Sustainable Engineering Materials
ISSN: 3105-1960 (Print); ISSN: 3105-1979 (Online)
http://www.sustain-dpl.com/picnews.asp?id=177
DOI: 10.54113/j.suem.2026.000020

REVIEW ARTICLE

Mapping bio-asphalt technologies and deep investigation: a systematic bibliometric analysis

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Abstract: Bio-asphalt has emerged as a strategic solution for reducing the environmental footprint of pavement infrastructure by partially replacing petroleum-based binders with renewable biomass-derived resources such as bio-oil, lignin and agricultural by-products. Despite the rapid growth of experimental studies, a consolidated understanding of the intellectual evolution, performance-oriented research directions, and implementation challenges of bio-asphalt remains limited. This study presents a systematic bibliometric and performance-integrated review of 343 Scopus-indexed publications published between 1995 and 2025 to map the global development of bio-asphalt technologies. The results reveal an exponential increase in research output after 2015, driven by sustainability mandates, circular-economy initiatives, and advances in biomass conversion technologies. Science mapping indicates a clear thematic transition from early material substitution toward performance-oriented research focusing on rheology, durability, aging resistance, and hybrid modification strategies. A persistent performance imbalance between high-temperature rutting resistance and fatigue or low-temperature cracking resistance is identified as a central design challenge. Bio-oils are primarily used to enhance workability, rejuvenation efficiency, and cracking resistance, whereas lignin, polymers, and nanomaterials are increasingly incorporated to restore stiffness and mitigate rutting susceptibility. By integrating bibliometric analysis with engineering performance synthesis, this study identifies key research gaps and proposes a framework for the development of balanced, durable, and low-carbon bio-asphalt systems.

Keywords: bio-asphalt, bibliometric analysis, performance balance, rutting resistance, cracking resistance, sustainable pavements

1 Introduction

The decarbonization of transportation infrastructure has become a global priority in response to climate change, resource depletion, and the growing demand for resilient and sustainable pavement systems [1]. Conventional petroleum-based asphalt binders are associated with high energy consumption, significant greenhouse gas emissions, and continued dependence on finite fossil resources. Consequently, increasing research efforts have been directed toward the development of binders derived from renewable and waste-based materials. Among these alternatives, bio-asphalt has emerged as a promising pathway for advancing low-carbon and circular pavement engineering [2].

Received: 4 January 2026; Received in revised form: 20 April 2026; Accepted: 8 July 2026

In the literature, the term “bio-asphalt” is broadly used to describe asphalt binder systems incorporating biomass-derived materials. However, these systems can be classified into two distinct categories according to the functional role of the biomass component within the binder matrix. The first category is bio-oil modified asphalt, in which conventional petroleum bitumen is partially blended with biomass-derived oils, such as pyrolysis bio-oil or waste cooking oil. In this case, the bio-based component primarily functions as a rejuvenator, softening agent, or viscosity modifier, thereby altering the rheological behavior of the base binder. The second category is bio-binders, where biomass-derived constituents partially or substantially replace petroleum-based binder components. These materials may originate from lignin-rich residues, bio-polymers, or other biomass conversion products and contribute directly to the structural function of the binder system. Distinguishing between these two categories is essential, as they involve different physicochemical mechanisms, modification strategies, and engineering implications for pavement performance.

These two categories influence asphalt performance through distinct, yet sometimes complementary, mechanisms. Over the past three decades, extensive laboratory-scale studies have demonstrated that biomass-derived materials can significantly modify the physical, chemical, and rheological properties of asphalt binders. Bio-oils produced through thermochemical conversion processes have been widely reported to reduce binder viscosity, improve workability, and enhance fatigue resistance as well as low-temperature cracking performance [3]. In contrast, lignin-rich materials and bio-based polymers generally increase binder stiffness, improve elastic recovery, and enhance resistance to oxidative aging and high-temperature deformation[4]. Collectively, these findings highlight the considerable potential of biomass-derived modifiers for improving asphalt performance, while also indicating the need to optimize competing mechanical responses under different service conditions.

Despite these advantages, the practical implementation of bio-asphalt remains constrained by a fundamental engineering challenge: the inherent trade-off between rutting resistance at high service temperatures and cracking resistance under intermediate and low-temperature conditions. Bio-oil-rich systems often exhibit improved flexibility and damage tolerance, but may suffer from excessive softening, resulting in reduced resistance to permanent deformation. Conversely, lignin or polymer-dominated systems enhance stiffness and rutting resistance, but may also increase brittleness and susceptibility to cracking if not properly optimized. Achieving an effective balance between these competing performance requirements has therefore emerged as a central research question in bio-asphalt engineering and represents a critical barrier to its widespread adoption within performance-based pavement design frameworks [4].

In addition to performance trade-offs, several structural and policy-related challenges continue to limit the large-scale deployment of bio-asphalt technologies. Biomass feedstocks exhibit significant chemical variability depending on their source, processing pathway, and conversion conditions, which can lead to inconsistent binder performance. The absence of standardized specifications, material classifications, and acceptance criteria for bio-asphalt further complicates regulatory approval and industrial implementation[5]. Moreover, long-term field performance data remain limited, creating uncertainty regarding durability, aging behavior, and climate resilience under real traffic and environmental conditions. From a policy perspective, these uncertainties hinder the integration of bio-asphalt into national pavement standards and sustainability-oriented infrastructure programs.

Although numerous review studies have examined specific aspects of bio-asphalt materials, preparation techniques, and laboratory performance, most existing syntheses rely primarily on narrative or systematic review approaches. While these methods remain valuable, they are limited in their ability to quantitatively capture the intellectual structure, thematic evolution, and global research dynamics of this rapidly expanding field. More importantly, existing reviews rarely integrate science mapping with engineering performance analysis, particularly the fundamental trade-off between rutting resistance and cracking resistance that governs practical bio-asphalt design. In particular, there remains a lack of large-scale bibliometric studies capable of tracing the evolution of bio-asphalt research from early material substitution toward performance-oriented, hybrid-modification, and sustainability-driven paradigms.

