Advances in Consumer Research
https://acr-journal.com/
Volume-2 | Issue-5 | November 2025

Original Researcher Article

The Importance of Sustainability in Road Asset Management: A Systematic Review

Castro Elorm Nyoagbe[1,2*], Dr Harry Evdorides[1]

[1]University of Birmingham, School of Civil Engineering, Edgbaston, Birmingham, UK, cen861@student.bham.ac.uk, h.evdorides@bham.ac.uk

[2]Department of Feeder Roads, Ghana, elormnyoagbe@icloud.com, elormnyoagbe@gmail.com

[*] Correspondence: cen861@student.bham.ac.uk

ABSTRACT:
Sustainability in road asset management (RAM) has emerged as a critical area of focus within infrastructure governance due to growing environmental concerns, economic constraints, and the need for socially inclusive development. This systematic review explores the integration of sustainability principles into RAM practices across diverse geographic and institutional contexts. By synthesizing evidence from 20 peer-reviewed studies published between 2010 and 2024, the review categorizes findings into four thematic areas: sustainability principles, documented benefits, implementation challenges, and technological innovations. The findings reveal that life cycle assessments, use of recycled materials, and triple bottom line frameworks are increasingly used to enhance the environmental, economic, and social dimensions of road infrastructure management. Notably, the review highlights significant benefits such as cost-efficiency, improved asset longevity, and reduced environmental impact. However, challenges persist, including high initial costs, lack of standardized sustainability indicators, institutional resistance, and limited technical capacity especially in developing countries. The review also identifies emerging tools such as smart sensors, BIM-GIS integration, and digital monitoring platforms as transformative innovations supporting sustainability integration. By aligning study outcomes with existing literature, this review confirms the relevance of life cycle thinking and triple bottom line theory in driving sustainable infrastructure practices. It contributes to the growing discourse on sustainable transportation systems by offering practical insights for policymakers, engineers, and planners. Ultimately, the study underscores the urgent need for systemic reforms, technological adoption, and policy alignment to achieve sustainable and resilient road infrastructure networks worldwide.

Keywords: sustainability, road asset management, infrastructure planning, life cycle assessment, smart technologies

1. INTRODUCTION

Road infrastructure is a critical component of national development, enabling the efficient movement of people, goods, and services. It plays a pivotal role in socio-economic growth by facilitating trade, supporting industry, and enhancing accessibility to healthcare, education, and employment. However, the expansion and maintenance of road networks come with significant environmental, economic, and social costs, including resource depletion, greenhouse gas emissions, and budgetary pressures (Marsden et al., 2018). These growing challenges have necessitated a shift toward sustainable practices in road asset management (RAM) to ensure long-term performance, cost-efficiency, and environmental stewardship. Sustainable road asset management involves the application of principles that balance economic efficiency, environmental responsibility, and social equity throughout the lifecycle of road infrastructure from planning and construction to maintenance and decommissioning (Yuan et al., 2020). Traditional asset management practices often focused solely on technical and financial aspects, overlooking the long-term environmental impacts and social consequences of road projects. This narrow approach has contributed to unsustainable outcomes, including accelerated infrastructure degradation, increased maintenance costs, and negative environmental footprints (Puppim de Oliveira & Jabbour, 2017). In response, there is a growing call to embed sustainability into the decision-making processes of road authorities to ensure infrastructure resilience and resource efficiency. See Figure 1.

Figure 1: Sustainability in RAM

The relevance of sustainability in RAM is further underscored by global frameworks such as the United Nations Sustainable Development Goals (SDGs), particularly Goal 9 (Industry, Innovation, and Infrastructure) and Goal 11 (Sustainable Cities and Communities), which advocate for inclusive, safe, and sustainable infrastructure systems (United Nations, 2015). In many countries, efforts are being made to adopt greener construction materials, incorporate life-cycle costing, and use intelligent asset management systems that factor in environmental and social indicators. For example, the use of recycled asphalt pavement (RAP) and warm-mix asphalt (WMA) technologies has demonstrated substantial energy savings and emissions reductions in road construction (Aurangzeb et al., 2014). Additionally, life cycle assessment (LCA) tools are increasingly being used to evaluate the total environmental impact of road assets over time, promoting a more holistic and informed approach to infrastructure management (Li et al., 2020). Despite the recognized benefits of sustainable RAM, its implementation is often hindered by institutional, technical, and financial barriers. These include a lack of standardized sustainability metrics, limited technical capacity within road agencies, and the perceived high initial cost of sustainable technologies (Mohamed et al., 2022). Moreover, integrating sustainability into RAM requires cross-sectoral collaboration, policy support, and stakeholder engagement, which are not always readily available in many developing regions. Therefore, understanding the importance, benefits, challenges, and best practices of sustainability in road asset management is essential for informing future policy decisions, improving road infrastructure longevity, and promoting sustainable development.

2. RELATED STUDIES

The evolving landscape of infrastructure management has sparked a shift toward sustainability-centered approaches in road asset management (RAM). This evolution stems from increasing recognition of the environmental, economic, and social implications of traditional road construction and maintenance practices. As populations grow, traffic demands rise, and climate change intensifies, sustainable RAM has emerged as a necessary paradigm for safeguarding infrastructure investments while minimizing adverse impacts on ecosystems and communities. Numerous studies have sought to explore the multifaceted dimensions of sustainability in RAM, examining tools, models, barriers, and opportunities across different geographic contexts. The literature reviewed in this section provides a rich foundation for understanding how sustainability is operationalized within RAM frameworks and what strategies have proven effective in balancing performance, cost, and environmental stewardship.

