Comparative Life Cycle Assessment of Pavements Using Recycled Aggregates vs. Virgin Aggregates: A Machine Learning Approach

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Abstract: Construction industry significantly contributes to global environmental challenges due to high resource consumption and waste generation. Pavement construction, reliant on virgin aggregates (VA), exacerbates this issue through resource depletion, carbon emissions, and habitat disruption. Recycled aggregates (RA), derived from construction and demolition waste, present a sustainable alternative that reduces environmental impacts while promoting circular economy practices. This study conducts a cradle-to-grave Life Cycle Assessment (LCA) to compare the environmental impacts of pavements constructed using RA and VA, integrated with machine learning (ML) for predictive modelling and optimisation. Data from reliable sources, including FORWAST, Ecoinvent, and ELCD databases, support this analysis across stages such as raw material extraction, transportation, construction, usage, and end-of-lifemanagement. The results reveal that RA pavements achieve a 35% reduction in Global Warming Potential (GWP) and 50% lower waste generation compared to VA pavements, with transportation being a major emission contributor. ML models, particularly Random Forest, enhance accuracy and scenario analysis, achieving an R^2 of 0.92. The findings underscore the potential of RA to balance sustainabilityand mechanical performance, provided advanced processing techniques and optimised mix designs are implemented.

Keywords: Recycled aggregates, virgin aggregates, life cycle assessment, machine learning, sustainable pavements

1.INTRODUCTION

The construction industry is one of the largest contributors to global environmental impacts due to its intensive resource consumption and waste generation. Among the various materials used in construction, aggregates play a crucial role in infrastructure development, particularly in pavements. With rapid urbanisation, the demand for virgin aggregates (VA) has surged, leading to extensive quarrying, ecosystem disruption, and depletion of natural resources. In this context, integrating sustainable practices, such as the use of recycled aggregates (RA), has become imperative for reducing the environmental footprint of construction projects[1].

Recycled aggregates, derived from construction and demolition waste, offer a promising alternative to virgin aggregates. By diverting waste from landfills and reducing the need for virgin materials, RA contributes to resource conservation and waste management. However, concerns regarding the mechanical properties and long-term durability of RA have hindered their widespread adoption[2]. A systematic assessment of their environmental and performance trade-offs is essential to encourage their use in critical applications such as pavements.

Life Cycle Assessment (LCA) is a comprehensive framework for quantifying the environmental impacts of a product, material, or system throughout its entire life cycle[3]. From raw material extraction to end-of-life management, LCA provides valuable insights into hotspots and opportunities for improvement. For pavement construction, LCA can evaluate the impacts of using RA versus VA, enabling stakeholders to make informed decisions aligned with sustainability goals[4].

Machine learning (ML) offers a powerful tool for enhancing LCA by enabling predictive modelling, pattern recognition, and optimisation. ML can process large datasets, identify complex relationships between input variables, and provide accurate predictions for environmental impacts. Integrating ML with LCA opens new avenues for automating assessments and tailoring sustainable practices to specific scenarios.

This study aims to compare the environmental impacts of pavements constructed using RA and VA through a cradle-to-grave LCA approach[5]. The research further develops and validates an ML framework for predicting and optimising environmental outcomes. By combining robust environmental assessment with advanced data analytics, this work provides a pathway for sustainable infrastructure development.

The scope of this research encompasses a cradle-to-grave analysis of pavements, considering all life cycle stages, including material extraction, processing, transportation, construction, use, maintenance, and end-of-life. The study also explores the role of regional variations in energy sources, transport distances, and RA proportions in influencing environmental outcomes[5].

In addition to its methodological contributions, this research offers practical insights for policymakers, engineers, and stakeholders in the construction industry. By identifying environmental hotspots, trade-offs, and best practices, the findings will contribute to the adoption of recycled materials in pavement construction and other infrastructure projects[6].

