A Case Study of Life Cycle Eco-Assessment of Recycled Asphalt Materials in Iraq Using OpenLCA and SimaPro

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Received: 29 July 2025 | Revised: 23 August 2025 and 7 September 2025 | Accepted: 9 September 2025

 DOI: https://doi.org/10.48084/etasr.13720

ABSTRACT

This study examines the environmental performance of asphalt pavement mixtures that incorporate recycled materials in Iraq, using Life Cycle Assessment (LCA) methods. Three pavement scenarios were evaluated: a baseline mix with 0% recycled content (S1), and two alternatives with 30% Recycled Asphalt Material (RAP) (S2) and 30% RAP plus 10% Crumb Rubber (CR) (S3) recycled content. The analysis used two well-known LCA tools, OpenLCA and SimaPro, to evaluate key impact categories: Global Warming Potential (GWP), Fossil Resource Scarcity, Human Toxicity Potential, Freshwater Eutrophication, and Acidification Potential. The results show that increasing the recycled content significantly reduces the environmental impacts across all categories. Scenario S3 had the lowest GWP, human toxicity, and acidification levels, demonstrating that recycled materials can reduce the carbon emissions. Adding CR resulted in reduced material demand, enhanced pavement durability, and lowered future maintenance and environmental impacts. Both OpenLCA and SimaPro showed similar trends, with OpenLCA proposed for future use because of its greater accessibility and cost-effectiveness. Overall, this research highlights the importance of using recycled materials in road construction to support sustainable development, especially in developing regions. It also stresses the need for region-specific Life Cycle Inventory (LCI) data to improve the model accuracy and guide environmentally responsible decisions in pavement engineering.

Keywords-recycled pavement materials; life cycle assessment; OpenLCA; SimaPro; sustainable construction

I. INTRODUCTION

Iraq's transportation infrastructure faces pressure from the rising traffic demands, deteriorating the pavement conditions, and scarce maintenance resources. Road rehabilitation is required, especially in areas impacted by conflict or harsh environmental factors, like extreme heat and sandstorms. Simultaneously, the nation aims to adopt more sustainable and economical construction techniques to reduce the environmental damage and dependence on new resources [1, 2].

One effective approach is to use recycled pavement materials, like Reclaimed Asphalt Pavement (RAP) and CR derived from waste tires. These materials can replace up to 30–40% of virgin aggregates and binders without affecting performance, while diverting the solid waste from landfills and enhancing the elasticity and rutting resistance of the asphalt mixtures [3-7]. By utilizing RAP and CR, the raw material extraction, greenhouse gas emissions, and long-term maintenance needs can be decreased, making them ideal for sustainable road construction in regions such as Iraq.

LCA has become an effective approach for evaluating the environmental impacts associated with pavement materials and construction methods. By taking into account the full life cycle of a product or system, from raw material extraction to disposal, LCA proves particularly beneficial for comparing the sustainability of both recycled and virgin pavement mixtures [8, 9].

Among the many available LCA software tools, OpenLCA and SimaPro stand out as two of the most recognized platforms. OpenLCA is an open-source, adaptable tool extensively used in academic and policy environments [10, 11], whereas SimaPro is a commercial software praised for its comprehensive database access and detailed modeling functions [12]. Although they aim to achieve similar outcomes, their differences in methodology, databases, and user interfaces can result in varying results.

In this study a comparative environmental assessment of the recycled pavement materials in Iraq using OpenLCA and SimaPro was conducted. A practical case study was carried out on a segment of Expressway No. 1 (Section R9), which connects western Baghdad to the city of Hit. A mixture that included RAP and CR was compared with a conventional virgin asphalt mixture. The objective of this study was to comprehend the benefits and drawbacks of each software tool in promoting sustainable pavement practices in Iraq. Additionally, this study fills a gap in localized LCA research in Iraq, considering the unique environmental, economic, and infrastructural contexts of the country.

II. LITERATURE REVIEW

A. Recycled Materials in Pavement Construction

The use of recycled materials, including RAP and CR, in asphalt mixtures has received worldwide attention for its environmental and economic advantages. RAP is created by milling old asphalt layers, facilitating the reuse of aged bitumen and aggregates. CR, derived from discarded tires, boosts the performance of asphalt mixtures by enhancing the elasticity and resistance to deformation [4, 13-16].