Bibliometric science mapping provides a robust analytical framework for addressing this gap by quantitatively examining publication trends, citation networks, keyword co-occurrence, and thematic evolution over extended time periods. When integrated with performance-oriented synthesis, this approach enables a deeper understanding of how binder chemistry, rheological behavior, and engineering performance-particularly the rutting-cracking balance-have co-evolved in response to sustainability objectives, technologies advances, and policy pressures. This integrated perspective is especially relevant for bio-asphalt, which lies at the intersection of materials science, pavement engineering, and environmental policy and therefore requires evaluation beyond conventional single-discipline approaches.

Accordingly, the objective of this study is to provide a comprehensive bibliometric and performance-integrated synthesis of global bio-asphalt research published between 1995 and 2025. Specifically, this study aims to:

i. quantify global research growth, productivity patterns, and regional contributions;
ii. identify the influential journals, authors, institutions, and countries shaping the field;
iii. analyze keyword networks and thematic evolution to reveal shifts toward performance-based and sustainability-driven research;
iv. critically evaluate the core engineering performance domains, with particular emphasis on the rutting-cracking balance, aging resistance and rejuvenation mechanisms; and
v. identify critical technical and policy-relevant gaps to support the transition of bio-asphalt from laboratory-scale research to standardized, field-scale implementation.

By explicitly integrating bibliometric evidence with engineering performance-trade-offs and policy-relevant constraints, this study provides a structured frameworks linking research dynamics, materials chemistry, and pavement performance in bio-asphalt systems. The resulting roadmap identifies emerging research frontiers, unresolved technical barriers, and practical pathways for translating laboratory-scale innovations into standardized, field-ready, and low-carbon pavement solutions. Accordingly, the findings are expected to support researchers in refining performance-based bio-asphalt design strategies, assist practitioners in material selection and optimization, and inform policymakers seeking to incorporate bio-asphalt into sustainability-oriented pavement specifications and infrastructure programs.

2 Background

Bio-asphalt is a broad term used to describe asphalt binder systems incorporating biomass-derived materials from renewable or waste-based sources [2], [6]. These materials may originate from thermochemical conversion products such as pyrolysis bio-oil, lignin-rich residues from pulp and bioethanol industries, agricultural by-products, or bio-based polymers. Because these materials can play different functional roles within asphalt binders, bio-asphalt technologies are commonly categorized according to the role of the biomass-derived component in the binder system [7]. This diversity provides significant flexibility in binder design and enables the valorization of waste streams; however, it also introduces substantial variability in chemical composition and performance behavior, which remains a central challenge in bio-asphalt development[6].

The first category consists of bio-oil modified asphalt systems, in which petroleum bitumen is partially modified with biomass-derived oils. Bio-oils are commonly characterized by oxygenated compounds and light aromatic fractions that reduce binder viscosity and enhance molecular mobility[8]. As a result, bio-oil modified binders generally show improved workability, enhanced fatigue resistance, and superior low-temperature cracking performance. In contrast, lignin-rich materials and bio-based polymers exhibit higher aromaticity and elastic potential, contributing to increased stiffness, improved elastic recovery, and enhanced resistance to oxidative aging and permanent deformation at elevated service temperatures[9]. These contrasting tendencies underscore that bio-binders should not be viewed as a single material class, but rather as a tunable binder system whose performance depends critically on modifier type, dosage, and interaction with the base asphalt.

The second category consists of bio-binders, in which biomass-derived materials partially replace petroleum-based binder fractions. These systems are commonly derived from lignin-rich residues, bio-polymers, or other biomass conversion products. Unlike bio-oil modifiers, which mainly alter viscosity and workability, bio-binders contribute more directly to the structural characteristics of the binder by influencing stiffness, elastic recovery, and resistance to oxidative aging. The central performance challenge emerging from this material diversity is the need to achieve a rutting-cracking performance balance across service temperatures. Excessive softening induced by high bio-oil contents may compromise resistance to permanent deformation under high-temperature loading, whereas overly stiff systems dominated by lignin or polymeric modifiers may increase brittleness and susceptibility to fatigue or low-temperature cracking[10]. This balance is inherently governed by the viscoelastic properties controlling rutting resistance and stress relaxation capacity required to mitigate cracking. Consequently, optimizing bio-asphalt performance requires an integrated consideration of temperature-dependent behavior rather than the isolated maximization of individual performance indicators. Together, these two categories illustrate the diverse functional roles of biomass-derived materials in asphalt binder systems.

Aging and durability considerations further complicate the performance balance of bio-asphalt systems. Oxidative aging alters binder chemistry and rheological behavior over time, typically leading to increased stiffness and reduced resistance to cracking [11]. The presence of biomass-derived modifiers may influence this aging process through different mechanisms. Certain oxygenated compounds present in bio-oils can accelerate oxidative reactions under specific conditions, potentially increasing stiffness during long-term aging. In contrast, phenolic structures commonly found in lignin-rich materials may exhibit antioxidant characteristics that help retard oxidative degradation and improve aging resistance. In addition to aging behavior, moisture susceptibility also plays an important role in pavement durability, as the polarity of biomass-derived modifiers can influence adhesion at the binder-aggregate interface. These interacting mechanisms indicate that the performance of bio-asphalt systems is multidimensional, time-dependent, and strongly influenced by both material composition and environmental exposure [12]. Understanding these aging and durability mechanisms is therefore essential for designing bio-asphalt systems that maintain balanced performance under long-term service conditions.

Over the past three decades, bio-asphalt research has evolved through several technological phases, reflecting increasing scientific maturity and alignment with sustainability-driven objectives. Early investigations, conducted primarily before 2010, focused on assessing the feasibility of vegetable oils and first-generation bio-oils as softening agents or partial substitutes for petroleum-based binders. Although these studies demonstrated potential environmental benefits and improved workability, they were often limited by issues such as high volatility, chemical instability, and inconsistent performance outcomes. Between 2011 and 2015, research efforts began to shift toward more stable and functional modification strategies. During this period, increasing attention was given to lignin-modified binders, bio-oil-based rejuvenators for reclaimed asphalt pavement (RAP), and improved compatibility between bio-based materials and conventional asphalt matrices. These developments marked an important transition from simple material substitution toward performance-oriented binder modification. These developments laid the foundation for the subsequent transition toward performance-oriented and hybrid modification strategies in bio-asphalt research.

