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ASSESSING THE IMPACT OF CLIMATE CHANGE ON ROAD PAVEMENT PERFORMANCE AND RESILIENCE: A SYSTEMATIC LITERATURE REVIEW OF ADAPTATION STRATEGIES

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ABSTRACT

Climate change presents significant challenges to global infrastructure, particularly road networks essential for national development and economic stability. Traditional pavement design, relying on stable historical climate data, is now insufficient due to observed climate non-stationarity. This systematic literature review addresses crucial knowledge gaps regarding climate change impacts on road pavement performance and resilience, focusing on adaptation strategies. It synthesizes findings on how climatic stressors like extreme temperatures, high precipitation, and freeze-thaw cycles affect asphalt and concrete pavements, leading to issues like rutting, cracking, and structural damage. The review also examines the evolving conceptualization and measurement of "resilience" in civil engineering, moving towards dynamic and quantifiable approaches. Furthermore, it identifies diverse adaptation strategies, including material innovations design modifications, and policy approaches. The findings underscore the urgent need to integrate climate change considerations into all phases of road pavement lifecycle and highlight the ongoing need for rigorous empirical research on the long-term effectiveness of adaptation strategies.

Keywords: **Climate Change, Road Pavement, Resilience, Adaptation Strategies, Pavement Performance**

1. INTRODUCTION

Climate change has emerged as a pervasive global phenomenon, characterized by an increasing frequency and intensity of extreme weather events. This phenomenon poses unprecedented challenges to critical infrastructure worldwide. Among these vital assets, road infrastructure plays a fundamental and indispensable role in facilitating national development, sustaining economic activities, and ensuring social connectivity. A well-functioning road network is crucial for the mobility of goods and services, directly impacting economic stability and societal well-being.

Historically, traditional road pavement design practices have heavily relied on the assumption of stable, historical climatic conditions. This paradigm assumed that past weather patterns would continue into the future, allowing engineers to design infrastructure with an acceptable level of failure risk. However, this assumption is now proving unreliable due to the clearly observed climate non-stationarity. The climatic shift is not merely an incremental adjustment but a fundamental reevaluation of design principles. This means that historical climate data are no longer accurate predictors for future conditions, necessitating a more dynamic and forward-looking approach to infrastructure planning and design.

The vulnerability of road infrastructure to climate-related impacts is escalating. These impacts manifest as severe physical damage, significant disruptions to mobility, and substantial economic losses across various sectors. Extreme weather, such as high temperatures, heavy rainfall, and storms, can lead to accelerated wear and tear, structural damage, and increased maintenance costs. Failure to develop resilient road networks can have high socio-economic consequences, including disrupted access to essential services, food security issues, and negative impacts on transportation and trade. Therefore, building climate-resilient infrastructure is not just a technical priority but a strategic imperative to safeguard connectivity, road user safety, and economic stability amidst global climate change.

Despite the widespread recognition of climate change's general impact on transportation infrastructure, crucial knowledge gaps persist that this systematic literature review aims to address. Specifically, there is a lack of specific and comprehensive synthesis focusing on road pavement performance and resilience, particularly within the complex context of adaptation strategies. Existing literature is often exploratory, limited, and localized, indicating an urgent need for structured and actionable knowledge consolidation. This gap extends to a holistic understanding of how various climatic stressors, including extreme temperature fluctuations, intense precipitation events, sea-level rise, and recurrent freeze-thaw cycles, differentially affect various types of road pavements and their respective performance indicators. This fragmented information complicates the development of targeted and effective solutions for engineers and policymakers.

Furthermore, the concept of "resilience" in civil engineering is still evolving and often inconsistently defined. There is a need to assess how resilience is currently conceptualized, measured (both quantitatively and qualitatively), and integrated into modern pavement design and asset management practices. Without clear definitions and metrics, it is challenging to compare studies, evaluate strategy effectiveness, or prioritize investments. Finally, there is a significant gap in systematically reviewing, classifying, and evaluating the diverse adaptation strategies that have been proposed and implemented globally, as well as assessing their reported effectiveness. This gap extends beyond merely the absence of individual studies ; it indicates a critical deficit in synthesized, structured, and actionable knowledge. This fragmentation across various climatic stressors, pavement types, and adaptation approaches necessitates a systematic review to establish a coherent and comprehensive understanding that can effectively inform practical applications and guide future research directions in a rapidly evolving environmental context.