In Iraq, the use of RAP and CR in pavement construction remains restricted, despite pilot studies indicating their potential advantages. For example, incorporating up to 30% RAP in surface courses can sustain performance while lowering the material expenses [1]. Authors in [3] highlighted the necessity for greater use of recycled materials to enhance the benvironmental objectives and infrastructure resilience.

B. LCA in Pavement Engineering

LCA offers a structured method for measuring the environmental effects of the construction materials and processes throughout their entire lifespan. It allows for the comparison of various pavement designs by taking into account stages, like material extraction, transportation, construction, maintenance, and end-of-life treatment [8, 17].

Numerous studies have utilized LCA to analyze the sustainability of incorporating RAP and CR into the road construction. For instance, authors in [18] conducted an LCA on RAP for highway rehabilitation and discovered decreases in the energy use and greenhouse gas emissions compared with conventional mixtures. Similarly, in [7], rubber-modified asphalt was evaluated, noting a higher mixing energy but overall environmental benefits from the longer service life and reduced maintenance requirements.

Even with these developments, there are very few localized LCA studies in Iraq. The majority of evaluations depend on default data from international databases, which might not truly represent Iraqi circumstances, like fuel types, transport logistics, or material sourcing.

C. Comparison of LCA Software: OpenLCA versus SimaPro

OpenLCA and SimaPro are popular LCA software platforms, each offering distinct features. OpenLCA is open-source, providing complete transparency and customization, which makes it ideal for academic and governmental applications in developing countries [11]. It supports various databases, including Ecoinvent, Agribalyse, and the Social Hotspots Database. In contrast, SimaPro is a commercial platform recognized for its intuitive interface, sophisticated simulation capabilities, and extensive databases, like Ecoinvent, USLCI, and ELCD. It is widely utilized in both industry and policymaking for product-level assessments [12].

Although both tools adhere to the ISO 14040/44 standards, variations in the impact assessment methods, baseline assumptions, and database content may cause differences in the final outcomes. Previous studies have shown that the results produced by the two software tools can vary by as much as 15–30% based on the life cycle stage and the impact category being examined [19].

D. Research Gap

In Iraq's transportation sector, a significant gap exists in region-specific LCA applications, especially regarding recycled pavement materials. Additionally, research comparing the results of OpenLCA and SimaPro within identical contexts and data constraints is limited. This study aims to address this gap by utilizing both tools in a real-world Iraqi case study, investigating how methodological decisions and software platforms shape the sustainability findings.

III. METHODOLOGY

This study employed a comparative LCA approach using two prominent software tools, OpenLCA and SimaPro, to assess the environmental impacts of recycled asphalt mixtures in an actual highway rehabilitation project in Iraq. The objective was to investigate how varying LCA platforms affect

the environmental impact outcomes while maintaining consistent system boundaries and data assumptions. The LCA models considered Iraq's local energy mix, material sourcing, and transport logistics. While regional data were used, additional localized data could improve the accuracy of the results.

A. Research Framework

This study followed the ISO 14040 and ISO 14044 guidelines for LCA, which included the following four phases:

1. Goal and scope definition
2. LCI analysis
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation

Both OpenLCA and SimaPro were used to carry out the full LCA cycle based on the same data inputs to ensure consistency and comparability. Figure 1 illustrates the research framework stages of the methodology, including LCA using the proposed techniques and the related assumptions and outputs.