From 2016 onward, bio-asphalt research entered a performance-oriented phase characterized by the adoption of hybrid modification strategies and advanced characterization techniques. Researchers increasingly explored the combined use of bio-oils with lignin, polymers, and nanomaterials to mitigate excessive softening while enhancing high-temperature stability and rutting resistance. During this period, rheological and mechanistic evaluation frameworks gained increasing importance, supporting the transition from empirical property-based assessments toward performance-based pavement design approaches [13]. More recently, research on bio-asphalt has expanded to incorporate broader sustainability considerations. These include the integration of circular economy principles, the utilization of high reclaimed asphalt pavement (RAP) contents, the application of warm mix asphalt technologies, and the incorporation of environmental assessment tools such as life-cycle analysis. Collectively, these developments indicate a gradual shift from laboratory-scale feasibility studies toward implementation-oriented innovations aimed at developing reliable, low-carbon pavement materials [14].

Despite these technological advances, several critical barriers continue to limit the large-scale implementation of bio-asphalt in practical pavement applications. One of the primary challenges lies in the inherent variability of biomass-derived materials, which can lead to inconsistent binder performance and complicate quality control during production. In addition, current asphalt specifications and acceptance criteria are predominantly developed for petroleum-based binders and may not adequately capture the complex behavior of bio-modified systems, particularly under long-term aging and temperature-dependent loading conditions. Another significant but often underexplored challenge is related to environmental and occupational concerns during construction. The use of certain bio-oils may lead to the emission of volatile organic compounds (VOCs) and odor during mixing and paving processes, which can affect worker safety and environmental compliance. Without clear standards and mitigation strategies for VOC emissions, the environmental advantages of bio-asphalt may be partially offset during field application [15]. Furthermore, the limited availability of long-term field performance data introduces additional uncertainty regarding durability, climate resilience, and life-cycle performance under real traffic conditions. These technical, environmental, and regulatory challenges collectively hinder the transition of bio-asphalt technologies from laboratory-scale research toward standardized and reliable field implementation.

Furthermore, the interaction between biomass-derived components and petroleum-based bitumen is often complex and not yet fully understood. Factors such as chemical compatibility, phase stability, and molecular interactions can significantly influence the rheological behavior and long-term durability of bio-asphalt systems. In some cases, poor compatibility between biomass-derived modifiers and the base binder may lead to phase separation, instability during storage, or accelerated aging behavior. These challenges highlight the need for a deeper understanding of the physicochemical interactions governing bio-asphalt formulation, particularly when designing binder system that balance workability, durability, and resistance to environmental and traffic loading. These technical challenges underscore the importance of systematically synthesizing existing research to better understand the evolving knowledge structure and performance implications of bio-asphalt technologies.

Despite these advances, existing studies remain fragmented, highlighting the need for a comprehensive and systematic synthesis of bio-asphalt research. Bibliometric analysis provides a quantitative framework to map the intellectual structure and thematic evolution of the field through publication trends, citation networks, and keyword co-occurrence patterns. When integrated with performance-oriented synthesis, this approach enables a deeper understanding of how material chemistry, rheological behavior, and engineering performance, particularly the balance between rutting and cracking, have co-evolved in response to sustainability objectives and technological advancements. This integrated framework directly informs the organization and interpretation of the results presented in the following section, ensuring that bibliometric findings are meaningfully linked to performance-driven pavement engineering challenges rather than treated as isolated science observations.

Given the multidimensional and evolving nature of bio-asphalt research, a structured and quantitative synthesis is required to systematically map its intellectual development, thematic evolution, and performance-oriented research directions

3 Methodology

This study adopts an integrated bibliometric and performance-oriented review framework to systematically map the intellectual development, thematic evolution, and performance-driven research directions of bio-asphalt studies. The methodological workflow consists of four main stages: data collection and screening, bibliometric mapping, science mapping, thematic evolution analysis, and performance-oriented synthesis.

3.1 Data Source and Search Strategy

The Scopus database was selected as the primary data source because it provides one of the most comprehensive and curated collections of peer-reviewed literature across engineering, materials science, environmental studies, and sustainability research. Scopus is widely recognized in bibliometric studies due to its broad journal coverage, high indexing accuracy, and strong compatibility with science-mapping tools such as VOS-viewer and bibliometric [16]. Accordingly, a comprehensive search was conducted for all available years from 1995 to 2025, corresponding to the earliest documented scientific publication related to bio-asphalt. A refined Boolean search string was developed to ensure accurate retrieval of publications focusing on bio-asphalt materials, binder modification, performance characterization, and sustainability dimensions, following recommended Bibliometric search design principles. To define the search period, key terms, and journal coverage, a structured keyword query was formulated as follows:

“Pavement OR pavements OR road AND asphalt OR bitumen OR "bituminous mixture" OR bioasphalt OR "bio asphalt" OR "natural asphalt" OR "organic asphalt" OR "green asphalt" OR bio-asphalt OR "biobased asphalt" AND bio-char OR biochar OR bio-oil OR bio-binder OR bio-mass OR agricultural OR "agricultural waste ashes" OR "agricultural by-product" OR waste OR palm AND oil OR palm OR ash OR bio-oil OR “cooking oil” AND aging OR ageing OR fatigue OR rutting OR rut OR “moisture damage” OR “permanent deformation” OR “thermal cracking” OR “thermal crack” OR “thermal cracking” OR “mechanical performance”.

The query was designed to minimize duplication and ensure high retrieval precision across binder- and mixture-related studies.

3.2 Inclusion and Exclusion Criteria

To ensure methodological rigor and maintain the quality of the resulting bibliometric dataset, publications were screened using predefined inclusion and exclusion criteria consistent with recommended science-mapping practices [17]. The inclusion criteria required that documents be peer-reviewed journal articles or conference papers, written in English, indexed in Scopus, and directly related to bio-asphalt materials, rheology, performance evaluation, sustainability, or binder modification. Conversely, patents, theses, dissertations, book chapters, technical report, and non-peer reviewed materials were excluded to ensure data reliability and comparability. Studies unrelated to asphalt or biomass-derived binders, documents lacking accessible full text, and records with incomplete metadata, duplication, or poor bibliographic quality were also removed, following established bibliometric cleaning protocols.