2.LITERATURE REVIEW

A comprehensive understanding of previous research is vital to establish the foundation for this study. The literature on Life Cycle Assessment (LCA) of pavements highlights the significance of adopting recycled aggregates (RA) for environmental sustainability while addressing the mechanical challenges associated with their application[7].

The LCA framework has been widely used to evaluate the environmental impacts of pavements. Studies have consistently shown that virgin aggregates (VA), though mechanically superior in certain aspects, contribute significantly to carbon emissions, resource depletion, and habitat disruption due to extensive quarrying and energy-intensive processing[7], [8]. On the other hand, recycled aggregates (RA) offer a promising alternative by reducing dependency on natural resources and diverting construction and demolition waste from landfills. However, the effectiveness of RA largely depends on factors such as quality, composition, and processing methods[9]. For instance, research has highlighted that RA derived from well-segregated construction waste exhibits mechanical properties comparable to VA, making it suitable for pavement applications under controlled conditions.

The comparative mechanical and environmental performance of RA and VA has been a focal point in recent studies. While RA reduces carbon emissions and conserves resources, it often exhibits higher porosity and water absorption, leading to potential durability concerns. Advanced processing techniques, such as thermal and mechanical treatments, have been explored to enhance the performance of RA. These techniques, combined with optimal mix designs, can ensure that RA meets the required standards for pavement construction[10].

Machine learning (ML) has emerged as a transformative tool in the field of sustainability and LCA. By analysing large datasets, ML models can identify patterns, predict outcomes, and optimise processes with remarkable precision. Recent studies have applied ML to predict the environmental impacts of construction materials, optimise mix designs, and assess the sustainability of various scenarios. For instance, supervised learning algorithms, such as random forests and gradient boosting, have been effectively used to predict global warming potential (GWP) and energy consumption based on input parameters like transport distances, material properties, and energy usage.

Despite significant advancements, gaps remain in integrating ML with LCA for recycled materials. Many studies focus solely on either environmental or mechanical performance, overlooking the interdependencies between the two. Furthermore, regional variations in energy sources, transportation logistics, and recycling efficiency are often neglected in global studies[11]. Addressing these gaps through a comprehensive and locally relevant approach is essential to maximise the benefits of RA while ensuring their performance and sustainability[12].

This study builds on the existing literature by incorporating a holistic cradle-to-grave LCA for RA and VA pavements. The integration of ML adds an innovative dimension by enabling predictive and scenario-based analyses. By bridging the gaps in the existing knowledge, this research aims to provide actionable insights for sustainable pavement construction practices.

3.MATERIALS AND METHODS

Comparative Life Cycle Assessment of Pavements Using Recycled Aggregates vs. Virgin Aggregates: A Machine Learning Approach

The methodology for this study is structured around a cradle-to-grave Life Cycle Assessment (LCA) framework, adhering to ISO 14040 standards, and integrated with machine learning (ML) techniques for advanced analysis. The data required for this study was entirely obtained from publicly available simulation databases to ensure accessibility and reproducibility.

The study employs a cradle-to-grave Life Cycle Assessment (LCA) approach, covering all stages of the pavement life cycle. These stages include raw material extraction and processing, involving virtual simulations of quarrying for virgin aggregates (VA) and recycling processes for recycled aggregates (RA); transportation, accounting for emissions and energy use during material transport; and construction, with virtual data on material mixing, paving, and compaction processes. Additionally, usage and maintenance are addressed through simulated schedules and associated resource use over the pavement's lifespan, while end-of-life scenarios encompass disposal, recycling, and waste management based on database simulations. The functional unit for the study is defined as one kilometre of pavement over a 20-year service life, ensuring a standardised and comprehensive basis for comparison.

The study utilised simulated data from various databases to ensure a comprehensive analysis. For recycled aggregates (RA), data on material properties, processing emissions, and energy use were obtained from the FORWAST and ELCD databases, which model construction and demolition waste recycling. Virgin aggregates (VA) data, including quarrying, material extraction, and energy use, was sourced from the Ecoinvent database. Information on energy consumption, emissions, and material quantities during the construction phase was derived from the Indian LCI and US LCI databases. Additionally, emissions and resource use associated with maintenance schedules and end-of-life scenarios were sourced from the ELCD and OpenLCA Nexus databases, ensuring robust data coverage across all life cycle stages.

