



Micropaving in Road Infrastructure: A Systematic Review of the Factors That Limit Its Application

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Abstract

Micropaving is an efficient and sustainable alternative for road infrastructure conservation and maintenance; however, its application remains limited in various contexts. This situation is due to multiple factors that restrict its adoption, including technical ignorance, lack of clear regulations, institutional resistance to change, and weaknesses in the training of responsible actors. Therefore, the purpose of this research is to identify, based on a review of the academic literature, the main barriers that affect the use of micropaving, both in road construction and maintenance processes. Methodologically, the study was developed using a qualitative approach, with a descriptive scope and a design based on a document review. The results show that the limitations are related to technical, economic, and administrative factors. It is concluded that it is necessary to design strategies that strengthen the dissemination of knowledge about micropaving and promote its incorporation into public road infrastructure policies, given its proven effectiveness in various international scenarios.

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Introduction

Road infrastructure is an essential component for economic development, territorial connectivity, and regional competitiveness. According to Khahro (2022) and Ayalew (2022), proper road maintenance reduces logistics costs, improves road safety, and promotes sustainable economic growth. Among the techniques applied to road maintenance, micropaving has established itself in some countries as an efficient, low-cost alternative with less environmental impact than other conventional solutions (Boralkar and Nirkhe, 2023). This cold surface treatment, composed of asphalt emulsion, fine aggregates, water, and additives, is particularly valued for its rapid application and for minimizing traffic disruption (Ravekar and Jaju, 2022). However, despite its many technical and economic benefits, its application in various regions remains limited.

In Latin America, and particularly in Colombia, the use of micropaving has not been widely adopted, partly due to a lack of technical knowledge among decision-makers and professionals in the sector, the absence of specific regulations, and the lack of training programs in this technology (Fares y Zayed, 2023). Furthermore, as noted by the Colombian Chamber of Infrastructure (2020), there is an institutional preference for traditional road maintenance methods, which limits innovation in this field. Studies conducted by (De Rose et al., 2023) have identified that, although micropaving has performed well in strategic corridors, it still faces resistance to its implementation by some local administrations and contractors. This situation reveals significant gaps in the dissemination, appropriation, and systematization of technical knowledge related to this technique.

Given this problem, it is important to identify and understand the factors that limit the implementation of micropaving in road construction and maintenance projects. This review is valuable not only from a technical perspective, but also from a strategic point of view for planning public policies that promote sustainable technologies. As Alhjouj et al. (2022) point out, modern road infrastructure management must incorporate innovative solutions that optimize resources and contribute to the sustainability of the transportation system.

The purpose of this research is to establish, based on a review of academic literature, the barriers that affect or limit the use of micropaving in both road construction and maintenance. In particular, it seeks to identify the factors that restrict its implementation, analyze its implications in the technical and administrative spheres, and propose recommendations aimed at promoting its application in the context of road infrastructure.

Theoretical framework

This theoretical framework aims to establish the conceptual and technical foundations for understanding micropaving as an alternative in road infrastructure conservation and maintenance processes. Given that this technique has shown positive results in terms of efficiency, sustainability, and cost, it is necessary to explore its characteristics, benefits, and differences from other road technologies. Understanding these aspects will subsequently facilitate the analysis of the factors that have limited its adoption in different contexts, particularly in regions where its application is still in its infancy. In this sense, the framework is structured around three axes: the conceptualization of micropaving and its technical characteristics, the advantages it offers in road maintenance, and a comparison with other traditional paving technologies.

Conceptualization and technical characteristics of micro-paving

Micropaving is a surface treatment technique used mainly in preventive road maintenance programs. It consists of the cold application of a mixture of polymer-modified asphalt emulsion, fine mineral aggregates, Portland cement, water, and additives, which is placed on existing surfaces to restore texture, improve adhesion, and extend the service life of the pavement (Moura et al., 2023). This technology is developed using specialized equipment that mixes the components and spreads them evenly, allowing for rapid reopening to traffic, making it an efficient solution in terms of time and cost.

One of the main technical characteristics of micropaving is that it does not require heating, which significantly reduces energy consumption during its application, as well as reducing the carbon footprint compared to other traditional techniques (Bhargava et al., 2021). In addition, its design is aimed at correcting minor deformations, improving the macrottexture of the pavement, and increasing road safety without the need to remove the existing surface, which also minimizes waste generation.

The thickness of application usually ranges between 6 and 10 millimeters, depending on the type of road and the existing deterioration, and can be laid in one or two layers, depending on the project requirements. Due to its versatility, it is especially recommended for urban roads and highways with medium traffic levels, although its use has been successfully extended to high-traffic corridors in countries such as Chile, Mexico, and the United States (Bhargava et al., 2019).