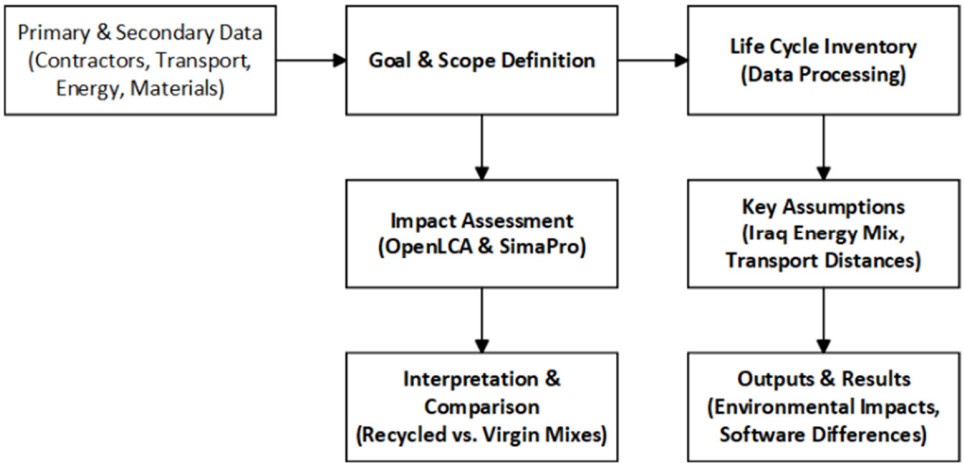

Fig. 1. Research framework.

B. Case Study Location

This case study focuses on Section R9 of Expressway No. 1, which spans 123.5 km from western Baghdad to Hit in Iraq. This section is undergoing rehabilitation owing to significant structural deterioration and heavy traffic. To assess the sustainability outcomes, recycled materials, namely 30% RAP and 10% CR, were proposed for the surface layer in comparison to a control (virgin) asphalt mixture.

C. Functional Unit

The functional unit was specified as 1 km of rehabilitated asphalt pavement with a thickness of 5 cm, designed to last 20 years. This definition allows for effective comparisons among various materials and LCA platforms.

D. System Boundary

A cradle-to-grave system boundary was adopted, encompassing:

- Extraction of raw materials (virgin aggregates, bitumen, RAP, and CR)
- Material production and transportation to the construction site
- Asphalt mixing and plant emissions
- Transportation of the mix to the project site
- Pavement laying and compaction
- Maintenance over the 20-year life cycle
- End-of-life milling and reuse/recycling

E. Data Collection and Assumptions

Primary data were collected directly from local contractors in Baghdad, encompassing crucial details, such as mix design quantities, fuel consumption, and transportation distances, pertinent to construction activities. Additionally, secondary data were sourced from reliable LCI databases. Specifically, Ecoinvent v3.8 and AGRIBALYSE were employed in OpenLCA software, whereas Ecoinvent v3.8 and the USLCI were used in SimaPro.

To ensure consistency in the analysis, the ReCiPe 2016 (Midpoint) impact assessment method was uniformly applied across both LCA tools. Standardized transport distances were set for material deliveries: the aggregates were transported 50 km, bitumen 100 km, CR 80 km, and RAP was assumed to be milled and reused on-site, reflecting an effective transport distance of 20 km. Furthermore, the estimated energy consumption for the asphalt plant was 300 MJ per ton of asphalt produced, based on local average data.

Primary data were gathered from local contractors in Baghdad using structured surveys and direct measurements. To ensure the data's representativeness and reliability, the present study cross-checked for consistency and used averages to minimize the variations, especially in transportation distances and energy consumption. Challenges, like incomplete reporting

and varied contractor practices, were assessed through verification and data validation procedures.

F. Scenarios Compared

This study evaluated three different pavement mixture scenarios. Scenario 1 (S1) is a traditional virgin asphalt mixture, which does not include RAP or CR. Scenario 2 (S2) features an asphalt mixture containing 30% RAP, showcasing a more sustainable option using recycled materials. Scenario 3 (S3) takes sustainability a step further by blending 30% RAP with 10% CR, creating a rubberized asphalt mix. Each scenario was modeled separately with the OpenLCA and SimaPro software tools to guarantee a thorough and comparative life cycle assessment.

G. Impact Categories

The midpoint impact categories analyzed in this study were based on ReCiPe 2016:

- GWP (kg CO_2-eq)
- Human Toxicity Potential (HTP) (kg 1,4-DCB-eq)
- Freshwater eutrophication (kg P-eq)
- Terrestrial acidification (kg SO_2-eq)
- Fossil Resource Scarcity (FRS) (kg oil-eq)

IV. CASE STUDY RESULTS AND DISCUSSION

This section provides the comparative results of the LCA for three asphalt mix scenarios modeled in OpenLCA and SimaPro. The scenarios comprise S1, S2, and S3. The functional unit is defined as 1 km of rehabilitated asphalt pavement, 5 cm thick, with a service life of 20 years.