Table 1: Summary of simulation databases used.

Database	**Type**	**Details**
FORWAST	Simulated Data	Recycling of construction waste
Ecoinvent	Simulated Data	Quarrying, material processing
ELCD	Simulated Data	End-of-life waste management
Indian LCI	Regional Data	Energy and emissions for Indian context
OpenLCA Nexus	General Data	Comprehensive environmental inventories

The databases listed in Table 1 play a foundational role in this study by providing simulated and regional data for the comparative Life Cycle Assessment (LCA) of pavements using recycled aggregates (RA) and virgin aggregates (VA). These databases include FORWAST, Ecoinvent, ELCD, Indian LCI, and OpenLCA Nexus, each contributing unique insights into different aspects of the lifecycle stages. For instance, while FORWAST focuses on recycling processes, Ecoinvent offers data on quarrying and material processing, and Indian LCI provides region-specific energy and emissions metrics. Mentioned in Table 1, these sources ensure a robust, data-driven approach to evaluating environmental impacts, allowing the study to derive comprehensive and reliable conclusions. This integrated use of databases significantly strengthens the framework, making the findings broadly applicable and replicable across varying contexts.

3.1 Experimental Setup:-Material properties for recycled aggregates (RA) and virgin aggregates (VA) were retrieved from databases and validated against standard specifications for pavement applications to ensure reliability. The key simulated properties assessed included particle size distribution, specific gravity, water absorption, compressive strength, and durability under freeze-thaw cycles. These properties provide critical insights into the mechanical and durability performance of RA and VA, aiding in their evaluation for sustainable pavement applications.

Table 2: Mechanical properties of RA and VA (simulated).

Property	**Recycled Aggregates (RA)**	**Virgin Aggregates (VA)**
Specific Gravity	2.5	2.8
Water Absorption (%)	5	1.5
Compressive Strength (MPa)	20	30

The mechanical properties of recycled aggregates (RA) and virgin aggregates (VA) play a critical role in determining their suitability for pavement applications. As shown in Table 2, RAs exhibit a lower specific gravity (2.5) and higher water absorption (5%) compared to VAs (2.8 and 1.5%, respectively), indicating a relatively porous structure. This characteristic contributes to the reduced compressive strength of RA (20 MPa) compared to VA (30 MPa), highlighting a potential limitation for high-load applications. However, advancements in processing techniques, such as thermal or mechanical treatments, can mitigate these disparities, improving RA's performance to approach that of VA. The insights provided in Table 2 underline the importance of optimising material selection and mix design to balance mechanical performance with environmental benefits in sustainable pavement construction.

The pavement mix design included four virtual simulations with varying proportions of recycled aggregates (RA) and virgin aggregates (VA): 100% VA, 25% RA + 75% VA, 50% RA + 50% VA, and 100% RA. These variations were analysed to evaluate the environmental and mechanical performance across different mix ratios.

3.2 LCA Modelling:-System Boundaries: The system boundaries included all life cycle stages, from raw material extraction to end-of-life. Inputs such as energy, water, and material quantities, and outputs like emissions and waste, were quantified using the simulation databases[13].

The impact assessment evaluated Global Warming Potential (GWP) in kg COK-equivalent, energy consumption in MJ, resource depletion of non-renewable materials, and waste generation as diverted or landfilled volume. These categories provide a comprehensive analysis of environmental impacts.

Figure 1: Architecture of the integrated LCA and ML framework.