Finally, from a regulatory standpoint, micro-paving has technical specifications contained in road maintenance manuals, such as those published by the National Roads Institute (INVIAS, 2022) in Colombia, as well as international standards that guide its design, application, and quality control.

Advantages and benefits of microsurfacing in road maintenance

Microsurfacing is a road construction and maintenance technique that offers multiple technical, economic, and environmental benefits. Its main advantage lies in its ability to rehabilitate the road surface without removing the existing pavement, which significantly reduces execution times, operating costs, and environmental impact (Mousa et al., 2021). This technique improves the surface texture of the pavement, increases skid resistance, and seals minor cracks, helping to extend the service life of the base pavement by three to seven years, depending on traffic and weather conditions (Bashar et al., 2019).

Compared to other conventional solutions such as overlaying, micro-paving requires less heavy machinery and does not require heat, which translates into lower energy consumption. This feature not only reduces costs but also helps to reduce pollutant emissions and the carbon footprint associated with road projects (Zheng et al., 2021).

Another noteworthy aspect is the speed with which traffic can be restored once the mixture has been applied. In most cases, traffic can resume between 30 minutes and one hour after application, which is ideal for urban environments and strategic roads where prolonged closures are not possible. This operational advantage has been particularly valued in countries such as Spain, where micropaving is frequently used in nighttime highway repairs to minimize disruption to users (Kilić Pamuković et al., 2021).

In addition, micro-paving performs well in terms of crack reflection, oxidation aging, and loss of surface texture, making it a comprehensive solution for maintaining road functionality and safety. Furthermore, it can be applied as part of a routine or periodic maintenance strategy, adapting to different needs and geographical conditions (INVIAS, 2022).

In summary, micro-paving represents a versatile, sustainable, and cost-effective option for road maintenance. Its adoption can contribute not only to optimizing the technical and financial resources of the entities responsible for infrastructure, but also to improving the quality of road services offered to citizens.

Comparison of micro-paving with other road maintenance technologies

Road maintenance includes a variety of treatments and techniques that vary depending on the type of deterioration, traffic levels, and environmental weather conditions. Among the most widely used technologies are hot overlay construction, double surface treatments (TSD), slurry seal, crack sealing, and micro-paving. Although all these options seek to preserve pavement functionality, they differ in aspects such as cost, execution time, durability, and environmental impact (Nair and McGhee, 2022).

The hot overlay technique, for example, involves placing a new layer of asphalt mix on top of the existing structure. Although this technique offers high strength and durability, it involves high material, transportation, and operating costs, as well as requiring prolonged road closures and higher energy consumption due to the use of high temperatures (Alharbi et al., 2022). In contrast, micro-paving is applied cold, which reduces the environmental impact and allows for almost immediate reopening of the road. (Hesami et al., 2022).

On the other hand, slurry seal, although also a cold-applied mixture, performs worse than micro-paving in terms of strength and durability. Slurry is mainly used as an aesthetic solution or to improve adhesion on low-traffic roads, while micro-paving can be used on medium- or even high-traffic corridors, thanks to its better mechanical performance and greater thickness (Buss and Claypool, 2022; De Rose et al., 2023).

As for double surface treatments, these offer good waterproofing and wear resistance results, but require a greater amount of aggregates and emulsion, and their application can generate increased rolling noise and particle detachment in the initial phase of use (Umutoniwase et al., 2023). Micropaving, on the other hand, offers a uniform and continuous texture, improving user comfort and reducing subsequent maintenance (Chen et al., 2021).

The choice between these technologies depends not only on technical characteristics, but also on institutional willingness to adopt innovative solutions. In many contexts, the preference for traditional methods is more a response to management habits or resistance to change than to efficiency criteria (Nascimento et al., 2023). Thus, although micropaving has clear advantages in many respects, its implementation is still limited, partly due to the lack of technical information and clear regulations promoting its use.

This comparison shows that micropaving is not only competitive, but in several scenarios, it is more favorable than other solutions, especially when seeking sustainability, speed, and resource optimization.

Methodology

This research was conducted using a qualitative approach with a descriptive scope, based on a systematic literature review design guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol. This methodological choice addresses the need to rigorously and reproducibly identify, analyze, and synthesize the main barriers limiting the application of micro-paving in road infrastructure projects. The adopted design allowed for an examination of the current state of scientific knowledge on the subject, the identification of recurring patterns in the academic literature, and the recognition of the technical, economic, and administrative factors that influence the adoption of this technology in various geographic contexts.