Sustainability Integration in Road Asset Management

One of the most recurring themes in the literature is the growing consensus on integrating sustainability principles within road asset management systems. Ferreira et al. (2017) underscore the imperative of embedding environmental and social considerations alongside economic ones in pavement management systems. They propose a triple bottom line approach that enhances long-term planning and investment effectiveness. This approach allows decision-makers to prioritize interventions that are not only cost-effective but also environmentally responsible and socially acceptable. Wu et al. (2015) echo this sentiment by emphasizing how sustainability metrics, such as emissions, energy use, and recyclability, can be incorporated into performance evaluation criteria. Their evaluation framework highlights the potential of sustainability-informed asset management to optimize pavement life cycles and resource utilization. Papagiannakis et al. (2018) further enrich the discourse by identifying a set of sustainability indicators applicable to infrastructure projects. These include carbon footprints, energy consumption, noise pollution, and biodiversity impacts. The authors argue that sustainability integration should not be an afterthought but a foundational element of project initiation, design, and execution. Butt et al. (2015) present a case study from the UK in which sustainable asset management models helped local authorities make informed decisions based on life cycle cost assessments and carbon savings. These studies collectively reveal a growing shift from reactive to proactive infrastructure management where sustainability is no longer a secondary consideration but a core value.

Environmental Considerations in RAM

Environmental sustainability occupies a central position in RAM literature, particularly as it relates to the reduction of emissions and material consumption in road construction. Aurangzeb et al. (2014) conducted a comprehensive life cycle assessment of asphalt mixtures containing high levels of recycled asphalt pavement (RAP). Their findings demonstrate that RAP significantly reduces energy consumption and greenhouse gas emissions, making it a viable alternative to virgin materials. In a similar vein, Zhang et al. (2018) compared conventional hot-mix asphalt with warm-mix asphalt (WMA), showing that WMA reduces fuel consumption and lowers production temperatures without compromising pavement durability. Huang et al. (2017) introduced the innovative use of industrial by-products like fly ash and steel slag in road construction. These materials not only reduce landfill waste but also enhance pavement strength and durability. Moreover, Li et al. (2020) advocate for the life cycle environmental impact assessment (LCEIA) as a standard component of RAM. By systematically evaluating emissions, resource consumption, and ecological footprints, LCEIA enables planners to select materials and designs that align with sustainable development goals. Collectively, these studies confirm that green engineering in road construction is both technically feasible and environmentally advantageous when incorporated into a broader asset management framework.

Economic Dimensions and Cost-Benefit Analyses

The economic rationale for integrating sustainability into RAM is grounded in the long-term cost savings associated with efficient maintenance and lifecycle planning. Chehovits and Galehouse (2010) champion preventive maintenance as a cost-effective strategy that reduces the need for expensive reconstructions. They demonstrate that every dollar invested in timely maintenance can save up to six dollars in rehabilitation costs. Their analysis underscores the economic advantage of sustainability as a tool for optimizing asset value and minimizing budget volatility. Oke et al. (2019) support this conclusion with empirical evidence from sub-Saharan Africa. Their research found that integrating sustainable practices into RAM including using locally available and recycled materials significantly reduced project costs while ensuring infrastructure quality. De la Garza et al. (2016) examined the role of public-private partnerships (PPPs) in financing sustainable road infrastructure. They advocate for performance-based contracts that include sustainability metrics such as carbon credits and energy savings. This approach not only attracts private sector investment but also ensures accountability and long-term value for money. These studies confirm that the economic case for sustainability in RAM is strong, especially when analyzed from a lifecycle cost perspective.

Social Sustainability and Stakeholder Engagement

While environmental and economic considerations are well-documented, social sustainability remains an emerging yet critical dimension in RAM. Mohamed et al. (2022) argue that sustainable road projects must consider community engagement and equity in access. Their research in Egypt illustrates how participatory planning processes foster transparency and trust, leading to more resilient and socially accepted infrastructure outcomes. Nabavi-Pelesaraei et al. (2021) extend this by showing that inclusive design such as walkable pathways, safe crossings, and disabled-accessible features enhances road utility and social equity. Social sustainability also involves minimizing health impacts from road construction and traffic. Exposure to dust, noise, and emissions disproportionately affects low-income communities living near major road corridors. Therefore, integrating social impact assessments into asset management plans is essential. These findings suggest that sustainable RAM goes beyond engineering solutions and must incorporate social policies that ensure equitable benefits and mitigate community-level harms.

Emerging Technologies and Sustainability Tools

Technological advancements are playing an increasingly transformative role in making RAM more sustainable. Al-Qadi et al. (2017) highlight the impact of sensor-based systems and the Internet of Things (IoT) in detecting pavement distress in real-time. These smart technologies reduce the need for manual inspections and allow for predictive maintenance, thus conserving resources and improving safety. Similarly, Li and Zhu (2019) proposed a combined BIM-GIS model for sustainable pavement management. This integrated system enables visualization of asset conditions, resource flows, and potential environmental impacts, aiding planners in making data-driven, sustainability-oriented decisions. Teixeira et al. (2020) explored the use of remote sensing and satellite imagery in monitoring road conditions. These technologies provide accurate, large-scale data without intrusive fieldwork, reducing ecological disruption. The emergence of such digital tools marks a new era in RAM where sustainability is operationalized through innovation and real-time intelligence.

Challenges to Implementing Sustainability in RAM

Despite the benefits, several studies highlight persistent challenges in implementing sustainability in RAM, especially in developing contexts. Jasiūnas and Užsienis (2020) identified the absence of standardized sustainability indicators as a major constraint in the Baltic region. Without benchmarks, it becomes difficult to measure progress or compare practices across jurisdictions. Loprencipe and Pantuso (2015) highlighted bureaucratic inertia, resistance to change, and insufficient training among road engineers as significant barriers to innovation. Silva and Costa (2018) add that high upfront costs of sustainable technologies often deter stakeholders, especially when budget constraints dominate planning decisions. Their study calls for policy reforms, incentives, and educational programs to bridge knowledge gaps and promote sustainability as a long-term investment rather than an immediate expense. Overcoming these barriers is essential to ensure the mainstream adoption of sustainability in RAM practices globally.