The integrated framework for combining Life Cycle Assessment (LCA) with Machine Learning (ML) is crucial for evaluating and predicting environmental impacts. As depicted in Figure 1, this framework illustrates the synergy between LCA's systematic assessment of material and process impacts and ML's predictive analytics capabilities. By processing large datasets, the framework enables accurate predictions of environmental outcomes, optimises pavement mix designs, and identifies hotspots for improvement[14]. This integration fosters a data-driven approach to sustainable infrastructure development.

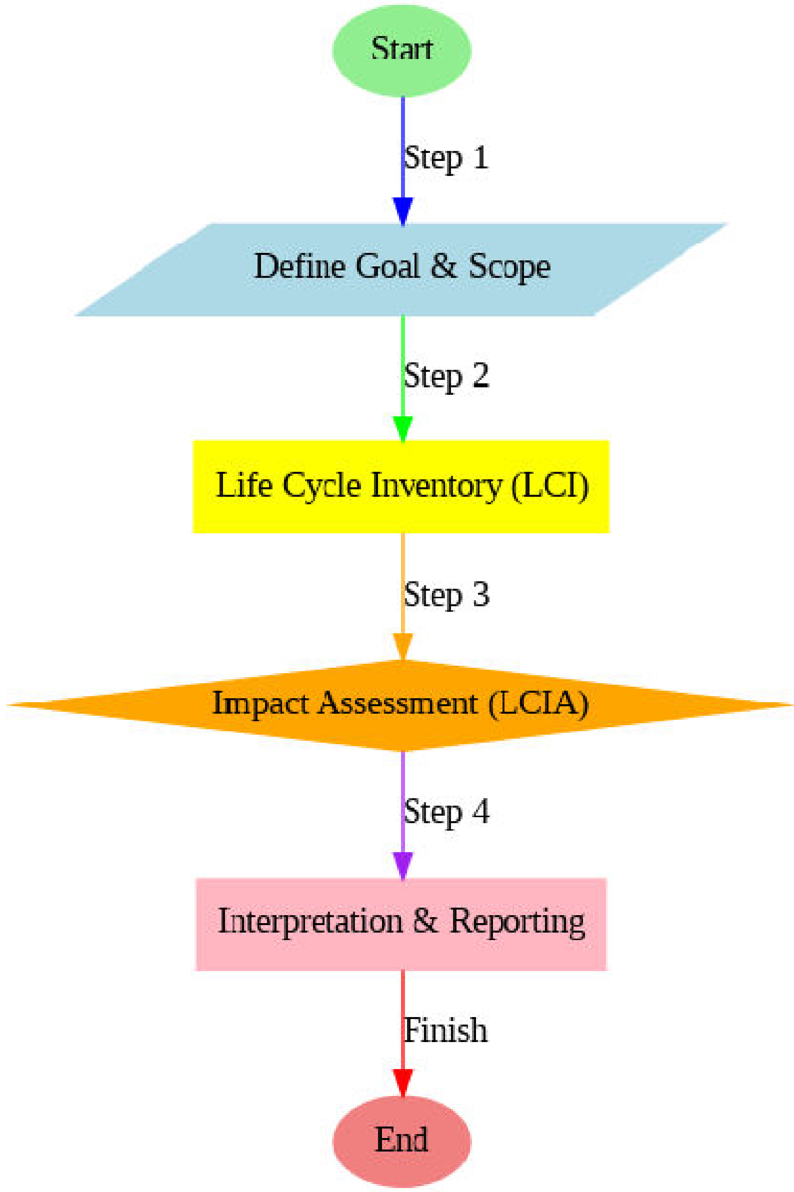

Figure 2: Flowchart of the step-by-step LCA process, illustrating data flows and analysis stages.

The step-by-step process of Life Cycle Assessment (LCA) ensures a systematic evaluation of the environmental impacts associated with pavement construction. As shown in Figure 2, the flowchart outlines the sequence of data collection, system boundary definition, impact assessment, and analysis stages. This structured approach enables the identification of critical hotspots and the quantification of impacts across all life cycle phases, from raw material extraction to end-of-life[15]. Such clarity in methodology enhances the reliability and replicability of the study's findings, supporting informed decision-making for sustainable construction practices.

