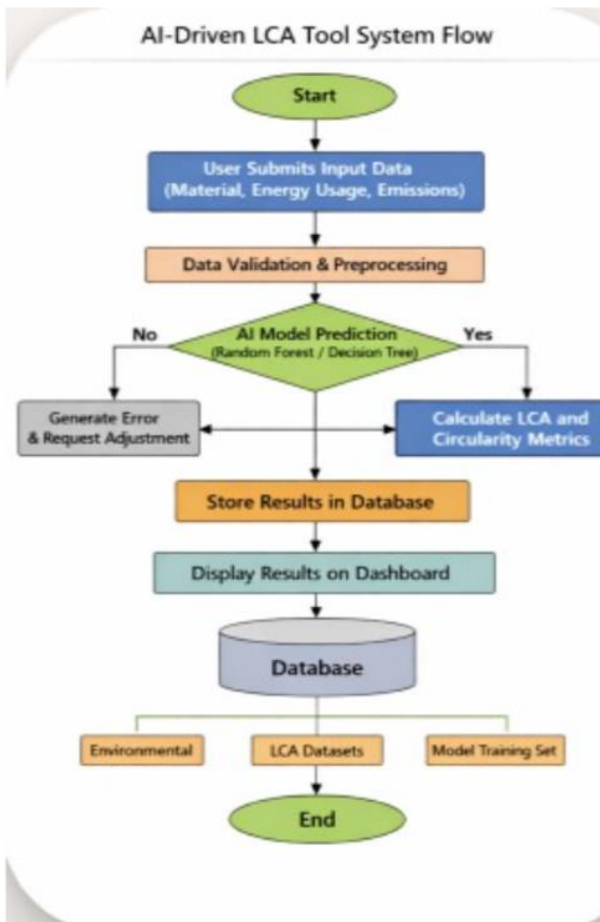


Fig.1. System Architecture

#### 4. RESULTS

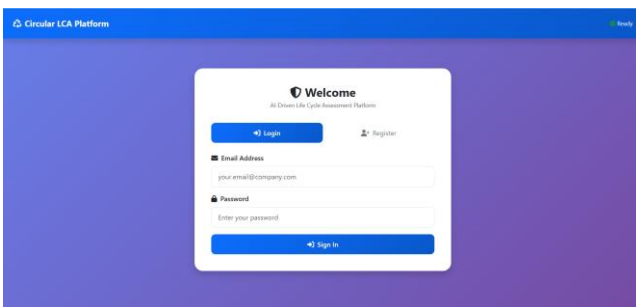


Fig.1.Login/Registration Page

The Login/Registration interface serves as the secure entry point to the AI-Driven LCA Tool. It implements role-based authentication, ensuring that users such as Sustainability Managers, Process Engineers, and Administrators access only the functionalities relevant to their roles. The system employs encrypted password storage and session management to maintain data privacy and prevent unauthorized access. This interface supports both new user registration and returning user login, streamlining access control and enhancing the overall security posture of the platform.

Material Type: Aluminium

Production Route: PRIMARY PRODUCTION – Primary Production for Aluminium

Energy Use (kWh/tonne): Optional - AI will predict  
Leave empty for AI prediction

Energy Source: Select energy source

Distance (km): [Input field]

Transport Mode: Select

End-of-Life Strategy:  Landfill  Recycling  Reuse  Closed Loop

Recycled Content (0.0 - 1.0): Optional

Fig.2. Process Configuration

The Process Configuration screen enables users to define the parameters of their life cycle assessment by selecting materials, process routes, and energy sources. This modular interface allows for the customization of production scenarios, including the specification of transport distances, energy types (e.g., coal, hydro, solar), and recycled content. The configuration data serves as the foundational input for the machine learning engine, which uses it to predict emission factors and calculate environmental impacts. This feature empowers users to simulate various production strategies and assess their sustainability outcomes in real time.

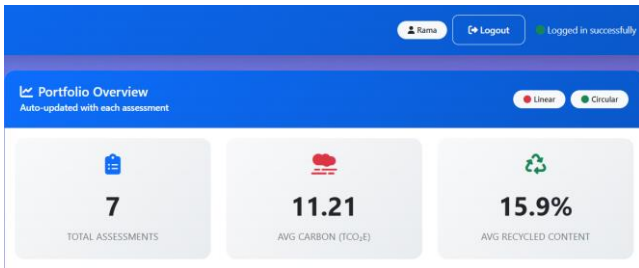


Fig.3. Portfolio Overview

The Portfolio Overview dashboard provides users with a consolidated view of all submitted assessments and their corresponding sustainability metrics. It displays key indicators such as average carbon footprint, energy consumption, water usage, and circularity scores across multiple projects or departments. This high-level summary facilitates organizational benchmarking, trend analysis, and strategic planning. By offering a centralized repository of assessments, the portfolio view enhances transparency and supports data-driven decision-making at the enterprise level.