A. Global Warming Potential

The GWP was evaluated to gauge the carbon footprint linked to each pavement mix scenario. As anticipated, Scenario 1 (0% recycled material) had the highest GWP, primarily due to its heavy reliance on virgin materials and energy for production. In contrast, the inclusion of recycled materials significantly lowered emissions, with S2 (30% RAP) and S3 (30% RAP and 10% CR) displaying progressively lower GWP. This pattern underscores the environmental advantages of reusing materials in pavement applications, particularly in mitigating the greenhouse gas emissions. The comparative findings from OpenLCA and SimaPro are presented in Figure 2.

Both tools confirmed that introducing RAP and CR substantially reduced the greenhouse gas emissions. S3 achieved a ~25% reduction compared to the virgin mix (S1). Slight differences (2–5%) between the software were mainly due to variations in database-specific emission factors for the basphalt production and transport processes.

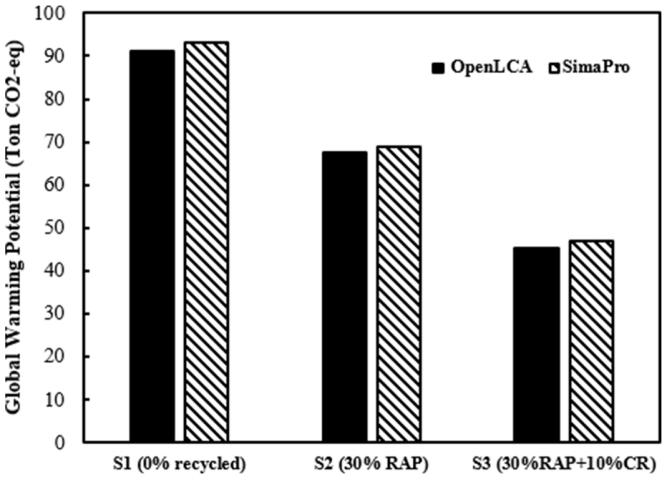

Fig. 2. GWP results for the 3 pavement scenarios using OpenLCA and SimaPro.

B. Fossil Resource Scarcity

The analysis of FRS assessed the depletion of non-renewable energy sources linked to each pavement scenario. In S1, which utilized 0% recycled materials, there was a maximal dependence on fossil resources, highlighting the energy-demanding processes involved in the extraction and processing of virgin materials. Conversely, as the use of recycled content increased in S2 and S3, there was a notable decrease in FRS values, showcasing an enhanced resource efficiency. This decline underscores the capability of recycled materials to reduce the reliance on limited fossil fuels. The FRS results from both OpenLCA and SimaPro are shown in Figure 3.

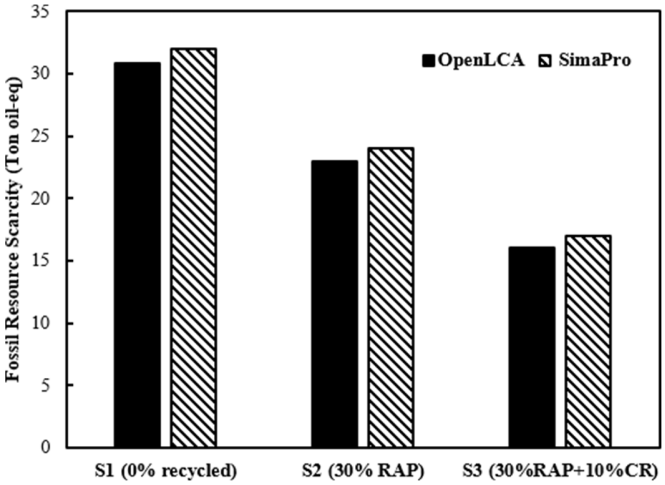

Fig. 3. FRS for the 3 pavement scenarios using OpenLCA and SimaPro.