The information search and retrieval strategy was developed through searches of high-impact academic databases, including Scopus, Web of Science, ScienceDirect, IEEE Xplore, Redalyc, Dialnet, and Google Scholar. To ensure the relevance of the documents, search queries were formulated using the Boolean operators AND and OR, combining key terms in Spanish and English such as “micropavimento,” “micro-surfacing,” “road maintenance,” “road infrastructure,” and “implementation barriers.” The searches were limited to the 2019–2023 period to identify recent trends. Additionally, relevant technical and regulatory documents were included to complement the analysis.

The process of selecting the document corpus was structured according to the four phases of the PRISMA protocol: identification, screening, eligibility, and inclusion. During the identification phase, 100 bibliographic references were retrieved from the searches conducted. Subsequently, during the screening phase, inclusion criteria were applied to scientific articles, graduate theses, technical reports, and regulatory documents in full text related to the application or implementation of micro-paving in road maintenance. Excluded were studies conducted exclusively in a laboratory setting, duplicate documents, publications without institutional backing, and those outside the established time frame. Following a critical review of abstracts and full-text documents, a final corpus of 68 sources was compiled.

The study was conducted in three sequential stages. The first stage focused on the search, retrieval, and systematic organization of bibliographic sources, using reference management software to ensure the traceability of the process. The second stage focused on the qualitative analysis of the literature through comprehensive reading, thematic coding, and the identification of patterns, trends, and gaps associated with limitations in the implementation of micro-paving. The third stage consisted of a critical discussion of the findings, comparing them with the theoretical framework and formulating recommendations to promote the adoption of this technology in public road infrastructure policies.

Results

The results of this systematic review are derived from a qualitative analysis of the selected body of literature, conducted in accordance with the PRISMA protocol. Based on the 68 sources that met the inclusion criteria, a process of comprehensive reading and thematic coding was conducted, which allowed for the identification of recurring patterns, research trends, and gaps in the literature regarding the application of micro-paving in road infrastructure. These results provide a structured overview of the current state of knowledge and the factors that limit its implementation in different contexts.

The literature review revealed that, although micro-paving is recognized as an efficient and sustainable technique, its adoption faces multiple barriers that go beyond strictly technical considerations. The studies reviewed highlight regulatory, economic, and administrative factors that significantly influence institutional decision-making. In this regard, the findings provide insight into the complexity of the phenomenon and the interaction between technical and public management variables.

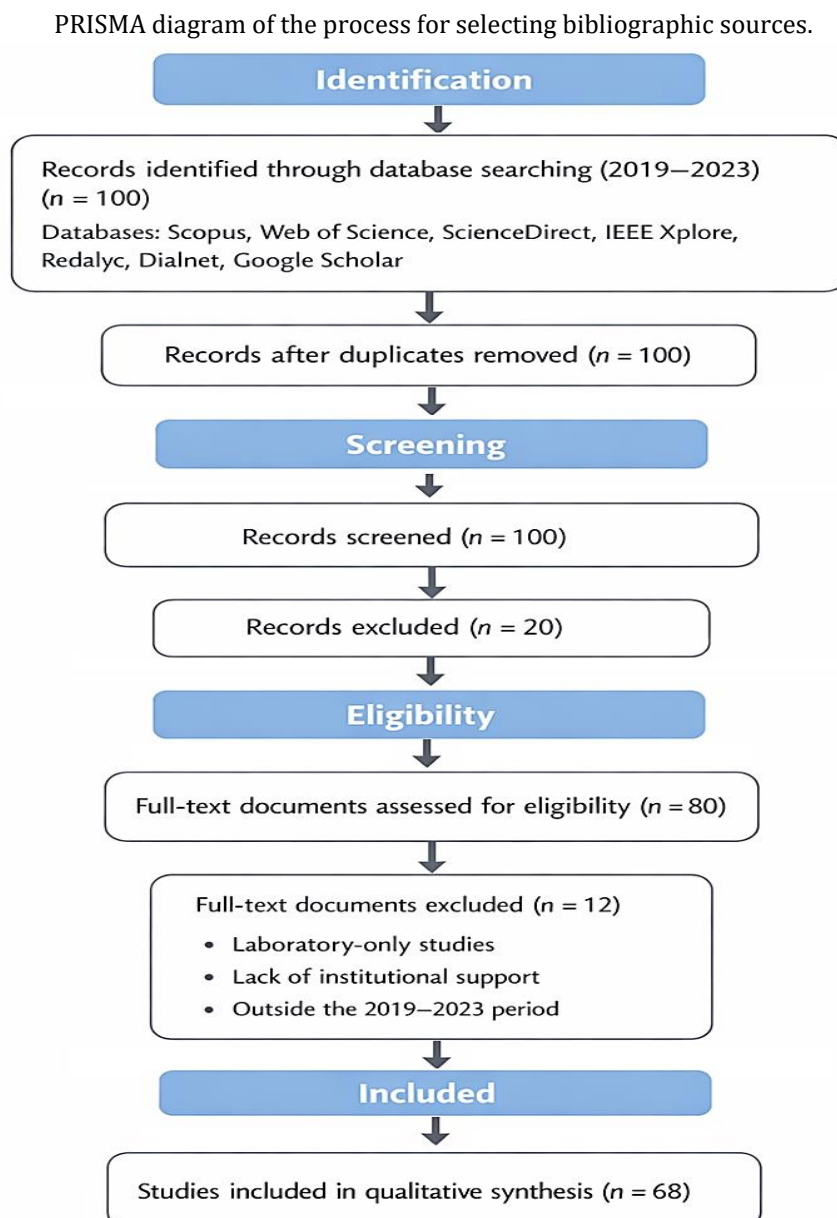
The presentation of the results is organized according to the stages of the research process. First, the findings related to the identification and characterization of the bibliographic sources that made up the final corpus are presented. Next, the results of the qualitative literature analysis are presented, organized into emerging thematic categories. Finally, the main findings that underpin the discussion and the recommendations formulated in the study are summarized.