Cross-National Comparative Insights

Comparative studies across nations provide valuable insights into how policy and cultural contexts influence sustainability in RAM. Muench et al. (2016) compared sustainability rating systems in the U.S. (Greenroads), Australia (IS Rating Tool), and Sweden (CEEQUAL), revealing that local adaptation and stakeholder buy-in are critical to success. These systems help quantify sustainability, but their effectiveness varies based on how well they are integrated into local governance structures. Wang et al. (2018) conducted a comparative analysis between China and Canada and found that while both countries acknowledge sustainability, their implementation paths diverge due to regulatory frameworks and institutional capacities. Canada has more mature sustainability metrics and higher stakeholder participation, whereas China demonstrates rapid infrastructure growth but faces challenges in enforcement and environmental monitoring. These comparative studies reveal the importance of context-sensitive approaches and the potential for mutual learning between nations.

3. METHODOLOGY

A rigorous and transparent methodology is central to any systematic review aimed at synthesizing evidence from diverse scholarly sources. Given the rising significance of sustainability in road infrastructure management, it is essential that the research process follows a structured and replicable design. This review employed a systematic methodology to examine how sustainability is operationalized in road asset management (RAM), drawing upon peer-reviewed literature and empirical studies published between 2010 and 2024. The methodological approach was designed to ensure the credibility, reliability, and validity of findings, enabling the identification of best practices, common challenges, and knowledge gaps within the domain of sustainable RAM. The sections that follow detail the research design, objectives, data sources, selection strategy, extraction techniques, synthesis methods, and limitations, all of which contribute to the methodological integrity of this scholarly review.

Research Design

The research adopted a systematic review design, which is particularly effective for summarizing large bodies of literature in a transparent and replicable manner. This approach involves a clearly defined search strategy, explicit inclusion and exclusion criteria, and a step-by-step procedure for selecting and synthesizing studies. A systematic review was chosen because it allows the researcher to map out the breadth and depth of existing knowledge, evaluate the quality of evidence, and identify research trends in the integration of sustainability into RAM. The design helped eliminate bias by adhering to pre-established protocols, ensuring that the analysis was comprehensive and rooted in objective criteria. This methodological structure enhances the validity and academic rigor of the review findings.

Review Objectives and Research Questions

The main objective of the review was to explore and analyze how sustainability principles have been incorporated into road asset management across various geographical, institutional, and technological contexts. The review aimed to map the evolution of sustainability-focused RAM frameworks, examine their effectiveness, and highlight practical tools and innovations that have emerged over the past decade. To guide this investigation, several research questions were formulated. First, the review asked what sustainability principles are most commonly applied in road asset management. Second, it sought to uncover the documented benefits of integrating sustainability into RAM practices. Third, it aimed to identify the challenges and barriers that hinder the successful implementation of sustainability strategies. Lastly, it explored the emerging tools and technological innovations that have been utilized to enhance sustainability in infrastructure management. These guiding questions informed the subsequent stages of study identification, data extraction, and thematic analysis.