The fossil fuel consumption decreased significantly in the recycled mixes. This benefit comes from the reduced virgin bitumen and aggregate production. SimaPro tended to report slightly lower impacts due to updated datasets for bitumen extraction.

C. Human Toxicity Potential

HTP was assessed to estimate the potential harm to the human health caused by toxic emissions throughout the pavement life cycle. S1 (0% recycled materials) recorded the highest HTP values in both OpenLCA and SimaPro analyses, primarily due to the extensive use of virgin materials and associated industrial processes. As the recycled content increased in S2 and S3, the HTP values decreased notably, indicating a reduced release of harmful substances, such as heavy metals and volatile organic compounds. This decline reflects the environmental and health advantages of incorporating recycled materials, which help limit the exposure to the toxic emissions across the pavement supply chain. The comparative results from both software platforms are displayed in Figure 4.

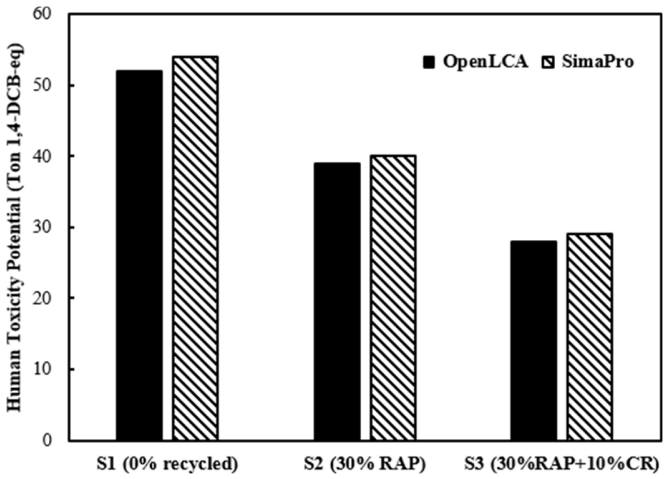

Fig. 4. HTP results for pavement scenarios using OpenLCA and SimaPro.

Both tools showed that using RAP and CR reduced the human toxicity impacts, particularly due to the fewer emissions from bitumen processing and reduced transportation requirements.

D. Freshwater Eutrophication and Acidification

This study expanded the environmental assessment by exploring the freshwater eutrophication and acidification potential for the three pavement scenarios. Freshwater eutrophication indicates a nutrient overload in water bodies, mainly due to phosphorus emissions, which can trigger algal blooms and disrupt ecosystems. Acidification potential assesses the emissions that lead to soil and water acidity, primarily from substances, like sulfur dioxide and nitrogen oxides. In the baseline scenario (S1), both impact categories recorded their highest values due to the extensive use of virgin materials and related industrial processes. However, with the increased recycled content in S2 and S3, significant reductions were observed in both eutrophication and acidification values. These results highlight the environmental benefits of using recycled pavement materials beyond their climate impact. The detailed results from OpenLCA and SimaPro are illustrated in Figures 5 and 6, respectively.

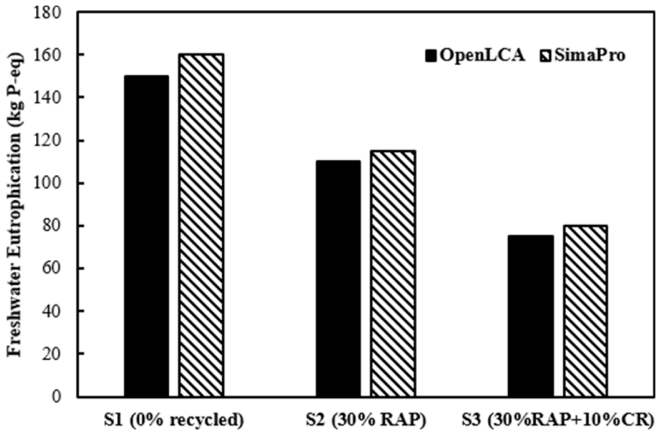

Fig. 5. Freshwater eutrophication results for pavement scenarios using OpenLCA and SimaPro.