Results – Stage 1: Retrieval and Characterization of Bibliographic Sources

The information retrieval process identified a total of 100 potentially relevant documents related to micro-paving and its application in road infrastructure maintenance. The sources come primarily from high-impact international academic databases, which demonstrates a growing interest in this technique in recent years. However, an uneven distribution of scientific output was observed, with a predominance of studies conducted in countries with established road maintenance policies.

The process of refining and selecting the document corpus was carried out in accordance with the phases of the PRISMA protocol: identification, screening, eligibility, and inclusion. As shown in Figure 1, after removing duplicate documents and applying the inclusion and exclusion criteria, a final corpus of 68 bibliographic sources was compiled. The PRISMA diagram allows for a systematic and transparent visualization of the methodological decisions made during the selection process.

Figure 1



Note: The figure illustrates the steps of the PRISMA protocol followed in the selection of bibliographic sources. The searches were conducted using key terms in Spanish and English, such as “micropavimento,” “micro-surfacing,” “conservación vial,” “infraestructura vial,” “pavement preservation,” and “road maintenance.” In terms of language, the analyzed corpus consists mainly of publications in English and

Note: The figure shows the grouping of key terms and their interrelationships, identifying the main thematic clusters associated with the technical, regulatory, economic, institutional, and educational barriers present in the analyzed literature.

Based on the analysis of the bibliometric network and analytical matrices, six main categories were identified that group the factors limiting the application of micro-paving: technical barriers associated with the application of micro-paving; regulatory limitations and gaps; economic factors and budgetary constraints; institutional resistance and administrative barriers; and deficits in education, training, and knowledge transfer. Each of these categories was constructed based on the recurrence and consistency of the findings reported in the specialized literature.

The following sections present detailed results for each of the emerging categories, describing the main factors identified. This structure provides a clear overview of the barriers that have limited the adoption of micro-paving and lays the groundwork for a critical discussion of the findings and the formulation of recommendations for public road infrastructure policy.

Technical barriers associated with the application of micro-surfacing

The results of the literature review show that technical barriers constitute the most frequently cited group of limiting factors in recent literature on micro-surfacing in road infrastructure. Various studies agree that, while this technique offers advantages in terms of preventive maintenance, its performance is highly dependent on technical variables that directly affect the quality of the final result (Shi et al., 2021; Bhargava et al., 2021). In this regard, the review shows that these barriers do not stem from the technology itself, but rather from the conditions under which it is applied. This recurring theme is consistently identified in research conducted in both developed and developing countries. Therefore, technical limitations emerge as a central focus for understanding the challenges of adopting micro-paving.

One of the most frequently cited technical factors in the literature is the high sensitivity of micro-paving to weather and environmental conditions during application. Recent studies report that variables such as ambient temperature, relative humidity, and the probability of precipitation significantly influence the curing process and the material's adhesion to the pavement surface (Chen et al., 2023). In particular, it is noted that extreme temperatures or unexpected rain can compromise the durability of the treatment. This dependence on weather limits its application in regions with unstable environmental conditions. Consequently, the literature recognizes climate as a decisive technical barrier to the planning and execution of micro-paving.