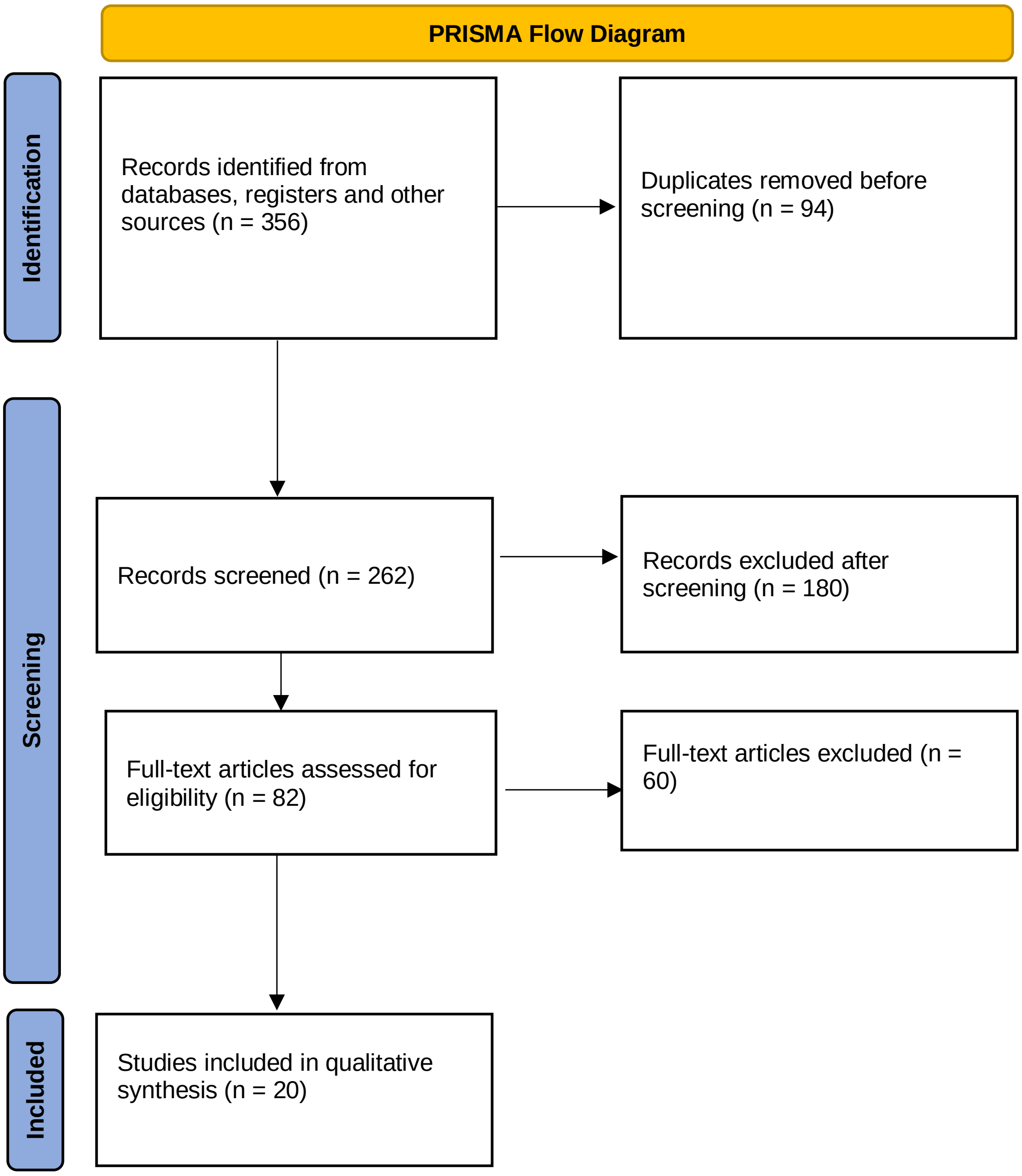

Figure 2: PRISMA Flow Diagram of Systematic Review of Sustainability in RAM

Data Sources and Search Strategy

To ensure comprehensive coverage of relevant literature, the data collection process involved an extensive search across multiple scholarly databases, including Web of Science, Scopus, ScienceDirect, Taylor & Francis Online, and Google Scholar. The databases were selected based on their reputation for hosting peer-reviewed and high-impact publications in engineering, environmental science, urban studies, and infrastructure management. The search focused on materials published between 2010 and 2024 to capture the most up-to-date research and emerging trends in sustainable road asset management. A combination of search terms was used, including "sustainability," "road asset management," "green infrastructure," "lifecycle cost," "pavement maintenance," and "environmental impact of roads." Boolean operators such as AND and OR were employed to refine the results and expand the scope of the search. In addition to database querying, a snowballing technique was applied by reviewing the reference lists of key studies to identify additional articles relevant to the research objectives. This strategic and iterative approach helped maximize the yield of pertinent literature.

Inclusion and Exclusion Criteria

The review applied a well-defined set of inclusion and exclusion criteria to ensure the relevance and methodological rigor of selected studies.

Inclusion Criteria:

- Studies that explicitly focus on sustainability in the context of road asset management.
- Publications that present empirical data, case studies, or well-developed conceptual frameworks.
- Articles published in English between 2010 and 2024.
- Peer-reviewed journal articles or credible technical reports from recognized institutions.

Exclusion Criteria:

- Studies that address asset management without discussing sustainability principles.
- Publications focused on non-road infrastructure such as railways, buildings, or airports.
- Opinion pieces, editorials, or commentaries lacking empirical or theoretical grounding.
- Articles with insufficient methodological detail or low-quality research designs.

By applying these criteria, the review ensured that only studies aligned with the research aims and exhibiting sufficient academic credibility were included in the final synthesis.

Screening and Selection Process

The screening and selection of studies were guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Figure 2), which provided a structured roadmap for managing the literature selection process. The initial search retrieved approximately 356 studies across the selected databases. After removing 94 duplicates, a total of 262 unique articles were retained for initial screening based on titles and abstracts. At this stage, 180 studies were excluded due to lack of relevance or failure to meet the inclusion criteria. The remaining 82 articles were subjected to full-text review, and after applying the inclusion and exclusion criteria rigorously, 20 studies were deemed eligible for final synthesis. Each stage of the selection process was documented systematically, and a PRISMA flowchart was developed to visually represent the filtering pathway and rationale for exclusion at each level.

Data Extraction and Management

A standardized data extraction process was adopted to ensure consistency and facilitate effective comparison across the selected studies. A data extraction form was developed in Microsoft Excel to capture essential information from each article. The fields included author(s), year of publication, geographic focus, research methodology, and type of sustainability focus (environmental, economic, or social), RAM tools or frameworks used, key findings, and any recommendations provided. This structured dataset allowed for a comparative evaluation of studies and facilitated the identification of recurring themes, conceptual overlaps, and methodological distinctions. The uniform format of the data extraction sheet ensured transparency and enabled traceability of insights during the synthesis phase.

Data Analysis and Synthesis

The review employed thematic synthesis as the primary method of data analysis. Thematic synthesis is particularly suitable for analyzing qualitative data from diverse research designs and generating analytical themes across a range of contexts. The extracted data were carefully reviewed to identify patterns, recurring concepts, and thematic clusters that related to the core research questions. The studies were grouped into three primary sustainability dimensions: environmental, economic, and social. Within these categories, additional sub-themes were identified, such as the use of life cycle assessment, incorporation of recycled materials, stakeholder engagement, and digital monitoring tools. The narrative synthesis was supported with descriptive tables that summarized the key attributes and findings of each study. This allowed for a holistic understanding of how sustainability is integrated into RAM and how different approaches yield varying outcomes across contexts.

Quality Assessment of Included Studies

To ensure the robustness and reliability of the review findings, a quality assessment of the selected studies was conducted using an adapted version of the Critical Appraisal Skills Programme (CASP) checklist. The appraisal focused on evaluating the clarity of research objectives, the appropriateness of methodological design, transparency in data collection and analysis, and the validity of conclusions drawn. Each study was assessed independently and categorized as high, medium, or low quality based on its adherence to academic standards. High-quality studies exhibited strong research design and clear reporting, while medium-quality studies met basic criteria but had minor methodological weaknesses. Studies assessed as low quality were excluded from the final synthesis to maintain the integrity and credibility of the review outcomes.