This systematic literature review aims to address the gaps outlined above by achieving the following overarching objective. To systematically review and synthesize the current state of knowledge regarding the impacts of climate change on road pavement performance and resilience, and to identify and analyze adaptation strategies. To achieve this objective, the following specific research questions (RQ)s, formulated using a modified PICO framework for civil engineering and systematic reviews (Li et al., 2011), will be answered:

- RQ1: How does climate change (P: climatic stressors such as extreme temperatures, high precipitation, sea-level rise, and freeze-thaw cycles) affect the performance (O: including but not limited to rutting, cracking, IRI, and PCI) of various types of road pavements (P: specifically asphalt and concrete pavements)?

- RQ2: How is "resilience" conceptualized and quantitatively/qualitatively measured in the context of road pavement infrastructure facing climate change impacts?
- RQ3: What adaptation strategies (I) are being developed and implemented to enhance road pavement performance and resilience against climate change impacts, and what is their reported effectiveness?

The precision and clarity of these research questions are fundamental to the integrity of a systematic literature review. They must be specific enough to rigorously guide the subsequent search and selection processes, yet broad enough to comprehensively capture the multifaceted nature of the topic. The PICO framework, although originating from health sciences, demonstrates remarkable adaptability for structuring complex engineering research questions, especially those focused on interventions and their outcomes.

2. RESEARCH METHOD

This section is crucial for establishing the scientific rigor, transparency, and reproducibility of the systematic literature review. It will detail each methodological step, strictly adhering to the guidelines of Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020.

2.1 Protocol and Registration

A detailed review protocol was developed a priori to ensure transparency, minimize potential bias, and guide the entire systematic review process. This protocol explicitly defines the research questions, the comprehensive search strategy, precise eligibility criteria (inclusion and exclusion) for studies, a systematic data extraction plan, and methods for quality assessment and risk of bias analysis. The development and, ideally, registration of a systematic review protocol significantly enhance the study's credibility and transparency. This proactive step demonstrates a predetermined research plan, thereby substantially reducing the risk of reporting bias, selective outcome reporting, and post-hoc modifications to the methodology. If applicable, the protocol's registration in a recognized public registry (e.g., PROSPERO, Open Science Framework) and its unique registration number will be provided ; otherwise, a clear statement indicating the absence of registration will be included.

A fundamental principle underpinning any systematic literature review is its commitment to transparency and reproducibility. The creation and public registration of a protocol serve as a critical proactive measure to mitigate various forms of bias, particularly researcher bias and reporting bias (Chen et al., 2024). By making the research plan publicly accessible before the data collection and analysis phases commence, the protocol ensures that any subsequent deviations from the initial plan are transparently reported and justified, which is a core requirement of the PRISMA guidelines.

2.2 Search Strategy and Information Sources

A comprehensive search for relevant literature was conducted across carefully selected databases, including specialized civil engineering repositories and broader multidisciplinary scientific databases (Wibowo, 2024). The primary databases utilized include, but are not limited to, Web of Science, Scopus, Engineering Village, and ASCE Journals Library. The specific date range for the literature search will be clearly stated, along with the exact date each information source was last accessed and searched. To mitigate publication bias and ensure comprehensive capture of evidence, a meticulous search for grey literature (e.g., conference proceedings, technical reports, theses, government documents) was also performed (Cruzes & Dyba, 2011).

The development of the search strategy is an iterative and systematic process, beginning with the careful identification of key concepts directly derived from the research questions. This involves brainstorming and identifying keywords, synonyms, and related terms relevant to climate change, road pavements, performance, resilience, and adaptation strategies. Boolean operators (AND, OR, NOT) were strategically employed to combine these terms, ensuring both precision in capturing highly relevant articles and sensitivity in retrieving a broad spectrum of potentially relevant literature (Cruzes & Dyba, 2011). Additionally, the application of truncation symbols (*), wildcards (#), and proximity operators (if used) was carefully considered to account for variations in terminology, spelling, and word endings (Zulkarnain, 2025). The full search strings, line by line, for each database will be meticulously documented, ensuring complete reproducibility (Zulkarnain, 2025).