3.3 PRISMA Screening Process

The PRISMA screening procedure was applied to ensure transparency and reproducibility in dataset selection following established systematic review standards [18]. During the identification phase, 654 records were retrieved from the Scopus database, from which 45 duplicates were removed, resulting in 609 unique documents. In the screening stage, titles and abstracts were examined, and 175 publications were excluded based on irrelevance or misalignment with the study scope. Subsequently, 434 full-text articles were assessed for eligibility, leading to exclusion of 91 additional records due to insufficient information, non-compliance with inclusion criteria, or incomplete metadata. Ultimately, 343 studies met all requirements and were included in the bibliometric dataset. This final dataset forms the foundation for subsequent performance indicators, network analyses, and thematic evolution mapping.

3.4 Bibliometric Tools and Analytical Workflow

Bibliometric analysis in this study employed three complementary tools to capture different dimensions of scientific structure and performance. Bibliometric, implemented through the R package and its web interface Biblio-shiny, was used to compute performance indicators such as annual scientific production, authorship patterns, country contributions, journal productivity, and descriptive statistic, including citation and publication metric. VOS-viewer supported the construction and visualization of keyword co-occurrence networks, co-citation maps, and cluster structures based on link strength and intellectual proximity[19]. Sci-MAT was applied to analyze thematic evolution across predefined time periods, enabling the identification of emerging, declining, basic, and motor themes, as well as the construction of overlapping thematic maps [20]. The analytical workflow followed established bibliometric procedures beginning with data import, cleaning, and standardization of authors, keywords, and institutional names. This was followed by the generation of performance indicators and the construction of co-occurrence and co-citation networks. The dataset was then segmented by period (1995-2010; 2011-2015; 2016-2020; 2021-2025) to assess thematic evolution. Finally, the bibliometric outputs were integrated with a qualitative deep investigation to interpret patterns in bio-asphalt research from both structural and performance perspectives [21]. This multi-tool approach provides a comprehensive assessment of scientific development and knowledge progression within the bio-asphalt field. **Fig. 1** shows the framework of the review paper, and **Fig. 2** shows the framework topics study in this review investigation.

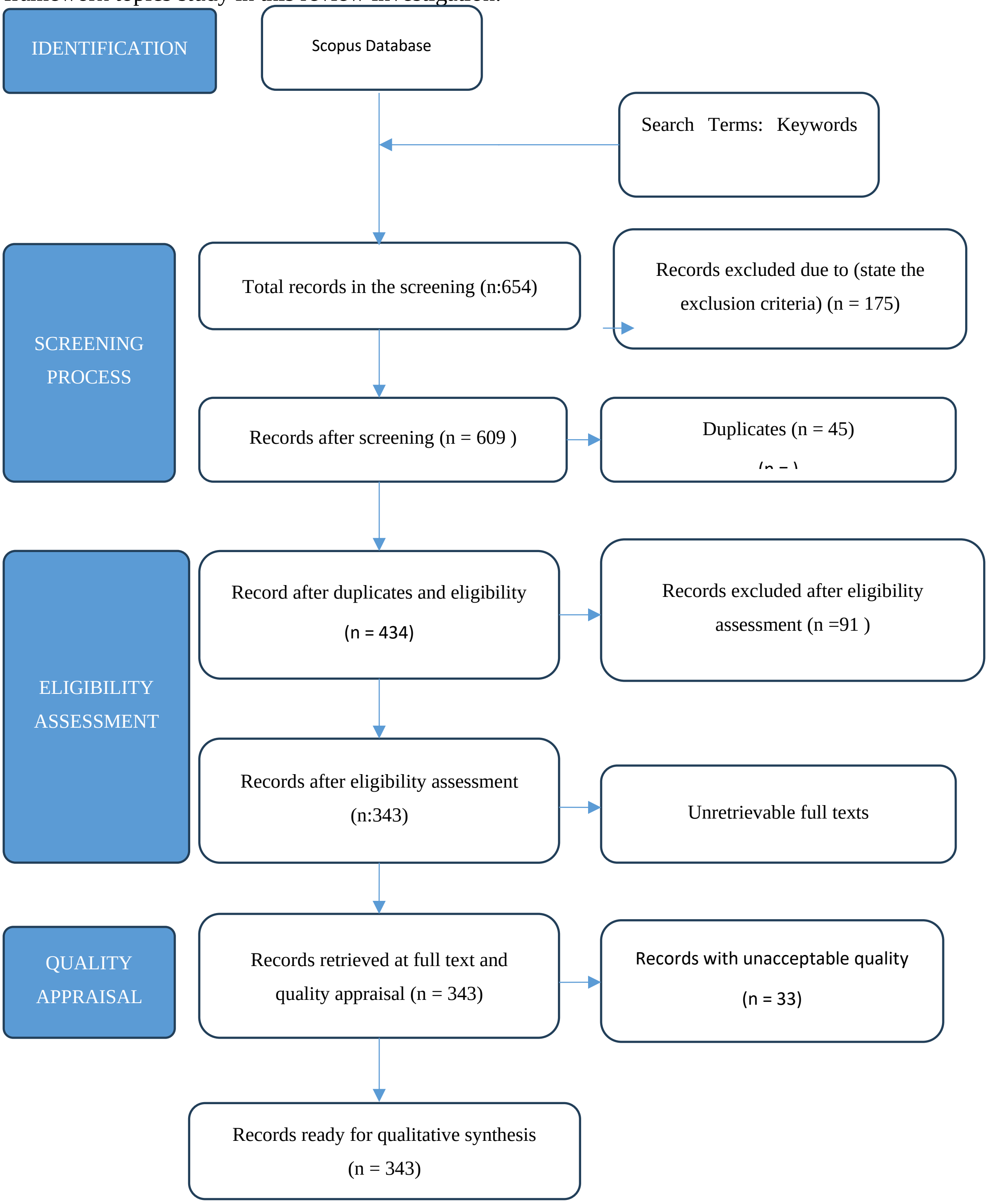

Fig. 1. Framework of the review paper.