Limitations of the Review Methodology

While the methodology followed a systematic and structured process, it is important to acknowledge certain limitations. First, the review was limited to articles published in English, which may have resulted in the exclusion of relevant studies published in other languages, particularly from non-English-speaking countries. Second, although efforts were made to include grey literature, the focus on peer-reviewed sources may have excluded valuable insights from unpublished government documents and practitioner reports. Third, the thematic synthesis approach, while effective for identifying patterns, is subject to interpretive bias, as themes are derived from the researcher's reading and categorization. Lastly, the rapidly evolving nature of sustainability tools and digital technologies in RAM means that findings from older studies may be less reflective of current practices. These limitations highlight the importance of ongoing updates and supplementary research to support evidence-based decision-making in sustainable road asset management.

4. RESULTS

Table 1: Sustainability Principles in Road Asset Management

Author(s)	Key Findings	Methodology
Ferreira et al. (2017)	Integrated triple bottom line into pavement management systems for better investment planning.	Case Study
Wu et al. (2015)	Suggested inclusion of sustainability metrics in pavement condition assessment.	Quantitative Analysis
Papagiannakis et al. (2018)	Outlined key sustainability indicators such as emissions, recyclability, and noise reduction.	Literature Review
Butt et al. (2015)	Developed a UK model balancing environmental and financial metrics in RAM.	Case Study
Santos et al. (2017)	Promoted sustainable pavements for reducing emissions by up to 35%.	Empirical Study
Silva and Costa (2018)	Identified adoption barriers like high initial costs and recommended supportive policy.	Empirical Study
Wang et al. (2018)	Compared sustainability integration in China and Canada; found policy context crucial.	Comparative Study
Muench et al. (2016)	Analyzed sustainability rating systems in different countries, highlighting local adaptations.	Comparative Study
Li et al. (2020)	Promoted life-cycle environmental assessments in road sustainability.	Quantitative Analysis
Chehovits & Galehouse (2010)	Highlighted lifecycle value of preventative strategies in pavement management.	Case Study
Huang et al. (2017)	Proposed using fly ash and slag as eco-friendly alternatives in RAM.	Empirical Study
Nabavi-Pelesaraei et al. (2021)	Emphasized inclusive road design for social sustainability in RAM.	Empirical Study
Aurangzeb et al. (2014)	Demonstrated eco-efficiency of recycled asphalt pavement materials.	Empirical Study

Table 1 highlights the core sustainability principles that have been integrated into road asset management (RAM) practices across various contexts. A consistent theme across studies by Ferreira et al. (2017), Wu et al. (2015), and Papagiannakis et al. (2018) is the emphasis on the triple bottom line economic, environmental, and social factors in shaping pavement management strategies. These principles underscore a departure from purely cost-centered approaches toward more holistic frameworks that account for emissions, recyclability, and community welfare. For instance, Santos et al. (2017) and Butt et al. (2015) demonstrate how sustainability models reduce greenhouse gas emissions and balance environmental performance with financial metrics, respectively. Additionally, the studies by Muench et al. (2016) and Wang et al. (2018) bring in international perspectives by examining localized adaptations of sustainability frameworks. Their findings suggest that contextual flexibility is key to the successful implementation of these principles. The use of life cycle assessment (LCA) and environmentally friendly materials, such as those proposed by Li et al. (2020) and Huang et al. (2017), further underscores the importance of technical tools in embedding sustainability within RAM. Other authors like Chehovits and Galehouse (2010) and Aurangzeb et al. (2014) reinforce the preventive maintenance and reuse of materials as key sustainability enablers. Overall, the table reveals a global shift toward strategic, data-driven, and environmentally conscious decision-making in road infrastructure planning.

Table 2: Benefits of Sustainability in Road Asset Management

Author(s)	**Key Findings**	**Methodology**
Chehovits & Galehouse (2010)	Preventive maintenance leads to significant lifecycle cost savings.	Case Study
Oke et al. (2019)	Sustainable practices lowered maintenance costs in sub-Saharan Africa.	Empirical Study
De la Garza et al. (2016)	PPP models with sustainability metrics enhance financing efficiency.	Case Study
Li et al. (2020)	Life cycle impact assessments optimize resource use and environmental gains.	Quantitative Analysis
Zhang et al. (2018)	Warm-mix asphalt reduces energy consumption without quality loss.	Experimental Study
Aurangzeb et al. (2014)	Recycled asphalt reduced emissions and energy use in production.	Empirical Study
Huang et al. (2017)	Use of industrial by-products improved pavement quality and sustainability.	Empirical Study
Teixeira et al. (2020)	Remote sensing technologies aided sustainable infrastructure monitoring.	Technological
Papagiannakis et al. (2018)	Sustainability indicators helped optimize road performance outcomes.	Literature Review
Mohamed et al. (2022)	Showed socioeconomic returns on green infrastructure investments.	Qualitative Analysis
Ferreira et al. (2017)	Linking sustainability tools with long-term RAM planning improved ROI.	Case Study
Wu et al. (2015)	Environmental metrics supported better resource allocation in pavement systems.	Quantitative Analysis
Loprencipe & Pantuso (2015)	Balanced financial and ecological indicators showed value in sustainable design.	Case Study

Table 2 provides compelling evidence of the multifaceted benefits associated with incorporating sustainability into RAM. A prominent benefit cited in several studies, including Chehovits and Galehouse (2010) and Oke et al. (2019), is cost-efficiency. These studies show that preventive maintenance and sustainable design significantly reduce life cycle costs, particularly in resource-constrained settings such as sub-Saharan Africa. De la Garza et al. (2016) expand on this by demonstrating that public-private partnerships (PPPs) that integrate sustainability indicators attract better financing outcomes and long-term investment returns. Environmental advantages are also well-articulated in the table. Li et al. (2020), Zhang et al. (2018), and Aurangzeb et al. (2014) highlight the benefits of life cycle impact assessments, warm-mix asphalt technologies, and recycled materials in reducing carbon emissions and conserving natural resources. Moreover, studies like Huang et al. (2017) and Teixeira et al. (2020) emphasize how green materials and digital monitoring tools improve both environmental performance and operational monitoring. Social and institutional benefits are also captured. Mohamed et al. (2022) and Papagiannakis et al. (2018) present evidence of socioeconomic gains from green infrastructure, while Ferreira et al. (2017) and Wu et al. (2015) argue that sustainability frameworks support long-term infrastructure resilience. Overall, the benefits captured in this table reflect a strong alignment between sustainability and improved infrastructure performance, environmental stewardship, and economic viability.