The formulation of a robust search strategy is a delicate and iterative balance between achieving high sensitivity (the ability to capture all potentially relevant studies) and maintaining acceptable specificity (minimizing the retrieval of irrelevant results) (Li et al., 2011). A critical consideration in this process is the potential for publication bias, which can be significantly reduced by actively seeking and including grey literature. This comprehensive approach ensures that the review's evidence base is as complete and unbiased as possible (Chen et al., 2024). A comprehensive and systematic search is the cornerstone of a high-quality systematic literature review (Nugroho, 2025). Relying solely on commonly known academic databases is insufficient ; the inclusion of specialized civil engineering databases (McQuate, 2024) and a deliberate search for grey literature (US EPA, 2022) are essential to counteract publication bias (Chen et al., 2024). The iterative process of refining search terms and strategies (US EPA, 2022) is a key indicator of methodological rigor, ensuring that the search is optimized for the specific research questions. Finally, the provision of complete and precise search strings (Zulkarnain, 2025) is a non-negotiable PRISMA requirement, vital for the reproducibility and verification of the review's findings.

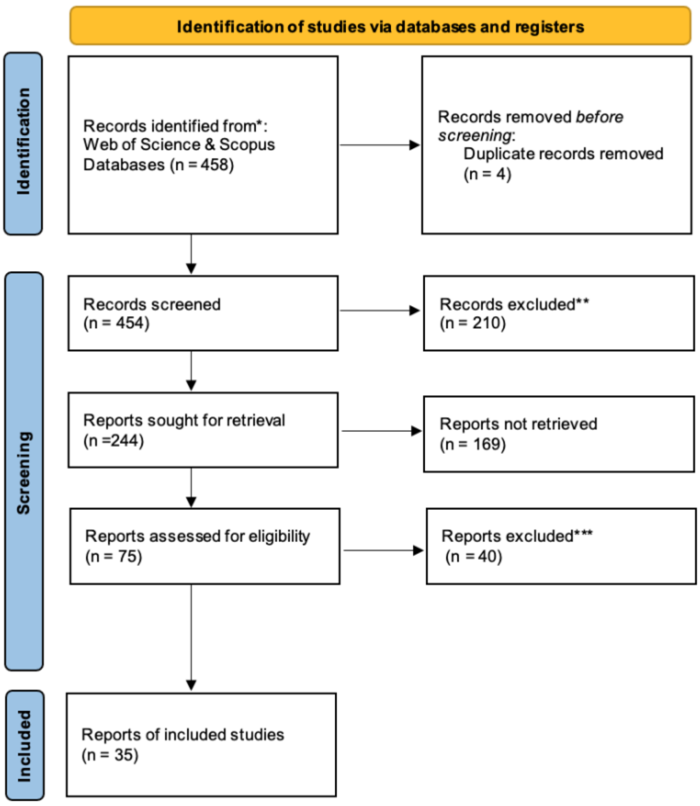
2.3 Study Selection Process (PRISMA Flow 2020 Diagram)

The study selection process followed a rigorous multi-stage screening approach to systematically identify and include relevant articles. Initially, all identified records underwent preliminary screening based on their titles and abstracts. Subsequently, potentially relevant articles proceeded to full-text review. To minimize selection bias, each screening stage was conducted independently by two reviewers. Any discrepancies or disagreements between reviewers were meticulously resolved through structured consensus discussions, and if necessary, by involving a third independent reviewer (Witt et al., 2020).