Furthermore, the results show that micro-paving is highly dependent on proper mixing and placement, which increases the risk of failure when rigorous technical controls are not in place. Various authors agree that even minor errors in the proportions of aggregates, emulsion, and additives can lead to problems such as early detachment, surface cracking, or loss of texture (Bhargava et al., 2022; Fooladi and Hesami, 2021). This characteristic makes micro-paving a technique that is less tolerant of errors compared to traditional methods. The reviewed literature indicates that this technical requirement acts as a barrier to its implementation in contexts with limited supervision capacity. Consequently, precision in execution is identified as a critical factor time and again.

In addition, several studies highlight the specific requirements for specialized equipment and technology as a significant technical limitation. The review shows that the proper application of micro-paving requires the use of specialized machinery that is calibrated and operated by trained personnel, which is not always available in all contexts (Khahro et al., 2021; ASTM International 2023). In settings where the use of conventional equipment predominates, this technical requirement restricts its adoption. Furthermore, the literature indicates that the lack of adequate equipment increases the likelihood of construction defects. Therefore, technological availability emerges as a structural barrier to its effective implementation.

Another recurring technical issue identified in the studies reviewed is the dependence on the quality of the aggregates and asphalt emulsions used in the process. Recent research highlights that variations in aggregate particle size or in the physicochemical properties of the emulsion can significantly affect the

performance of micro-pavement (Ji et al., 2023; Esfahani et al., 2022). This dependency limits its application in regions where access to certified materials is restricted. Likewise, it is reported that a lack of control over the selection of inputs increases the variability of results. Consequently, material quality is established as a critical technical factor in the reviewed literature.

Furthermore, the results show that micro-paving has limitations when applied to pavements with advanced structural deterioration, a fact that is repeatedly cited as a technical barrier to its adoption. Various authors agree that this technique is effective only as a surface and preventive treatment, being unsuitable for pavements with severe structural defects (Peshkin and Duncan, 2021; Nair and McGhee, 2022; Tyagi et al., 2022). This technical limitation reduces its applicability on road networks that have undergone delayed corrective maintenance. Consequently, the literature identifies a gap between the actual condition of many road infrastructures and the optimal conditions required for micro-paving. This technical incompatibility restricts its use in numerous contexts.

Finally, a comprehensive analysis of the sources reveals that these technical barriers often occur in conjunction with one another, thereby amplifying their negative effects on the implementation of micro-paving. Recent literature indicates that the combination of adverse weather conditions, dosing deficiencies, technological limitations, and low-quality materials significantly increases the risk of unsatisfactory results (Xia et al., 2022; Cao and Wang, 2022). This accumulation of technical factors reinforces the perception of complexity associated with the technique. Consequently, the reviewed studies agree that technical barriers are a central factor in explaining the difficulties of applying micro-paving in road infrastructure.

Regulatory constraints and regulatory gaps

The results of the qualitative analysis of the document corpus show that regulatory constraints and regulatory gaps are a cross-cutting factor that influences the adoption of micro-paving in road infrastructure. Several studies agree that the absence of clear regulatory frameworks reduces institutional confidence in this technique, despite the available evidence regarding its performance (Ruiz and Guevara, 2020; De Rose et al., 2023). In the reviewed literature, this factor frequently appears in Latin American contexts and in countries with road maintenance systems in the process of consolidation. In this regard, regulations are identified as a structural element that influences decision-making. Therefore, regulatory gaps emerge as a significant barrier to its implementation.

One of the most frequently cited issues is the absence or inadequacy of specific technical standards governing the design, application, and inspection of micro-paving. Recent studies indicate that, in many countries, this technique lacks its own specifications or is only mentioned in passing in general road maintenance standards (Khahro et al., 2021; Ruiz and Guevara, 2020). This lack of standardization leads to varying interpretations during implementation. Furthermore, the literature highlights that the absence of official protocols limits the ability to evaluate its performance in a consistent manner (Angelo et al., 2023). Consequently, the lack of regulations stands as a recurring barrier.

Furthermore, the results indicate that micro-paving has been poorly incorporated into official road maintenance and conservation manuals, which limits its use by public entities. Several authors note that the regulatory prioritization of traditional techniques reinforces corrective intervention approaches at the expense of preventive strategies (Grilli and Balzi, 2023; Styler et al., 2024). This regulatory exclusion limits its inclusion in institutional plans and programs. Furthermore, the literature highlights that the lack of formal recognition affects contracting and oversight processes. Therefore, the limited presence of micro-paving in official manuals constitutes an institutional barrier of regulatory origin.

Furthermore, the systematic review highlights the lack of clear guidelines for design, supervision, and quality control processes, which increases the perception of technical and administrative risk. Recent studies warn that the absence of defined regulatory criteria hinders the assessment of technical compliance during the execution of construction projects (Yap et al., 2022; Daud et al., 2023). This situation creates uncertainty for both contractors and regulatory bodies. Consequently, the literature indicates that gaps in

regulatory oversight mechanisms act as a disincentive to their adoption. This finding is consistently observed across different analytical contexts.