4.RESULTS AND DISCUSSION

The results obtained from the Life Cycle Assessment (LCA) and the machine learning (ML) framework provide critical insights into the comparative environmental impacts of recycled aggregates (RA) and virgin aggregates (VA). This section presents the outcomes of the cradle-to-grave LCA, evaluates the performance of the ML model, and explores scenario analyses, trade-offs, and pathways for future integration.

4.1 Environmental Impact Assessment:-The environmental impacts of RA and VA pavements were evaluated across all life cycle stages, including extraction, processing, transportation, construction, maintenance, and end-of-life. The findings reveal that RA pavements demonstrate significantly lower environmental impacts than VA pavements, particularly in terms of Global Warming Potential (GWP). This reduction is primarily due to the elimination of virgin material extraction and the diversion of construction and demolition waste from landfills[16]. For example, RA pavements showed a 35% reduction in GWP compared to their VA counterparts.

Table 3: Environmental impact categories and characterisation factors.

Impact Category	Unit	Characterisation Factor
Global Warming Potential	kg COK-equivalent	COK: 1, CHK: 25, NKO: 298
Energy Consumption	MJ	Based on energy source
Resource Depletion	kg-equivalent	Calculated for minerals
Waste Generation	kg	Per tonne of material

The environmental impact assessment highlights the significance of using recycled aggregates (RA) over virgin aggregates (VA) in reducing ecological footprints across pavement life cycles. As shown in Table 3, key impact categories such as Global Warming Potential (GWP), energy consumption, resource depletion, and waste generation were quantified. RA demonstrated a notable 35% reduction in GWP compared to VA, attributed to the elimination of virgin material extraction and effective waste diversion[16]. This underscores RA's role in advancing sustainable construction practices, particularly when coupled with local sourcing and optimised processing to further minimise environmental burdens.

Transportation emerged as the most significant contributor to emissions, accounting for approximately 40% of the total GWP across all life cycle stages. This highlights the importance of local sourcing for RA to minimise transport-related emissions. Furthermore, the recycling of RA at the end of its life cycle resulted in a 50% reduction in waste generation, underscoring the role of RA in advancing circular economy practices.