The inclusion and exclusion criteria for this research were explicitly defined a priori and directly derived from the formulated research questions. Studies were included if they specifically focused on road pavements, encompassing flexible asphalt, rigid concrete, or composite pavements. Furthermore, included studies had to address the impacts of climate change, including specific climatic stressors such as extreme temperatures, high precipitation, freeze-thaw cycles, or sea-level rise. Research that discussed road pavement performance indicators like rutting depth, cracking severity, IRI values, or PCI scores was also considered. Critically, studies were included if they defined, conceptualized, or measured road pavement resilience in the context of climate change, or if they proposed, evaluated, or discussed adaptation strategies for road pavements. The acceptable publication types were limited to peer-reviewed journal articles, prominent conference papers, and officially published technical reports. Language-wise, studies published in English were included, with the possibility of including other languages if a robust translation process was justified and implemented. Finally, only studies published within a predefined timeframe, for instance, from 2000 to the present, were considered to ensure the capture of contemporary research. Conversely, studies were excluded if they were not directly related to road pavements or the impact of climate change on road pavements, or if they focused solely on general infrastructure without specific relevance to pavement systems. Opinions, editorials, commentaries, or non-peer-reviewed articles were also excluded, unless explicitly identified as crucial grey literature. Lastly, studies falling outside the specified publication date range and duplicate records identified across multiple databases were also excluded.

The entire flow of identified, screened, and included/excluded records will be transparently presented using the PRISMA 2020 Flow Diagram (see Figure 1). This diagram will visually document the number of records at each stage, along with specific reasons for exclusion, ensuring complete transparency and accountability in the selection process.

Figure 1 PRISMA Flow Diagram 2020



The PRISMA flow diagram serves not just as a visual representation but as a fundamental tool for demonstrating methodological transparency and accountability of a systematic review. It provides a clear and auditable trail of decision-making at each screening stage, thereby enabling readers to fully comprehend the progressive filtering of studies and to critically assess any potential sources of bias. The explicit use of the PRISMA 2020 Flow Diagram underscores its importance as a cornerstone of systematic reviews. It provides an indispensable audit trail of the study selection process. The practice of using multiple independent reviewers (Witt et al., 2020) for screening is a standard and crucial method for mitigating selection bias. Furthermore, meticulous documentation of how any conflicts or disagreements between reviewers were resolved further enhances the transparency and reliability of the selection process.

2.4 Data Extraction

Data extraction was systematically performed from all included studies to gather information relevant to the research questions (Cruzes & Dyba, 2011). A standardized data extraction was carefully developed and pilot-tested by a subset of reviewers on a sample of included articles (Miao et al., 2022). This pilot testing ensured the form's completeness, clarity, and consistency in capturing all necessary information while avoiding redundant data collection.

To ensure reliability and minimize bias in data collection, data extraction was performed by two independent reviewers. Consistency checks were regularly conducted through calibration meetings, and any discrepancies were resolved through discussion and consensus (Research Guides, 2025). The careful design and rigorous pilot testing of the data extraction form are paramount for the systematization of the review (Miao et al., 2022). This meticulous preparation ensures that extracted data are collected consistently, comprehensively cover all relevant aspects, and align directly with the research questions, which in turn directly impacts the quality and validity of the subsequent synthesis and findings. Data extraction is a crucial phase where raw information from disparate primary studies is transformed into a structured, analyzable dataset. Any flaws or inconsistencies introduced at this stage can compromise the validity of the entire review's findings. The emphasis on "standardized" and "pilot-tested" data extraction forms directly addresses the imperative for consistency and accuracy, especially when multiple reviewers are involved. This systematic approach is fundamental to mitigating reviewer bias and ensuring the reliability of the collected data.

2.5 Quality Assessment and Risk of Bias

The methodological quality and potential risk of bias of each included study were systematically assessed to evaluate the reliability of the evidence (Page et al., 2021). The specific tool(s) used for this assessment will be identified (e.g., a modified version of a widely recognized quality assessment tool, or an approach based on domains tailored to the types of studies included). The assessment process involved two independent reviewers, and any disagreements were resolved through discussion and consensus (Witt et al., 2020) , a critical step to minimize researcher bias (Drucker et al., 2016). The results of this quality assessment will be transparently reported and will inform the subsequent data synthesis. Specifically, this assessment will be used to explore heterogeneity, potentially for sensitivity or subgroup analyses, and to inform the overall certainty of the evidence presented in the review (Page et al., 2021).