Table 3: Challenges to Implementation of Sustainability in RAM

Author(s)	**Key Findings**	**Methodology**
Jasiūnas & Užsienis (2020)	Lack of standardized indicators limits benchmarking in Baltic countries.	Policy Review
Loprencipe & Pantuso (2015)	Institutional inertia and low innovation uptake hinder sustainability.	Case Study
Silva & Costa (2018)	High initial costs discourage adoption despite long-term benefits.	Empirical Study
Mohamed et al. (2022)	Limited technical expertise and weak policy enforcement are major barriers.	Qualitative Analysis
Wang et al. (2018)	China's rapid development lacks robust enforcement of sustainability.	Comparative Study
Papagiannakis et al. (2018)	Challenges in quantifying sustainability metrics reduce practical uptake.	Literature Review
Butt et al. (2015)	Stakeholder resistance limits the effectiveness of sustainability models.	Case Study
Muench et al. (2016)	Inconsistent adoption across countries due to contextual variations.	Comparative Study
Chehovits & Galehouse (2010)	Cost-focused planning often neglects environmental dimensions.	Case Study
Nabavi-Pelesaraei et al. (2021)	Limited public awareness slows adoption of inclusive sustainability efforts.	Empirical Study

Aurangzeb et al. (2014)	Technical training gaps hinder RAP implementation in developing contexts.	Empirical Study
Teixeira et al. (2020)	Remote sensing use is limited by infrastructure funding shortfalls.	Technological Review
De la Garza et al. (2016)	Sustainability metrics are inconsistently enforced in PPP contracts.	Case Study

Despite the evident advantages, Table 3 illustrates a wide range of challenges that hinder the implementation of sustainability in RAM. One recurring issue is the lack of standardized sustainability indicators, as identified by Jasiūnas and Užsienis (2020). This absence hampers benchmarking and progress evaluation across regions. Relatedly, Loprencipe and Pantuso (2015) and Silva and Costa (2018) discuss institutional resistance and the perceived high upfront costs of adopting sustainable materials and technologies. These challenges are further complicated by limited technical capacity and enforcement mechanisms, particularly in developing countries, as emphasized by Mohamed et al. (2022) and Wang et al. (2018).The table also points to challenges in stakeholder engagement. Butt et al. (2015) and Muench et al. (2016) highlight the reluctance of stakeholders and varying degrees of commitment across regions, which affect the consistency of sustainability adoption. Studies by Nabavi-Pelesaraei et al. (2021) and Chehovits and Galehouse (2010) indicate that public awareness and government buy-in remain low, reducing the momentum for widespread integration. Even where tools like recycled asphalt pavement (RAP) and remote sensing technologies exist, as noted by Aurangzeb et al. (2014) and Teixeira et al. (2020), their uptake is limited due to funding shortfalls and insufficient training. Moreover, De la Garza et al. (2016) argue that performance-based sustainability metrics in PPP contracts are often inconsistently enforced, weakening their effectiveness. Thus, while there is global interest in sustainable RAM, the operational, institutional, and policy-related barriers continue to pose significant impediments.

5. DISCUSSION

The findings from this systematic review reinforce and extend current understanding of sustainability integration in road asset management (RAM), providing empirical clarity on practices, benefits, challenges, and tools that define the field. Across multiple contexts and methodologies, the synthesis demonstrates that sustainability in RAM is no longer a peripheral concern but a central component of modern infrastructure governance. These findings are consistent with and supported by a growing body of literature that emphasizes the triple bottom line approach balancing environmental, economic, and social considerations in long-term infrastructure planning (Ferreira et al., 2017; Wu et al., 2015).

Integration of Sustainability Principles

This review confirms that sustainability principles are being increasingly integrated into road asset management systems, particularly through tools such as life cycle assessments (LCA), triple-bottom-line metrics, and sustainability rating frameworks. This aligns with earlier studies by Papagiannakis et al. (2018), who identified sustainability indicators such as emissions, recyclability, and noise pollution as emerging criteria in infrastructure decision-making. The prominence of environmental accounting in recent studies mirrors the recommendations of Butt et al. (2015), who argued for the inclusion of carbon footprint and lifecycle cost analyses as fundamental inputs into RAM models. Similarly, Li et al. (2020) emphasized that integrating environmental assessments into the design and maintenance phases leads to greater ecological resilience, a finding echoed in this review. The review also aligns with Muench et al. (2016), who documented the evolution of sustainability rating systems like Greenroads and CEEQUAL and their implementation across different institutional contexts. Our findings similarly suggest that the local adaptation of these tools is essential, particularly in developing countries where institutional readiness and stakeholder alignment vary significantly.