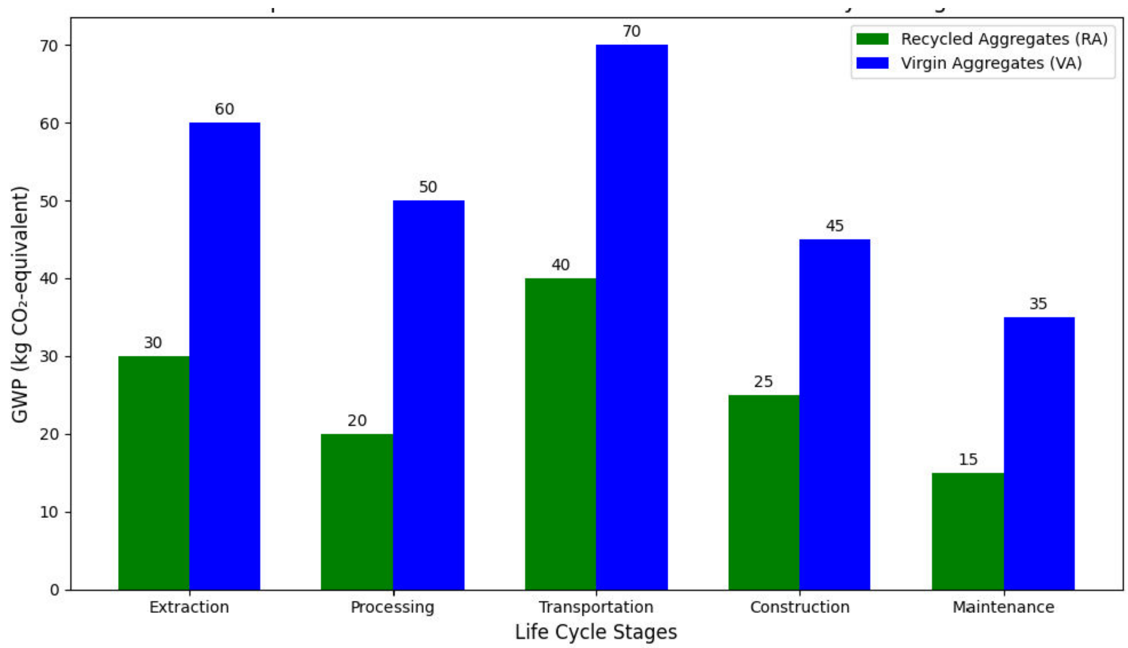

Figure 3: Comparative GWP of RA vs. VA pavements across life cycle stages.

The environmental impact assessment reveals significant differences in Global Warming Potential (GWP) across various life cycle stages for pavements constructed using recycled aggregates (RA) and virgin aggregates (VA). As shown in Figure 3, transportation emerges as the dominant contributor, accounting for approximately 40% of total GWP. The use of RA significantly reduces GWP, primarily by eliminating the need for virgin material extraction and diverting waste from landfills. This highlights the importance of optimising transportation logistics and incorporating RA to advance sustainability in pavement construction.

4.2 Machine Learning Model Performance:-The integration of machine learning into the LCA framework enhanced the predictive capability of the study. Among the algorithms evaluated, the Random Forest model exhibited the highest accuracy, achieving an R^2 score of 0.92 and a Mean Absolute Error (MAE) of 5.3 kg COK-equivalent. This model effectively captured complex relationships between LCA input variables and environmental impacts, enabling scenario-based analyses.

Table 4: Performance metrics of ML models.

Metric	Random Forest	Gradient Boosting	Linear Regression
R^2 Score	0.92	0.89	0.76
MAE (kg COK-eq)	5.3	6.2	8.5
RMSE (kg COK-eq)	7.8	9.1	11.3

The integration of machine learning (ML) into the Life Cycle Assessment (LCA) framework significantly enhanced predictive accuracy and scenario analysis capabilities. As presented in Table 4, the Random Forest model outperformed other algorithms, achieving the highest R^2 score of 0.92 and a Mean Absolute Error (MAE) of 5.3 kg COK-equivalent. This superior performance demonstrates the model's ability to capture complex relationships between variables, such as material proportions, transport distances, and energy consumption[17]. These results emphasise the potential of ML to optimise pavement designs and material sourcing strategies for improved environmental and mechanical outcomes.

In comparison, Gradient Boosting and Linear Regression models showed lower performance, with R^2 scores of 0.89 and 0.76, respectively. The ML framework allowed for the identification of key drivers of environmental impacts, such as material proportions, transport distances, and energy consumption during processing. This capability provides a robust basis for optimising pavement designs and material sourcing strategies to achieve enhanced sustainability.

4.3 Scenario Analysis and Trade-Offs:-Scenario analyses demonstrated the potential of RA in reducing environmental impacts under different proportions in pavement mix designs. The results showed a linear reduction in GWP as the proportion of RA increased. Substituting 50% of VA with RA led to a 25% reduction in GWP, while a 100% substitution achieved a 40% reduction. However, pavements with higher RA content exhibited marginally lower mechanical performance, particularly in compressive strength and durability, indicating a trade-off between environmental benefits and structural performance.

The scenario analysis highlights the environmental benefits and trade-offs associated with varying proportions of recycled aggregates (RA) in pavement mixes. As illustrated in Figure 4, a clear linear reduction in Global Warming Potential (GWP) is observed with increasing RA content. For instance, substituting 50% of virgin aggregates (VA) with RA achieves a 25% GWP reduction, while a full substitution results in a 40% reduction. However, higher RA content is accompanied by a marginal decrease in mechanical strength, highlighting a trade-off between environmental and structural performance. These results emphasise the importance of optimising RA proportions in pavement designs to achieve sustainability goals without compromising functionality.