Consequently, the results reveal a disconnect between national and international standards, which limits the transfer and adaptation of best practices. Several studies indicate that, although there are well-established international guidelines on the use of micro-paving, these are not always effectively integrated into national regulatory frameworks (Thom and Dawson, 2019; De Bortoli et al., 2022). This regulatory gap hinders the harmonization of technical criteria and the adoption of recognized standards. Overall, the reviewed literature indicates that regulatory limitations and gaps constitute a key barrier that constrains the systematic application of micro-paving in road infrastructure.

Economic Factors and Budgetary Constraints

An analysis of the studies shows that economic factors and budgetary constraints are among the most significant barriers to the adoption of micro-paving in road infrastructure. Various studies agree that decisions regarding road maintenance are often driven by short-term financial criteria, which limits the adoption of technologies aimed at preventive maintenance (Chen et al., 2023; Amin et al., 2022). In the reviewed literature, this factor appears repeatedly in both developed countries and emerging economies. In this regard, economic considerations are a key determinant in institutional decision-making. Consequently, budgetary constraints emerge as a structural barrier.

One of the most frequently cited factors in the studies reviewed is the perception that micro-paving involves high upfront costs compared to traditional road maintenance methods. Recent research indicates that, although this technique can be cost-effective in the medium and long term, its initial cost is often interpreted as a disadvantage by decision-makers (Pan et al., 2021; Zulu et al., 2020; Gouveia et al., 2022). This perception is reinforced by the lack of comparative economic analyses in local contexts. Consequently, the literature reveals a gap between technical evaluation and financial perception. This factor acts as a recurring barrier to its implementation.

Furthermore, the results indicate difficulties in justifying investments in preventive maintenance strategies, especially in environments with limited budgets. Various authors note that entities responsible for road infrastructure tend to prioritize corrective or rehabilitation interventions, which are considered more visible and politically justifiable (Gunathilaka and Amarasingha 2020; Montoya-Alcaraz et al., 2020). This budgetary logic reduces the scope for technologies such as micro-paving, whose benefits become evident over the long term. The literature highlights that this prioritization limits strategic road maintenance planning. Therefore, the lack of a preventive approach is identified as a significant economic barrier.

Furthermore, the systematic review highlights the limited availability of cost-benefit analyses and context-specific economic feasibility studies, which hinders informed decision-making. Recent studies indicate that much of the economic evidence comes from international contexts, making it difficult to directly apply it to local realities (Hamim et al., 2021; Arezoumand et al., 2023). This lack of local economic information increases the perception of financial risk. Consequently, the literature suggests that the absence of context-specific economic studies hinders the adoption of micro-paving.

Furthermore, the results show that the prioritization of corrective solutions over preventive strategies is also driven by structural budget constraints and short-term funding cycles. Various studies agree that resource allocation schemes do not favor interventions whose cost-effectiveness becomes apparent over long time horizons (Han et al., 2023; Bao et al., 2021; Majstorović and Jajac, 2022). This dynamic limits the incorporation of micro-paving into systematic maintenance plans. Overall, the reviewed literature shows that economic and budgetary factors constitute a decisive barrier that hinders the sustained adoption of this technology.

Institutional resistance and administrative barriers

Analysis of the sources comprising the document corpus reveals that institutional resistance constitutes a significant barrier to the adoption of micro-paving in road infrastructure. Numerous studies show that entities responsible for road maintenance tend to replicate traditional practices, even when technical alternatives with proven results exist (Ayalew et al., 2022; Grum et al., 2023). This trend is associated with rigid organizational structures and highly hierarchical decision-making processes. Consequently, the literature shows that technological innovation is not always a priority on institutional agendas. This pattern is repeated in various geographic contexts.

From another perspective, several authors note that the institutional preference for conventional technologies stems from administrative safety dynamics and the desire to reduce perceived risk. Recent research indicates that public officials often opt for widely recognized solutions to avoid technical or legal challenges (Lenderink et al., 2022; Cao and Wang, 2022). From this perspective, micro-paving is perceived as a less secure alternative from an administrative standpoint. Consequently, resistance to change emerges as a non-technical yet highly influential barrier. This pattern is recurrent in the reviewed literature.

Furthermore, the results show that inflexible contractual and administrative processes limit the adoption of innovative technologies such as micro-paving. Several studies highlight that contract specifications are often designed for traditional methods, making it difficult to include alternative technical specifications (Lenderink et al., 2022; Callens et al., 2022). This administrative rigidity reduces opportunities to experiment with preventive solutions. Thus, the contractual structure becomes an indirect limiting factor. The literature agrees that this obstacle is common.