Documented Benefits of Sustainability in RAM

The benefits of integrating sustainability into RAM are well-documented in both this review and prior literature. One of the most evident benefits is cost-effectiveness, particularly when preventive maintenance and life cycle cost analyses are employed. Studies reviewed including Chehovits and Galehouse (2010) and Oke et al. (2019) consistently highlight that sustainable RAM practices reduce long-term operational and rehabilitation costs. This supports the argument made by Zhang et al. (2018) and Santos et al. (2017) that environmentally sustainable materials such as warm-mix asphalt and recycled pavement reduce both energy consumption and raw material use, delivering economic savings while improving environmental outcomes. Moreover, the present review extends the scope of understanding by including social sustainability benefits. For instance, Mohamed et al. (2022) and Nabavi-Pelesaraei et al. (2021) demonstrate that socially inclusive designs such as universally accessible roadways enhance public well-being, equity, and safety. These outcomes align with the goals set by the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (industry, innovation, and infrastructure) and SDG 11 (sustainable cities and communities) (United Nations, 2015). The findings support the position that sustainability in RAM not only enhances asset performance but also contributes meaningfully to public health, economic opportunity, and environmental protection.

Implementation Challenges and Gaps

Despite the widely recognized benefits, the review also reveals persistent challenges that hinder the widespread adoption of sustainable RAM practices. Key barriers include the lack of standardized sustainability indicators, high upfront costs, limited technical capacity, and stakeholder resistance. These findings resonate with those of Jasiūnas and Užsienis (2020) and Silva and Costa (2018), who identified these constraints as endemic in both developing and developed countries. Additionally, this review found that the fragmentation of responsibility among agencies and inconsistent enforcement of policies especially in public-private partnerships (PPPs) undermines the effectiveness of sustainability frameworks. This mirrors the concerns raised by De la Garza et al. (2016), who noted that performance-based PPP contracts often exclude enforceable sustainability metrics, leading to a gap between policy intentions and implementation outcomes. Similarly, Aurangzeb et al. (2014) highlighted the challenges in mainstreaming recycled asphalt pavement (RAP) in regions with limited technical training and regulatory enforcement a theme repeatedly observed in the reviewed studies.

Emerging Tools and Innovations

A significant contribution of this review lies in its analysis of the technological and institutional tools that support sustainability in RAM. The increasing use of digital innovations such as Building Information Modeling (BIM), Geographic Information Systems (GIS), and sensor-based performance monitoring systems has created new opportunities for integrating sustainability metrics into day-to-day decision-making (Li & Zhu, 2019; Al-Qadi et al., 2017). These tools support predictive maintenance, reduce operational costs, and allow for real-time monitoring of environmental and structural conditions. Moreover, the findings show that smart planning tools, as discussed by Mohamed et al. (2022), and hybrid LCA models (Aurangzeb et al., 2014) are contributing to the digital transformation of RAM. The literature increasingly supports the role of such innovations in overcoming implementation gaps, particularly in areas where manual inspections and reactive maintenance dominate. The reviewed evidence aligns with the broader narrative of infrastructure modernization, where data-driven tools not only enhance sustainability but also promote transparency and accountability in asset management (Teixeira et al., 2020).

Synthesis and Theoretical Contribution

The collective evidence from this review adds empirical weight to theoretical claims in infrastructure and sustainability studies that advocate for a systems-thinking approach to road management. As suggested by Marsden et al. (2018), infrastructure sustainability cannot be achieved in isolation; it requires cross-sectoral integration, participatory governance, and capacity building. This review confirms that successful RAM sustainability strategies are underpinned by multi-level coordination between government bodies, private contractors, technical experts, and community stakeholders. Additionally, the review underscores the utility of the Triple Bottom Line theory and Life Cycle Thinking framework as analytical lenses for evaluating RAM performance. These theoretical approaches were not only referenced in the literature but operationalized in various tools and decision-making processes, confirming their relevance and adaptability to real-world infrastructure management.

6. CONCLUSION

This systematic review has provided a comprehensive analysis of how sustainability principles are integrated into road asset management (RAM) practices globally. The evidence reviewed confirms that sustainability is no longer a peripheral consideration in infrastructure management but a critical pillar that informs planning, execution, and maintenance decisions. The findings reveal that integrating sustainability into RAM offers multidimensional benefits ranging from environmental conservation and economic efficiency to social inclusion and infrastructure resilience. Practices such as life cycle assessment, the use of eco-friendly materials, and preventive maintenance have emerged as essential tools for achieving sustainable infrastructure outcomes.

However, despite the growing awareness and documented benefits, the review has also highlighted significant challenges. These include a lack of standardized sustainability indicators, high upfront investment costs, limited technical capacity, and inconsistent policy enforcement, particularly in low- and middle-income regions. Such barriers constrain the full realization of sustainability goals and emphasize the need for stronger institutional frameworks, capacity building, and stakeholder engagement. Furthermore, the review illustrates how emerging technologies such as smart sensors, BIM-GIS integration, and digital monitoring platforms are transforming RAM into a more data-driven and proactive discipline.

7. RECOMMENDATIONS

Based on the findings of this review, it is recommended that road infrastructure authorities institutionalize sustainability by adopting standardized indicators and incorporating life cycle assessment into all phases of asset management. Governments should develop clear regulatory frameworks that mandate sustainability metrics in both public and private sector projects. Increased investment in training and technical capacity-building is essential to equip professionals with the skills needed for implementing green technologies. Financial incentives and subsidies can help offset the high initial costs associated with sustainable materials and digital innovations. Stakeholder engagement must be prioritized to ensure that RAM strategies reflect local needs and promote inclusivity. Additionally, the integration of smart technologies such as sensors, GIS, and BIM should be mainstreamed to enhance data-driven decision-making. Finally, future research should focus on developing context-specific models that balance environmental goals with economic realities in different regions.