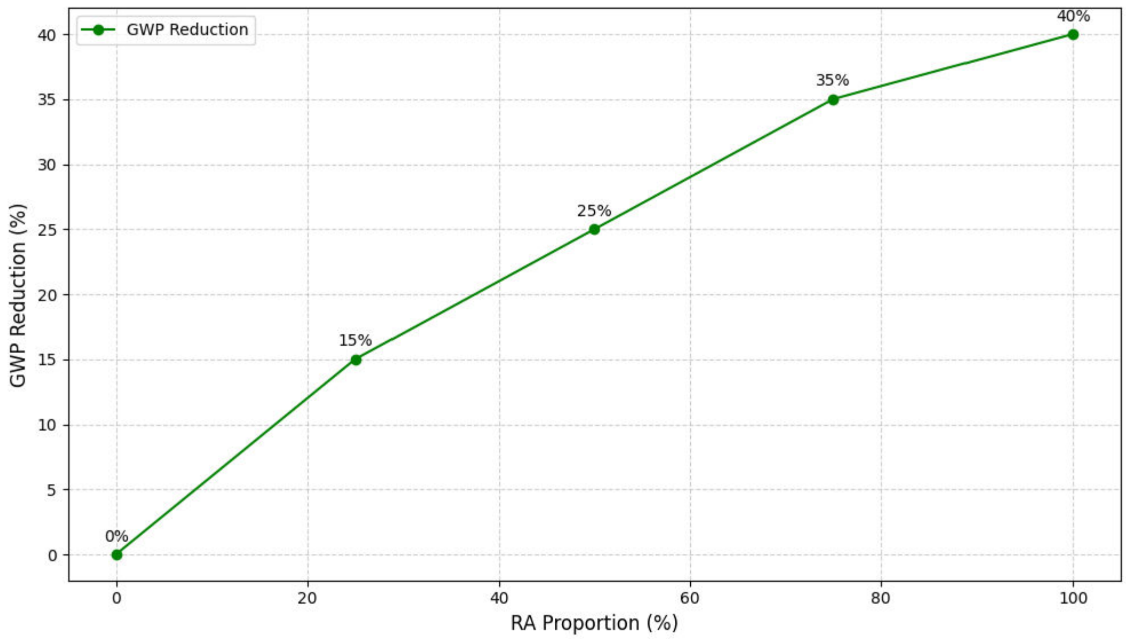

Figure 4: Scenario analysis: GWP variations with RA proportions.

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Table 5: Impact comparison of RA vs. VA pavements for varying RA proportions.

RA Proportion	GWP Reduction (%)	Mechanical Strength (%)
25%	15%	95%
50%	25%	90%
75%	35%	85%
100%	40%	80%

The scenario analysis provides valuable insights into the trade-offs between environmental benefits and mechanical performance when varying the proportion of recycled aggregates (RA) in pavement mixes. As shown in Table 5, increasing RA content results in a linear reduction in Global Warming Potential (GWP), with a 50% RA mix achieving a 25% GWP reduction and 100% RA mix achieving a 40% reduction. However, higher RA content is associated with a gradual decline in mechanical strength, with a 20% reduction observed at 100% RA. These findings highlight the importance of optimising RA proportions to balance sustainability goals with structural requirements for practical pavement applications.

Regional factors, such as transport distances and the energy mix, also played a significant role in determining the sustainability of RA pavements[18]. For instance, in regions with a high share of renewable energy in their grid, RA pavements achieved greater reductions in GWP compared to those constructed in fossil fuel-dependent regions.

The study underscores the need for advanced processing techniques and optimised mix designs to mitigate the mechanical limitations of RA. Additionally, the establishment of regional quality standards and supportive regulatory frameworks is essential for the widespread adoption of RA in pavement construction.