Furthermore, analysis of the corpus reveals a weak coordination among the technical, administrative, and political actors involved in road infrastructure management. Some studies indicate that maintenance decisions are not always based on technical criteria, but rather on political or budgetary considerations (Kim, 2022; Lerusse and Van de Walle, 2023; Mbiyana et al., 2023). This disconnect hinders the adoption of evidence-based solutions. In this context, micro-paving is sidelined in favor of more visible or politically profitable options. This finding appears repeatedly in the literature.

In light of the evidence analyzed, the results suggest that institutional resistance is reinforced by the absence of innovation-oriented organizational leadership. Recent research highlights that, in environments where there are no clear strategies for modernizing road management, the adoption of new technologies is limited (Zhang et al., 2022; Criado et al., 2023; Nascimento et al., 2023). The lack of internal incentives and pro-innovation institutional policies contributes to the perpetuation of traditional practices. Overall, the analyzed literature shows that administrative and institutional barriers play a decisive role in the limited application of micro-paving.

Shortcomings in education, training, and knowledge transfer

Some studies highlight that shortcomings in technical education and training are among the most frequently cited barriers to the implementation of micro-paving in road infrastructure. Researchers note that a significant proportion of professionals in the sector are unaware of the technical specifications, design criteria, and optimal application conditions for this technology (Oke et al., 2023; Perera et al., 2023). This situation limits the proper assessment of its feasibility in road maintenance projects. Consequently, this lack of technical knowledge results in low institutional confidence in micro-paving.

From another perspective, the results show that the limited availability of specialized training programs directly contributes to the limited adoption of micro-paving. Recent research highlights that, in many contexts, available training programs focus on traditional techniques, relegating preventive and innovative solutions to the background (Chen et al., 2021; Nascimento et al., 2023). This training gap affects both engineers and field technicians. As a result, conventional road maintenance practices are perpetuated.

In addition, the reviewed literature indicates that a lack of specific training for workers and site supervisors increases the risk of errors during the application of micro-paving. Some authors warn that deficiencies in staff training can lead to premature failure of the treatment, reinforcing negative perceptions of its

performance (Moura et al., 2023; Ji et al., 2023). This situation creates a cycle of technical mistrust. In this regard, studies agree that proper execution depends largely on the available human capital.

On the other hand, a qualitative analysis of the corpus reveals weaknesses in the processes of knowledge transfer from academia to implementing agencies. Several studies highlight that the results of research and pilot projects do not always translate into practical guidelines for road management (Esmalian et al., 2022). This disconnect limits the adoption of the knowledge generated. Consequently, micro-paving continues to be perceived as an experimental technology.

Furthermore, several studies highlight the limited dissemination of successful case studies as a factor that hinders the widespread adoption of micro-paving. Recent research indicates that the lack of systematization and dissemination of success stories prevents other entities from learning about the real benefits of this technology (Huang et al., 2023). This absence of practical examples limits institutional learning. Consequently, the available positive evidence fails to significantly influence decision-making.

From a complementary perspective, the results suggest that training gaps are also linked to the absence of institutional strategies for continuous learning. Some authors note that agencies responsible for road infrastructure lack systematic plans for technical refresher training for their staff (Huamaní et al., 2022; Nascimento et al., 2023; Gupta and Sahu, 2023). This shortcoming reduces the capacity to adapt to new technologies. Consequently, micro-paving fails to be incorporated in a sustained manner into maintenance programs.

Based on the body of reviewed studies, it is evident that limitations in education, training, and knowledge transfer act as a cross-cutting factor that exacerbates other technical, administrative, and regulatory barriers. The lack of specialized skills and effective mechanisms for disseminating knowledge contributes to the underutilization of micro-paving, even in contexts where its benefits have been demonstrated (Pandey et al., 2021; Blanco et al., 2022). Taken together, the analyzed literature identifies this factor as one of the most decisive in explaining the limited adoption of this technology in road infrastructure.

Discussion

The findings of this systematic review reveal that the limited adoption of micro-paving is not due to an inherent shortcoming of the technology, but rather to a complex interplay of contextual barriers that go beyond technical considerations. In interpreting the results, it is observed that, while micro-paving offers clear advantages in terms of sustainability and speed, its adoption is conditioned by the maturity of the road ecosystem where it is implemented. This suggests that the problem does not lie in the material itself as confirmed by Bhargava et al. (2021) and Mousa et al. (2021), who highlight its energy and operational efficiency but rather in the capacity of institutions to manage the critical variables required for its application. In this regard, the gap between demonstrated technical potential and operational reality in the field represents the main challenge for modern road maintenance.