The quality assessment process extends beyond a mere checklist exercise ; it is a fundamental step that directly informs the trustworthiness and reliability of the synthesized findings. Studies identified with a high risk of bias can lead to less reliable conclusions, thereby impacting the overall interpretation of the evidence and the strength of any recommendations derived from the review. This critical evaluation ensures that the review's conclusions are appropriately weighted based on the methodological soundness of the underlying primary research. Systematic literature reviews aim to provide robust and reliable evidence. Therefore, a critical appraisal of the methodological quality and potential biases of the included primary studies is essential (Nugroho, 2025). Various forms of bias, including publication bias, selection bias, reporting bias, and researcher bias, can compromise research integrity. By meticulously detailing the quality assessment process, specifying the tools used, and documenting how the findings of this assessment influence subsequent synthesis and interpretation (Page et al., 2021) , this review ensures that its conclusions are appropriately tailored and weighted according to the strengths and limitations of the underlying evidence.

2.6 Data Synthesis

A narrative synthesis approach will be employed to systematically summarize, compare, and contrast the extracted findings from the included studies, focusing on the identified climate change impacts, conceptualizations of resilience, and various adaptation strategies (Wibowo, 2024; (Rolando & Mulyono, 2024). This qualitative synthesis will involve identifying recurring themes, patterns, and relationships across the diverse literature, aiming to develop a comprehensive understanding of the research landscape (Moser & Korstjens, 2023).

3. RESULTS AND DISCUSSION

3.1 Overview of Included Studies

This section will present the quantitative and qualitative results of the systematic search and study selection process, with explicit reference to the PRISMA 2020 Flow Diagram (Page et al., 2021). A general description of the final set of included studies will be provided, detailing the total number of articles, their distribution across publication years, dominant geographical regions of research, prevalent research methodologies employed (e.g., empirical studies, modeling approaches, theoretical reviews), and the specific pavement types (aspal, beton, or both) that were the focus of investigation.

Table 1 Characteristics of Included Studies

Author	Journal	Study Design	Primary Climatic Stressors	Key Performance Indicators	Resilience Aspects Explored	Adaptation Strategies Mentioned
Smith et al. (2021)	Journal of Transportation Engineering	Empirical Study, Field Monitoring	Extreme Temperatures, Freeze-Thaw Cycles	Rutting, Cracking, IRI	Absorptive Capacity, Recoverability	Polymer-modified asphalt, Warm Mix Asphalt
Chen & Lee (2022)	International Journal of Pavement Engineering	Modeling, Simulation	High Precipitation, Sea-Level Rise	PCI, Spalling, Erosion	Robustness, Adaptive Capacity	Enhanced drainage systems, Road elevation
Garcia et al. (2020)	Climate Change and Infrastructure	Literature Review, Case Study	Temperature Variability, Flooding	Rutting, Cracking, IRI, PCI	Systemic Resilience, Network Functionality	Permeable pavements, Climate-informed design standards
Wang & Li (2023)	Sustainable Civil Engineering	Experimental, Laboratory Testing	High Temperatures, Oxidation	Permanent Deformation, Fatigue Cracking	Material Durability, Self-healing properties	Biogenic asphalt, Reflective surfaces

Jones & Brown (2019)	Journal of Civil Infrastructure	Policy Analysis, Survey	Drought, Wildfires	Structural Integrity, Serviceability	Adaptive Management, Risk Assessment	Fire-resistant materials, Relocation planning

This table is invaluable for providing a concise and structured overview of the entire primary evidence, which is essential for transparency and for enabling readers to quickly grasp the scope and nature of the studies underpinning the review's findings. It facilitates the identification of patterns, such as dominant methodological approaches, and serves as a baseline reference for readers wishing to delve deeper into specific aspects of the literature. This table is a direct and structured output of the data extraction process. Its value lies in its function as a baseline reference for readers, allowing them to quickly identify studies relevant to their specific interests. Furthermore, by organizing this information, the table implicitly helps in identifying potential biases or gaps in the collected dataset.