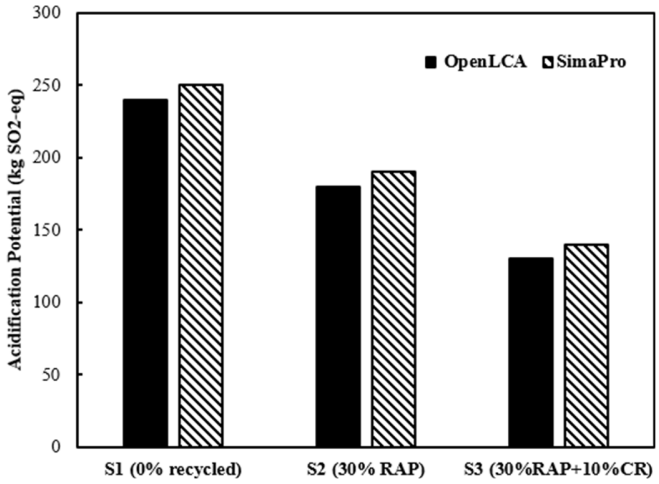

Fig. 6. Acidification potential results for the 3 pavement scenarios using OpenLCA and SimaPro.

The reductions in the freshwater eutrophication and acidification potential observed in S2 and S3 confirmed that increasing the use of recycled content in pavement mixtures contributes to lowering both the water and air pollution potentials. This is primarily attributed to the decreased reliance on virgin materials, which are typically associated with nutrient and acidifying emissions during extraction and processing. The inclusion of CR further enhanced the environmental performance, as its use not only reduces the input volume of the new raw materials, but also improves the mechanical durability of the pavement. This added durability can delay the deterioration and reduce the frequency of the maintenance interventions, leading to long-term environmental savings. These combined effects underscore the role of the recycled materials in promoting sustainable pavement systems.

Uncertainties related to input datasets and key assumptions, such as transportation distances, energy consumption, and local material sourcing, impact the results. Despite consistent overall trends, variations in these parameters can influence the magnitude of impacts. Sensitivity discussions show that small changes in inputs, like ±10% in energy use, may shift the results, but do not alter the comparative conclusions between

the recycled and virgin mixtures or between the OpenLCA and SimaPro outputs.

V. CONCLUSIONS

This study shows that incorporating recycled materials, such as Reclaimed Asphalt Pavement (RAP) and Crumb Rubber (CR), into asphalt mixtures can greatly lessen the environmental impact of pavement rehabilitation in Iraq. Using two established Life Cycle Assessment (LCA) tools, OpenLCA and SimaPro, the research compared the environmental effects and found that both tools produced consistent results, with only small numerical variations.

The results show that asphalt mixtures with 30% RAP combined with 10% CR have significantly lower environmental impact metrics, like Global Warming Potential (GWP), fossil resource scarcity, human toxicity, and freshwater eutrophication and acidification compared to virgin asphalt. Adding CR not only decreased the need for new materials, but also enhanced the pavement durability, reducing the maintenance needs and environmental effects. Although OpenLCA and SimaPro provided slightly different absolute values, both consistently identified the recycled mixes as more sustainable, confirming the reliability of the findings.

This research is unique in focusing on a region-specific case study for Iraq, an area where little work has been done on applying Life Cycle Assessment (LCA) in pavement engineering. While previous international studies have indicated that RAP and CR can lower the emissions and improve the mixture performance, this study builds on that by including local energy sources, transportation distances, and material sourcing. This approach makes the findings directly applicable to Iraq, emphasizing the need for localized Life Cycle Inventory (LCI) data to achieve more accurate and relevant sustainability evaluations.

This research offers important evidence, according to which, using recycled materials in pavement rehabilitation aligns with international findings and offers region-specific insights for Iraq. It shows that sustainable road construction can be successfully implemented in developing countries with the help of reliable LCA tools and localized data. These findings lay the groundwork for future studies that integrate environmental, economic, and social factors, enabling decision-makers to pursue holistic approaches to sustainable infrastructure development.

ACKNOWLEDGMENT

The authors acknowledge Mustansiriyah University through the Highway and Transportation Engineering Department for their continuous support in enhancing this research

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