4 Results (bibliometric mapping)

This section presents the bibliometric results derived from performance analysis, keyword network mapping, and thematic evolution assessment of the 343 selected publications. The findings highlight the intellectual structure, research hotspots, regional contributions, and temporal progression of bio-asphalt research across three decades.

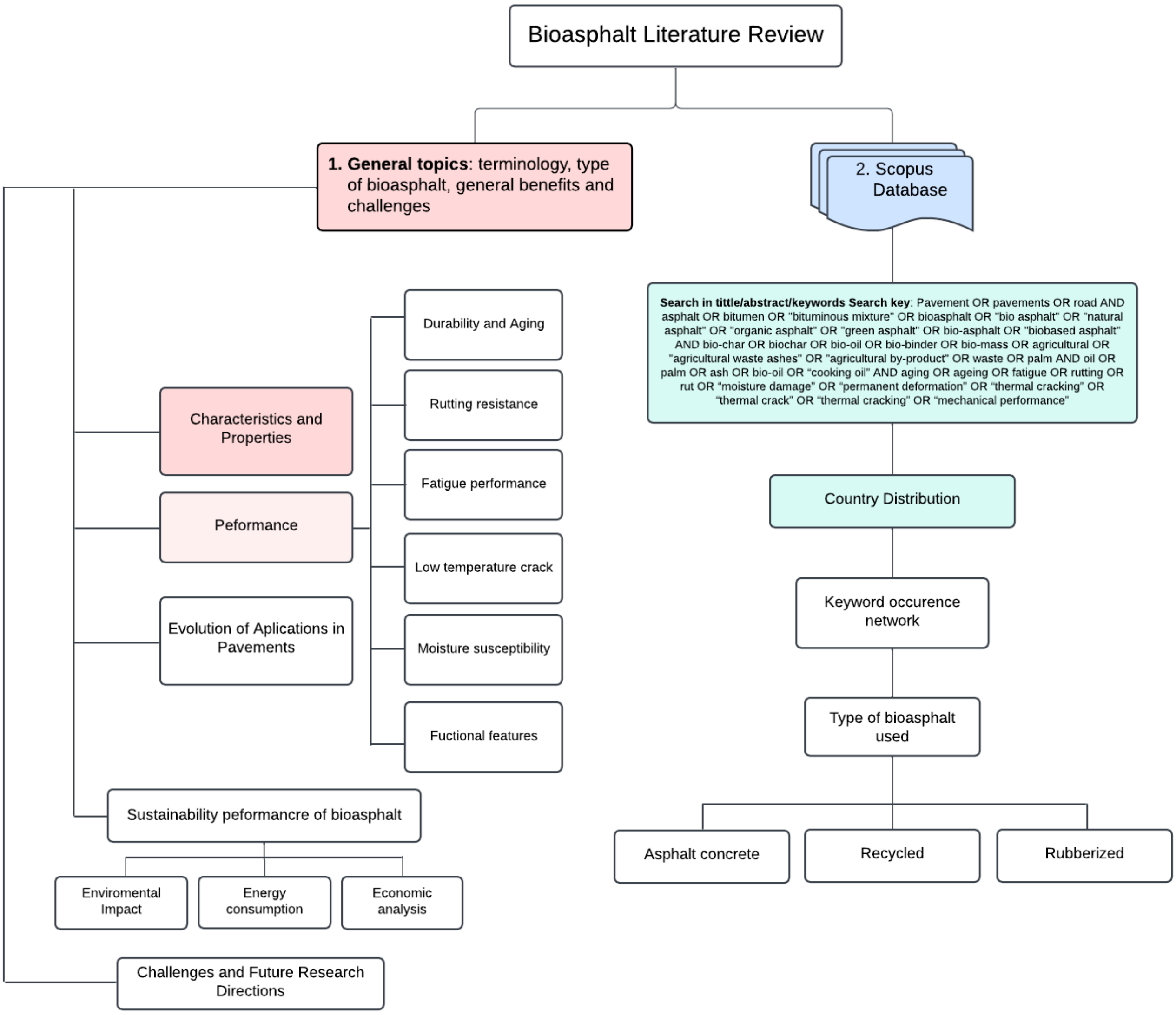

Fig. 2. Framework topics study in the review investigation

4.1 Publication Trends (1995-2025)

Fig. 3 and **Fig. 4** present the annual scientific production on bio-asphalt research from 1995 to 2025 based on Scopus-indexed journal articles. The temporal distribution of publications reveals a clear and sustained transition from a niche exploratory topic to a rapidly expanding global research domain, reflecting the growing global emphasis on sustainable materials and low-carbon pavement technologies. The evolution of bio-asphalt research can be broadly divided into three developmental stages characterized by distinct research intensity, technological focus, and alignment with sustainability-driven agendas.

During the emergence stage (1995-2010), publication activity remained sparse and irregular, with only a limited number of studies published annually. This period represents the early experimental phase of bio-asphalt research, in which investigations primarily focused on the feasibility of incorporating vegetable oils and simple biomass-derived materials as softening agents or partial substitutes for conventional petroleum-based binders. The low level of scientific output during this stage can be attributed to several factors, including limited understanding of material compatibility, insufficient control over biomass conversion processes, and the absence of strong industrial or policy-driven demand for sustainable pavement materials. As illustrated in **Fig. 4**, research activity during this period remained relatively stagnant, reflecting the exploratory nature of early bio-asphalt studies and the lack of technological maturity required for broader application. This stage laid the foundational knowledge for subsequent advancements in bio-based binder modification and performance-oriented research.