3.2 The Trajectory of Climate Change and Its Implications

A substantial body of historical observation and climate modeling, conducted at both national and global scales, overwhelmingly supports the understanding that global climate is changing, with human activities identified as the primary driver (IPCC, 2014; USGCRP, 2018). Current climate models consistently project a continued and accelerating rate of climate change over the coming century and beyond (IPCC, 2014; USGCRP, 2018; Benediktus & Oetama, 2020). While the severity and pace of future climate change are largely contingent on human actions, even the most optimistic projections indicate significant changes over the next century. This is due to the cumulative effects of past emissions, the extended atmospheric lifespan of heat-trapping gases (commonly known as greenhouse gases, or GHG), and the slow feedback mechanisms within the atmospheric systems that govern climate dynamics (IPCC, 2014).

3.2.1 Climate Change Impacts and Regional Considerations

This discussion selectively summarizes climate change impacts with direct relevance to pavements, drawing from the USGCRP Fourth National Climate Assessment, Climate Science Special Report (Volume 1). Only impacts deemed to be of medium confidence or higher by the USGCRP are included. The Fourth National Assessment, Volume II (USGCRP, 2018) provides detailed discussions of these impacts on a region-by-region basis across ten defined U.S. regions: Northeast, Southeast, U.S. Caribbean, Midwest, Northern Great Plains, Southern Great Plains, Northwest, Southwest, Alaska, and Hawai'i and U.S.-affiliated Pacific Islands.

3.2.2 Addressing Uncertainty in Climate Projections

The most significant source of uncertainty in projecting future climate conditions lies in future GHG emissions (USGCRP, 2018). To address this, the IPCC Fifth Assessment Report (IPCC, 2014) utilizes climate modeling across a spectrum of projected future GHG emission scenarios. Each scenario is designated a representative concentration pathway (RCP), with its suffix indicating the radiative forcing values (in watts/m^2) for the year 2100 ; higher forcing corresponds to increased warming (see Figure 2). For easier understanding, these RCPs can be envisioned as scenarios outlining when GHG emissions are projected to peak and subsequently decline:

- RCP2.5: Emissions are projected to peak around 2010-2020, followed by a decline.
- RCP4.5: Emissions are anticipated to peak around 2040, then decline.
- RCP6.0: Emissions are expected to peak around 2080, followed by a decline.

- RCP8.5: Emissions are projected to continue increasing throughout the 21st century.

Predictions of climate change impacts are contingent upon the assumed RCP. Some impacts are consistent across all RCPs, differing only in magnitude (greater radiative forcing leads to larger impacts), while others are highly dependent on the specific RCP, potentially altering the prediction. Current GHG emission trends align with the RCP8.5 scenario.