When synthesizing the evidence on technical and regulatory barriers, a significant tension emerges between the precision required by the technology and the flexibility of current regulatory frameworks. On the one hand, authors such as Chen et al. (2023) and Fooladi and Hesami (2021) emphasize that micro-pavement's sensitivity to weather and dosage requires rigorous controls that are not always available. On the other hand, Ruiz and Guevara (2020) along with De Rose et al. (2023) warn that the absence of specific regulations and updated manuals leaves contractors without standardized tools to ensure that quality. This convergence indicates that the lack of regulatory standardization exacerbates technical risks; that is, the technology is perceived as "risky" precisely because regulations do not provide the legal and technical certainty necessary to mitigate its operational sensitivity.

In the economic and institutional sphere, the findings suggest that resistance to change stems more from cognitive and budgetary biases than from an objective assessment of costs. While Pan et al. (2021) and Zulu et al. (2020) document that micro-paving is cost-effective in the long term, the perception of high initial costs reported by Amin et al. (2022) prevails in decision-making. This discrepancy is partially explained by the findings of Ayalew et al. (2022) and Lenderink et al. (2022), who identify an institutional preference for

traditional methods due to administrative risk aversion and short funding cycles. Therefore, the economic constraint is not merely a limitation of resources but a reflection of a management culture that prioritizes visible corrective action over strategic prevention, making it difficult to justify investments whose benefits materialize in the future.

Finally, an analysis of training gaps suggests that the lack of specialized human capital acts as a cross-cutting factor that amplifies all the aforementioned barriers. The literature reviewed by Oke et al. (2023) and Perera et al. (2023) agrees that a lack of technical knowledge among professionals and operators leads to mistrust of technology. This is reinforced by Nascimento et al. (2023) and Moura et al. (2023), who note that the limited transfer of knowledge from academia to the practical sector perpetuates implementation errors that ultimately discredit micro-paving. Thus, the lack of training is not an isolated problem, but rather the link connecting technical failures with institutional resistance; without trained personnel, even the most robust regulations prove ineffective.

In summary, the implications of these findings for the micro-paving sector are clear: the expansion of this technology requires a comprehensive strategy that goes beyond simply promoting its technical benefits. It is imperative that regulatory bodies, as inferred from the gaps identified by Khahro et al. (2021) and INVIAS (2022), update regulatory frameworks to include clear specifications that reduce contractual uncertainty. Likewise, a paradigm shift is required in budget management that prioritizes life cycle costs over initial costs, supported by ongoing training programs that bridge the identified knowledge gap. Only by simultaneously addressing the technical, regulatory, economic, and human dimensions can current resistance be overcome and micro-paving be established as a standard in sustainable road infrastructure.

Conclusions

The systematic review conducted establishes that micro-paving is a technically viable and environmentally sustainable technology, whose limited application is not due to inherent flaws in the material, but rather to deficiencies in the road management ecosystem. The evidence gathered demonstrates that, although the technique offers competitive advantages in terms of durability and speed of execution, its adoption is contingent upon the institutional and regulatory maturity of the environment in which it is implemented. Therefore, the main obstacle lies not in the product's engineering, but in the capacity of organizations to manage the risks associated with its implementation.

The findings confirm that the barriers to the application of micro-paving are multidimensional and mutually reinforcing. The technical requirements for dosing precision and climate sensitivity are exacerbated by the lack of specific regulations to standardize quality control processes. In turn, this regulatory uncertainty reinforces institutional resistance and a preference for traditional methods, fueled by an economic mindset that prioritizes initial cost over long-term benefit. Finally, gaps in education and training act as a cross-cutting factor that perpetuates execution errors, unjustifiably validating mistrust of the technology.

To overcome these limitations, it is imperative to transform current approaches to road maintenance. Regulatory frameworks must be updated to include clear technical specifications for micro-paving, thereby reducing discretion and contractual risk. At the same time, the responsible agencies must adopt life-cycle-based economic evaluation models that highlight the cost-effectiveness of prevention over remediation.

This must be accompanied by structured knowledge-transfer programs that bridge the gap between academia and the operational sector, ensuring that technical staff and operators have the necessary skills to guarantee the quality of the final product.

Generally speaking, the establishment of micro-paving as the standard in road infrastructure depends less on new material developments and more on strengthening institutional and human capacities. If the regulatory, economic, and training aspects identified in this study are addressed comprehensively, micro-paving has the potential to evolve from a niche alternative into a central component of public policies for sustainable road maintenance.

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