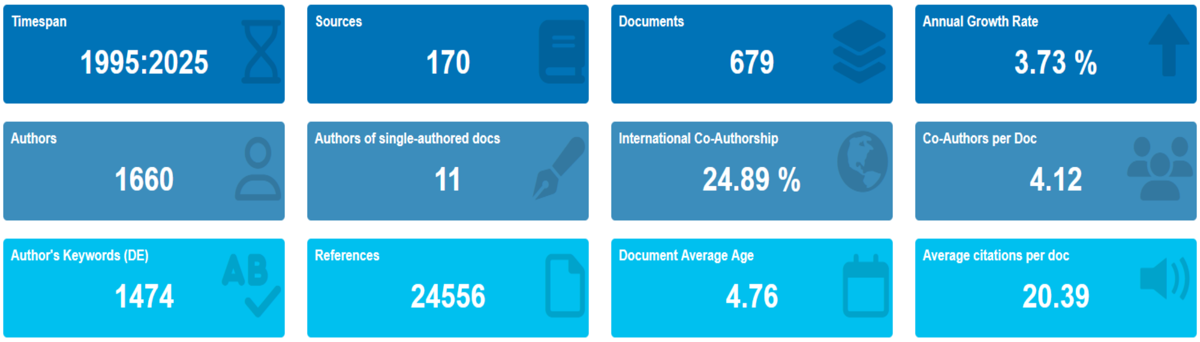

Fig. 3 Overall statistical information of data retrieved

A transition stage (2011-2015) is clearly observed in **Fig.4**, marked by a moderate but consistent increase in annual publication counts. This period represents a critical turning point in the development of bio-asphalt research, as advancements in biomass conversion technologies-particularly fast pyrolysis and improved lignin extraction methods-enabled the production of more stable and performance-relevant bio-based modifiers. During this stage, research focus shifted from feasibility-driven investigations toward more application-oriented studies, including binder modification strategies, the use of bio-oils as rejuvenators for reclaimed asphalt pavement (RAP), and the incorporation of rheological and mechanical performance evaluations. In parallel, the growing global emphasis on sustainability, resource efficiency, and waste valorization further stimulated scientific interest in bio-asphalt materials, contributing to the observed increase in research output [22]. This transition marks the beginning of a more structured and performance-driven research paradigm in bio-asphalt development.

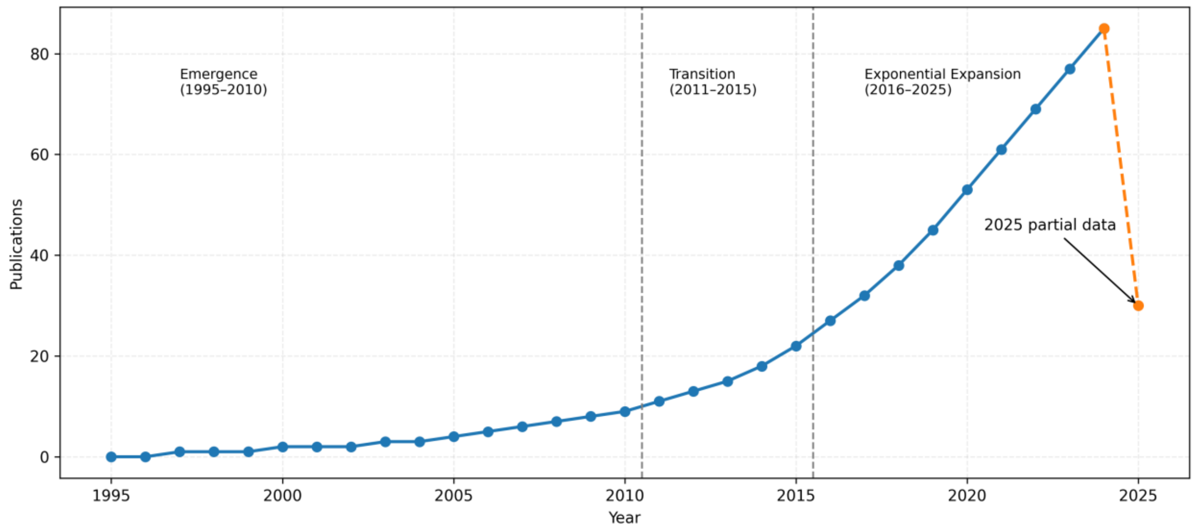

Fig 4 Annual scientific production on bio-asphalt research (1995-2025). Note: Data for 2025 represent partial data extracted up to January 2025. The dashed line indicates incomplete data rather than a projected trend

The most pronounced trend is observed during the exponential expansion stage (2016-2025), in which bio-asphalt research experienced a sharp and sustained surge in scientific output, with publication activity peaking between 2020 and 2024. This rapid growth reflects the convergence of multiple drivers, including global decarbonization policies, the adoption of circular economy principles in infrastructure development, and the maturation of performance-based pavement engineering frameworks. Studies published during this phase increasingly addressed advanced research topics such as hybrid bio-binder modification strategies, nano-modified bio-asphalt systems, higher lignin substitution ratios, and detailed mechanistic investigations of bio-oil rejuvenation behavior [23]. In parallel, compatibility with warm mix asphalt (WMA) technologies and the incorporation of comprehensive environmental assessments, including life-cycle assessment (LCA) and life-cycle cost analysis (LCCA), became more prominent. These developments indicate a clear transition from laboratory-scale feasibility studies toward implementation-oriented and sustainability-driven research agendas [24], highlighting the growing maturity and practical relevance of bio-asphalt technologies in modern pavement engineering. This stage underscores the transformation of bio-asphalt research into a rapidly evolving and strategically important domain within sustainable infrastructure development.

Overall, the exponential growth pattern captured in **Fig.4** confirms that bio-asphalt research has evolved from an exploratory concept into a rapidly expanding and strategically significant field within sustainable pavement engineering. The sustained increase in publication output reflects not only growing academic interest but also the rising practical relevance of bio-asphalt as a viable alternative to conventional petroleum-based binders. This trend is strongly aligned with global sustainability objectives, including decarbonization strategies, circular economy implementation, and the transition toward performance-based pavement design frameworks. As such, bio-asphalt research is no longer confined to laboratory-scale experimentation but is increasingly positioned as a key component in the development of low-carbon, resource-efficient, and resilient transportation infrastructure systems. These findings further justify the need for a comprehensive bibliometric and performance-oriented synthesis to better understand the evolving research landscape and identify future development pathways.