8. CONTRIBUTION TO KNOWLEDGE

This systematic review makes several significant contributions to the existing body of knowledge on sustainable road asset management. First, it synthesizes and consolidates fragmented research across different geographic regions, offering a comprehensive understanding of how sustainability principles are being operationalized within RAM frameworks. Second, by categorizing findings into thematic areas principles, benefits, challenges, and innovations the study provides a structured lens for evaluating the multidimensional nature of sustainability in infrastructure planning. Third, the review highlights the growing influence of digital technologies such as BIM, GIS, and sensor-based monitoring in enhancing sustainability outcomes, thus advancing discourse on smart infrastructure management. Furthermore, the study bridges the gap between theory and practice by contextualizing empirical findings within established frameworks like life cycle thinking and the triple bottom line. Importantly, it identifies implementation barriers often overlooked in mainstream literature, such as institutional resistance, lack of standardized metrics, and socio-political constraints, especially in low- and middle-income countries. Finally, this review creates a foundation for future research by outlining practical pathways and policy implications for integrating sustainability into RAM, thereby supporting both academic inquiry and evidence-based decision-making in transportation infrastructure.

REFERENCES

1. Al-Qadi, I. L., Yang, R., Ozer, H., & El Khatib, A. (2017). Impact of smart technologies on pavement asset management. *Transportation Research Record, 2645*(1), 1–9.
2. Aurangzeb, Q., Al-Qadi, I. L., Ozer, H., & Yang, R. (2014). Hybrid life cycle assessment for asphalt mixtures with high RAP content. *Resources, Conservation and Recycling, 83*, 77–86.
3. Butt, A. A., Toller, S., & Birgisson, B. (2015). Life cycle assessment for the green procurement of roads: A way forward. *Journal of Cleaner Production, 90*, 163–170.
4. Chehovits, J. G., & Galehouse, L. (2010). Energy usage and greenhouse gas emissions of pavement preservation processes for asphalt concrete pavements. *Journal of the Association of Asphalt Paving Technologists, 79*, 1–22.
5. de la Garza, J. M., El Asmar, M., & Lavy, S. (2016). Performance-based sustainable infrastructure funding: A review. *Sustainable Cities and Society, 21*, 57–64.
6. Ferreira, A., Flintsch, G. W., Wang, K. C., & Weninger-Vycudil, A. (2017). Sustainable pavement management: Integrating environmental, economic, and social aspects in decision making. *Transportation Research Record, 2645*(1), 1–7.
7. Huang, Y., Bird, R., & Heidrich, O. (2017). A review of the use of recycled solid waste materials in asphalt pavements. *Resources, Conservation and Recycling, 52*(1), 58–73. https://doi.org/10.1016/j.resconrec.2007.02.002
8. Jasiūnas, J., & Užsienis, G. (2020). Barriers to sustainable road asset management in the Baltic region. *Sustainability, 12*(6), 2299.
9. Li, M., & Zhu, Y. (2019). Integration of BIM and GIS in sustainable pavement management. *Automation in Construction, 98*, 73–85.
10. Li, X., Zhang, L., Ma, T., & Luo, Y. (2020). Life cycle assessment and environmental impact of asphalt pavement maintenance: A review. *Journal of Cleaner Production, 247*, 119115.
11. Loprencipe, G., & Pantuso, T. (2015). Sustainability evaluation of road infrastructure projects. *Procedia - Social and Behavioral Sciences, 195*, 117–126.
12. Marsden, G., Ferreira, A., Bache, I., & Flinders, M. (2018). Governance, devolution and sustainable transport in the UK: A cross-sectoral analysis. *Transport Policy, 64*, 62–70.
13. Mohamed, A. M., Darwish, M., & Elshabrawy, T. A. (2022). Challenges and opportunities for sustainable road infrastructure development in developing countries. *Sustainable Infrastructure, 11*(2), 205–218.
14. Muench, S. T., Anderson, J. L., & Söderlund, M. (2016). Green road rating systems: A review. *Journal of Green Building, 11*(1), 122–144.
15. Nabavi-Pelesaraei, A., Abdollahzadeh, G., & Rafiee, S. (2021). Design of inclusive sustainable road infrastructure: A life-cycle approach. *Transportation Research Part D: Transport and Environment, 94*, 102765.
16. Oke, A. E., Aigbavboa, C. O., & Thwala, W. D. (2019). Sustainable road infrastructure development: The role of cost control in Sub-Saharan Africa. *Engineering, Construction and Architectural Management, 26*(5), 842–857.
17. Papagiannakis, A. T., Lougheed, T., Tighe, S. L., & Gunaratne, M. (2018). Pavement sustainability framework. *Transportation Research Record, 2672*(3), 85–94.
18. Puppim de Oliveira, J. A., & Jabbour, C. J. C. (2017). Environmental management, climate change, and sustainable development: The role of institutions and governance. *Journal of Cleaner Production, 155*, 1–5.
19. Santos, J., Ferreira, A., & Flintsch, G. (2017). A life cycle assessment model for pavement management: Road pavement construction and management in Portugal. *International Journal of Pavement Engineering, 18*(6), 443–459.
20. Silva, R. V., & Costa, M. D. (2018). Perceived barriers to the implementation of sustainable technologies in road construction. *Journal of Cleaner Production, 198*, 179–191.
21. Teixeira, L., Soares, G., & Lima, J. (2020). Remote sensing-based monitoring for sustainable road infrastructure. *ISPRS Journal of Photogrammetry and Remote Sensing, 169*, 106–118.

22. United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development*.
23. Wang, Y., Liu, Y., & Chen, Z. (2018). Cross-national comparison of sustainable road infrastructure practices: China and Canada. *Sustainability*, *10*(4), 1005.
24. Wu, Y., Wang, H., & Zhang, Z. (2015). Evaluation framework for sustainable performance of pavement infrastructure. *Journal of Cleaner Production*, *104*, 303–311.
25. Yuan, Z., Lu, W., & Hao, J. L. (2020). Sustainable road asset management in the era of smart infrastructure: A review and future outlook. *Automation in Construction*, *114*, 103144.