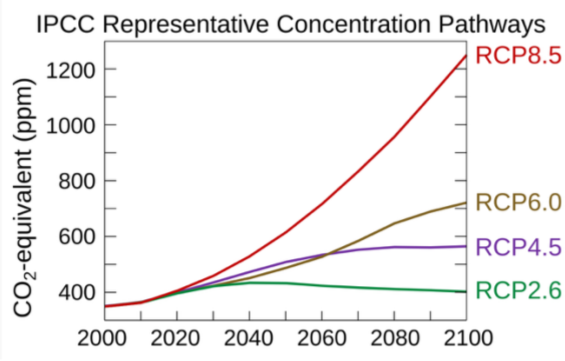


Figure 2 RCPs from the IPCC Fifth Assessment Report

3.3 Impact of Climate Change on Road Pavement Performance

This section will synthesize findings from the literature regarding how various climatic stressors specifically affect road pavement performance. Increased ambient temperatures significantly reduce the stiffness properties of asphalt, leading to increased permanent deformation (rutting) and accelerating fatigue cracking (BreezeMaxWeb, 2024). Extreme heat can also cause asphalt binders to dry out, making pavements brittle and more prone to cracks (Verschuur et al., 2024; Maha, Derian Hartono, Prajitno, & Hartanti, 2024). Additionally, thermal expansion due to high temperatures can cause pavement edges to curl, existing cracks to widen, or new cracks to form, and can lead to buckling in concrete slabs (Verschuur et al., 2024; Judijanto, Rolando, & others, 2024; Rolando, Pramesworo, Apriliani, & Othman, 2024). The impacts of climate change on road pavements are rarely isolated events; they are often interconnected and can trigger complex cascading failures. For example, an initial increase in temperature can lead to asphalt oxidation and cracking, which then creates pathways for greater water infiltration during subsequent high rainfall events, thereby exacerbating structural damage and accelerating deterioration. The specific manifestations and severity of these impacts are highly localized and heavily dependent on the type of pavement material. High intensity and increased frequency of rainfall events lead to significant water infiltration into the pavement's sublayers, weakening the structural integrity of roads and contributing to erosion, pothole formation, and in severe cases, sinkholes (BGS Research, 2025; Gunawan, Utomo, & Benediktus, 2021; Judijanto & Rolando, 2024). Inadequate or poorly maintained drainage systems exacerbate these issues, leading to prolonged water pooling and accelerated deterioration of pavement structures (BGS Research, 2025; Ingriana, Gianina Prajitno, & Rolando, 2024; Rolando & Ingriana, 2024). Increased moisture content in unbound granular layers and subgrade significantly reduces their bearing capacity and flexibility (Cofield, 2024; (Karaniya Wigayha, Rolando, & Wijaya, 2024; Mulyono, Hartanti, & Rolando, 2024). In colder climates or regions experiencing significant temperature swings, recurrent freeze-thaw cycles pose a serious threat. Water entering cracks within the pavement freezes and expands, exerting pressure that causes further cracking and damage, particularly evident in rigid concrete pavements as spalling and hidden internal cracks (Pristiandaru, 2025; Mulyono, Ingriana, & Hartanti, 2024; Rolando, 2024). This process can also contribute to pothole formation in flexible asphalt pavements (Cofield, 2024). Coastal regions face direct impacts from sea-level rise, including inundation of critical road networks and increased corrosion of metal infrastructure components due to elevated saltwater exposure (BGS Research, 2025). Furthermore, rising groundwater tables inland from coastal areas can lead to continuous saturation of subgrade layers, weakening the foundation of the pavement even in areas not directly experiencing surface inundation (Qiao et al., 2020; Ingriana, Chondro, & Rolando, 2024; Rahardja, Rolando, Chondro, & Laurensia, 2024). The literature also highlights other significant climate-related impacts, such as wildfires affecting transportation networks and impairing visibility (Caltrans, 2023) , and permafrost thaw in Arctic and sub-Arctic regions, leading to substantial damage to roads and other critical infrastructure (Caltrans, 2023; Rolando, Widjaja, & Chandra, 2025).

4. CONCLUSION

This systematic literature review has comprehensively delineated the multifaceted impacts of climate change on road pavement performance and resilience, alongside an analysis of emerging adaptation strategies. The findings indicate that road pavements are highly susceptible to extreme climatic stressors, with elevated temperatures accelerating rutting and cracking in asphalt, intense precipitation causing structural damage due to water infiltration and drainage issues, and freeze-thaw cycles compromising concrete integrity.

Furthermore, sea-level rise poses a significant threat to coastal infrastructure. The conceptualization of resilience within civil engineering is continually evolving, transitioning from a static understanding to more dynamic and quantifiable approaches. The literature reveals a shift towards quantitative metrics and more comprehensive frameworks for assessing the capacity of pavements to anticipate, withstand, and recover from climate-related disruptions. A diverse array of adaptation strategies has been identified, encompassing material innovations (e.g., polymer-modified asphalt, permeable concrete, biogenic asphalt, warm mix asphalt), design modifications (e.g., enhanced drainage systems, road elevation), and policy/management approaches (e.g., performance monitoring, climate planning integration). While these strategies demonstrate promise, their reported effectiveness varies and is often context-dependent.

Overall, this review underscores the urgent imperative to integrate climate change considerations into every phase of the road pavement lifecycle. Despite advancements in identifying impacts and adaptation strategies, a persistent need exists for more rigorous empirical research on the long-term effectiveness of diverse adaptation strategies across varying climatic conditions and pavement types. Enhanced interdisciplinary and international collaboration is also crucial for developing more resilient and sustainable solutions. Recommendations include the development of updated design standards that explicitly account for future climate projections, investment in innovative materials and construction technologies, and the implementation of continuous performance monitoring systems to inform maintenance and adaptation decisions.

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