4.2 Most Relevant Sources (Journals)

Fig. 5 and **Table 1** present the distribution of publications across scientific journals, providing an essential indicator of the intellectual structure, disciplinary orientation, and methodological trajectory of bio-asphalt research. Over the period 1995-2025, the bibliometric analysis highlights the concentration of scientific output across a limited number of key publication sources. The analysis reveals a clear clustering of publication sources into two dominant journal families: (1) material and pavement engineering-oriented outlets, and (2) multidisciplinary sustainable engineering journals. Together, these clusters signify an evolving shift from narrowly focused material characterization studies toward a broader interdisciplinary framework that integrates nanotechnology, chemistry, sustainability science, and circular economy principles.

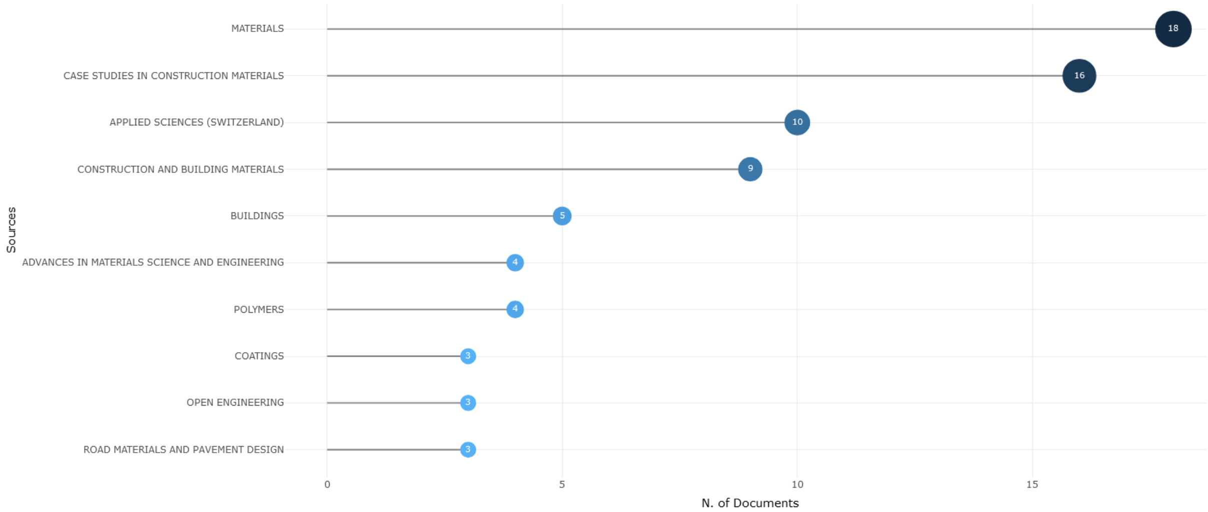

Fig. 5. Most relevant sources

The first and most dominant cluster consists of journals traditionally associated with materials science and pavement engineering, including Construction and Building Materials, Materials, Case Studies in Construction Materials, and Road Materials and Pavement Design. These journals form the intellectual core of bio-asphalt research, serving as the primary platforms for disseminating studies on binder modification, rheological characterization, and pavement performance evaluation. Research published in these outlets predominantly focuses on the physicochemical interactions between bio-based modifiers (such as bio-oil, lignin, and biomass derivatives) and conventional bitumen, as well as their influence on key performance indicators, including penetration, softening point, viscosity, modulus, rutting resistance, fatigue behavior, and aging susceptibility[25]. This dominant reflects the foundational role of these journals in establishing the material-performance framework of bio-asphalt research.

The prevalence of these journals in the bibliometric landscape reflects the historical foundation of bio-asphalt research, which initially emerged from the need to understand material compatibility, performance trade-offs, and binder-level modification mechanisms. During the early and transitional stages (1995-2015), research was predominantly grounded in conventional pavement engineering frameworks, emphasizing laboratory-based characterization and performance evaluation. As a result, journals such as Construction and Building Materials and Road Materials and Pavement Design became central nodes in co-citation and bibliographic coupling networks, reinforcing their role as the intellectual backbone of the field. This foundation has played a critical role in shaping subsequent advancements toward more complex and interdisciplinary bio-asphalt systems.

The second major cluster comprises multidisciplinary and sustainability-oriented journals, including Applied Science, Polymers, Coatings, and Advance in Materials Science and Engineering. These journals show a growing contribution to bio-asphalt research, particularly after 2016, corresponding to the exponential expansion phase identified in Fig.4. Unlike traditional engineering journals, studies published in these outlets adopt a broader scientific perspective, incorporating polymer chemistry, nanomaterials engineering, surface science, and renewable biomass valorization. Research in this cluster increasingly focuses on advanced hybrid modification strategies, combining lignin, nanomaterials, and polymeric additives to enhance both mechanical performance and environmental sustainability [26]. This trend reflects a significant paradigm shift in bio-asphalt research-from conventional binder modification toward the development of multifunctional, engineered materials that integrate performance optimization with sustainability-driven objectives. This expansion highlights the increasing convergence between materials science, environmental engineering, and sustainable infrastructure development within the bio-asphalt research domain.

This interdisciplinary expansion is further reflected in the thematic focus of journals such as Polymer, Applied Science, Coatings, which explore the interaction between bio-based modifiers and bitumen at more fundamental and mechanistic level. For instance, studies published in Polymers often investigate the role of bio-based polymers in modifying the colloidal structure of bitumen, influencing elastic recovery, temperature susceptibility, and aging resistance. Similarly, research in Applied Science and Coatings increasingly examines surface modification, adhesion mechanisms, and environmental durability, extending beyond conventional binder-level performance evaluation. These studies emphasize the integration of chemical, microstructural, and functional perspectives in understanding bio-asphalt behavior. This trend suggests that bio-asphalt research is evolving toward a more comprehensive and multi-scale approach, where material design is not only driven by performance requirements but also by chemical interactions and long-term durability considerations. This multi-scale perspective further reinforces the transition of bio-asphalt from a simple modifier-based system to an engineered material with complex functional behavior.