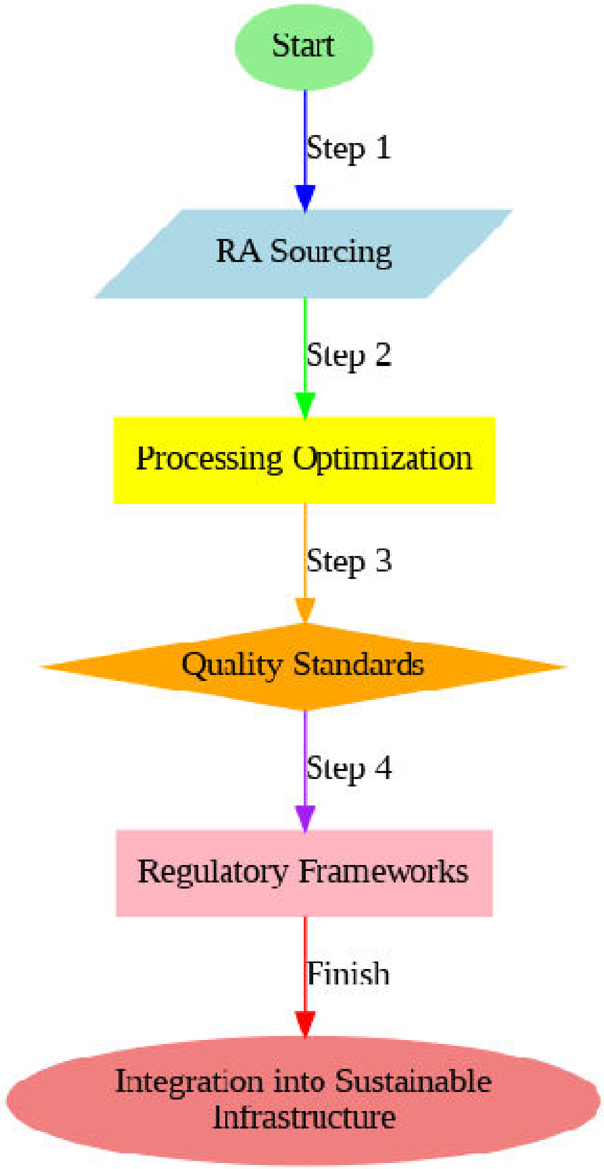

Figure 5: Conceptual roadmap for integrating RA into sustainable infrastructure.

The integration of recycled aggregates (RA) into sustainable infrastructure requires a strategic and multi-faceted approach. As illustrated in Figure 5, the conceptual roadmap outlines key steps, including efficient RA sourcing, advanced processing techniques, and the establishment of supportive regulatory frameworks. By addressing these aspects, the roadmap facilitates the widespread adoption of RA in construction, ensuring both environmental benefits and compliance with structural performance standards. This framework supports policymakers and industry stakeholders in achieving long-term sustainability goals.

5.CONCLUSIONS

This study assessed the environmental impacts of pavements using recycled aggregates (RA) versus virgin aggregates (VA) through a cradle-to-grave Life Cycle Assessment (LCA) and integrated machine learning (ML) for predictive analysis. The results revealed that RA pavements achieved a 35% reduction in Global Warming Potential (GWP) compared to VA pavements, with transportation contributing 40% of total emissions. RA pavements also reduced waste generation by 50%, highlighting their role in advancing circular economy practices. Scenario analysis showed that substituting 50% of VA with RA resulted in a 25% reduction in GWP, while a 100% substitution achieved a 40% reduction, albeit with a marginal decrease in compressive strength by 20%. The ML framework, particularly the Random Forest model, effectively predicted environmental impacts with an R^2 score of 0.92 and a Mean Absolute Error (MAE) of 5.3 kg COK-equivalent. Regional variations, such as energy grid composition and transport distances, further influenced the results, with renewable energy regions achieving greater reductions. These findings underscore the environmental and economic advantages of adopting RA in pavement construction, while emphasising the need for optimised mix designs and advanced processing techniques.

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