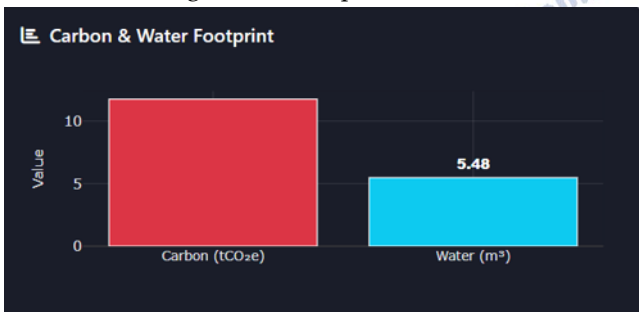


Fig.4. Carbon & Water Footprint

The Carbon & Water Footprint visualization module presents detailed insights into the environmental impact of selected production processes. It graphically represents the total carbon dioxide equivalent (CO<sub>2</sub>e) emissions and water usage in liters, enabling users to identify high-impact areas. The interface supports comparative analysis across different materials, energy sources, and process routes, helping stakeholders prioritize interventions that yield the greatest environmental benefits.

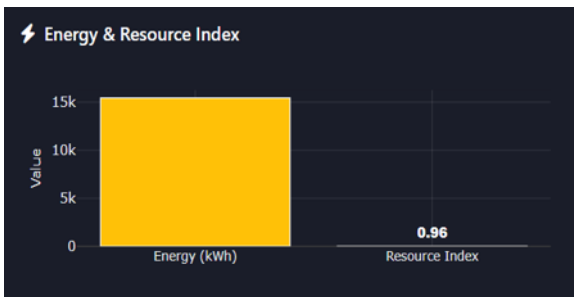


Fig.5. Energy & Resource Index

The Energy & Resource Index screen tracks the total energy consumption (in megajoules) and resource utilization for each assessment. It provides a breakdown of energy sources and material inputs, allowing users to evaluate the efficiency of their production systems. This module supports the identification of energy-intensive stages and promotes the adoption of more sustainable alternatives. Interactive charts and indices offer a clear understanding of resource dependencies and potential areas for optimization.



Fig.6. carbon Trend

The Carbon Trend visualization displays historical carbon footprint data across multiple assessments or time periods. By plotting emissions over time, this module enables users to detect patterns, seasonal variations, and the effectiveness of implemented sustainability measures. The trend analysis supports continuous improvement by highlighting progress toward emission reduction goals and identifying areas requiring further attention.

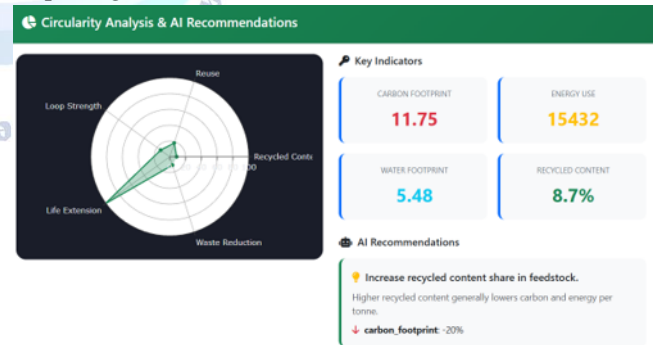


Fig 7. Circularity Analysis & AI recommendations

The Circularity Analysis & AI Recommendations module evaluates the proportion of recycled content, reuse efficiency, and closed-loop potential of each process. It calculates a Circularity Score based on the Material Circularity Indicator (MCI) framework and provides AI-generated suggestions for improving sustainability. These recommendations may include switching to alternative energy sources, increasing recycled input, or optimizing transport logistics. This

module empowers users to make informed decisions that align with circular economy principles.



Fig.8. Scenario Comparison & Flow Analysis

The Scenario Comparison & Flow Analysis interface allows users to compare linear and circular production pathways side by side. It employs visual tools such as Sankey diagrams and bar charts to illustrate material flows, energy consumption, and environmental impacts. Users can assess trade-offs between different scenarios, such as using virgin versus recycled materials, and quantify potential savings in carbon emissions and resource use. This feature supports strategic planning and stakeholder communication by making complex sustainability data accessible and actionable.

## 5. QUANTATIVE SUMMARY

Pilot implementation of the AI-Driven LCA Tool demonstrated significant operational improvements. Manual calculation time was reduced by over 60%, and report generation became approximately 70% faster compared to traditional methods. Data accuracy improved by around 30%, resulting in fewer discrepancies and more reliable sustainability metrics. User feedback collected through surveys indicated a satisfaction rate exceeding 85%, with users highlighting the tool's ease of use, real-time insights, and comprehensive reporting capabilities. The system enabled organizations to track environmental impacts dynamically and compare different production scenarios, supporting more informed and sustainable decision-making.

## 6. CONCLUSION AND FUTURE SCOPE

The AI-Driven LCA Tool represents a transformative advancement in environmental assessment for the metallurgy and mining sectors. By integrating artificial

intelligence with domain-specific knowledge, the tool enables real-time, accurate, and actionable sustainability insights. It addresses the limitations of traditional LCA methods and provides a scalable, cost-effective solution for organizations seeking to enhance their environmental performance.

Future enhancements to the system may include the integration of deep learning models such as Long Short-Term Memory (LSTM) networks for time-series forecasting of emission trends. Additionally, incorporating real-time data acquisition through IoT and SCADA systems could further improve the accuracy and responsiveness of the tool. Blockchain technology may also be employed to create digital product passports, ensuring traceability and transparency in material sourcing and lifecycle management.

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## Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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