A key insight emerging from this multi-cluster journal distribution is the increasing adoption of hybrid modification strategies in bio-asphalt research. Recent studies in high-impact journals increasingly explore synergistic combinations of lignin, nanomaterials, and polymeric additives to enhance multiple performance aspects simultaneously, including rutting resistance, cracking behavior, moisture susceptibility, and long-term aging stability. This trend indicates a clear shift from single-modifier approaches toward more engineered and optimized material design strategies, aimed at achieving a balanced performance across different service conditions. In parallel, there is a growing emphasis on sustainability-driven evaluation, with increasing attention to life cycle assessment (LCA), life cycle cost analysis (LCCA), carbon reduction potential, and circular economy frameworks. These developments demonstrate that bio-asphalt research is evolving toward an integrated paradigm that combines performance optimization with environmental sustainability, reinforcing its potential as a viable solution for next-generation low-carbon pavement systems. This shift further highlights the need for integrated design frameworks that simultaneously address mechanical performance and environmental impact.

Taken together, the presence of both traditional pavement engineering journals and multidisciplinary materials science outlets demonstrates the dual identify of bio-asphalt research. On one hand, the field remains firmly grounded in binder performance evaluation and mechanical behavior analysis. On the other hand, it is rapidly expanding into interdisciplinary domains encompassing nanotechnology, polymer chemistry, green materials innovation, and sustainability assessment. This duality highlights the transformation of bio-asphalt from a niche material modification approach into a sophisticated research domain with broad scientific, technological, and environmental relevance. The strong representation of high-impact journals further suggests that the field is entering a phase of methodological refinement, hybrid material innovation, and deeper integration with global sustainability agendas. These insights provide a strong foundation for understanding the evolving research landscape and guiding future developments in performance-oriented and sustainable bio-asphalt design.

Table.1. Most relevant sources

Journal	Rank	Freq	Cum Freq	Zone
Materials	1	16	18	Zone 1
Case Studies in Construction Materials	2	16	34	Zone 1
Applied Sciences	3	10	44	Zone 1
Construction and Building Materials	4	9	53	Zone 2
Building	5	5	58	Zone 2
Advances in Materials Science and Engineering	6	4	62	Zone 2
Polymers	7	4	66	Zone 2
Coatings	8	3	69	Zone 2
Open Engineering	9	3	72	Zone 2
Road Materials and Pavement Design	10	3	75	Zone 2

4.3 Country Scientific Production and Collaboration Patterns

Fig. 6 and **Fig. 7** present the global scientific contributions to bio-asphalt research, revealing a geographically uneven yet rapidly expanding landscape, with a pronounced concentration of productivity in Asia. China overwhelmingly leads in total publications, single-country publications (SCP), and multi-country publications (MCP), indicating both strong domestic research capacity and an active role in international collaboration. This distribution highlights the central role of Asia, particularly China, in shaping the global research trajectory of bio-asphalt development.

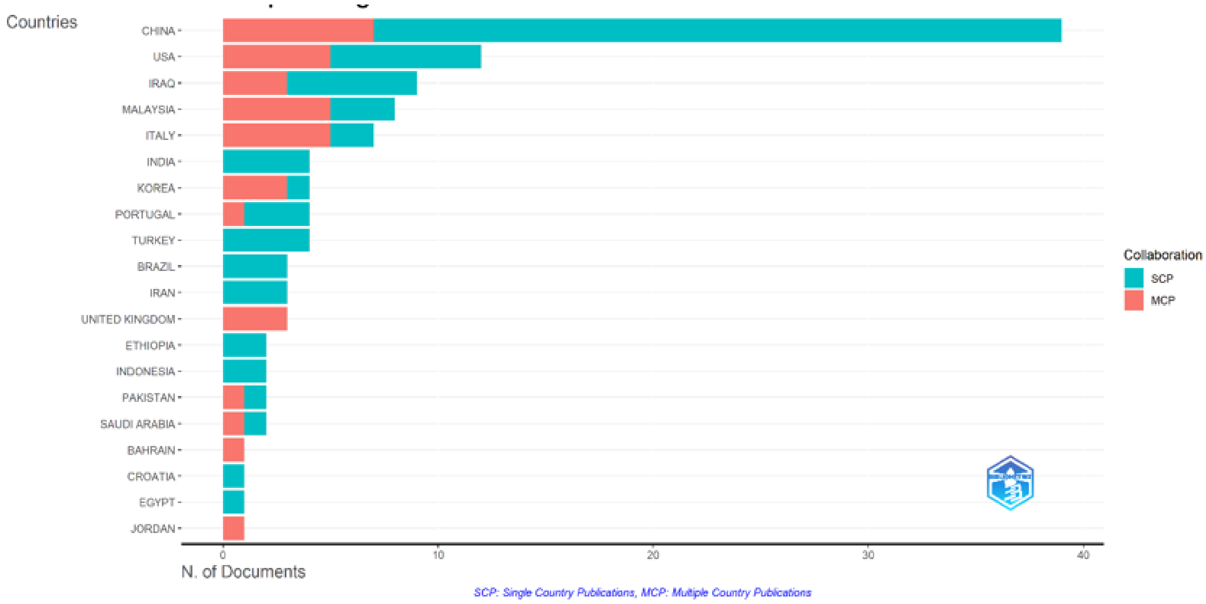

Fig 6. Corresponding author's countries

This dominance can be attributed to several interrelated factors, including the presence of major transportation and pavement engineering research centers, such as Chongqing Jiaotong University and

Chang'an University, as well as sustained national investment in sustainable infrastructure, waste valorization, and advanced material technologies. These factors not only enhance research productivity but also facilitate the integration of laboratory-scale innovation with large-scale infrastructure applications. As a result, China plays a pivotal role not only in knowledge production but also in shaping the research direction and technological advancement of bio-asphalt development at the global level.

Malaysia emerges as a significant regional contributor in Southeast Asia, with research activities strongly oriented toward palm oil-derived bio-binder technologies, including the valorization of Empty Fruit Bunches (EFB) biomass and the development of bio-oil-based rejuvenators for reclaimed asphalt pavement (RAP). This research focus reflects a strong alignment between locally available biomass resources and national sustainability priorities. Moore broadly, it illustrates a resource-driven research pattern in bio-asphalt development, where countries leverage their dominant agricultural or industrial by-products to develop context-specific and sustainable pavement materials.

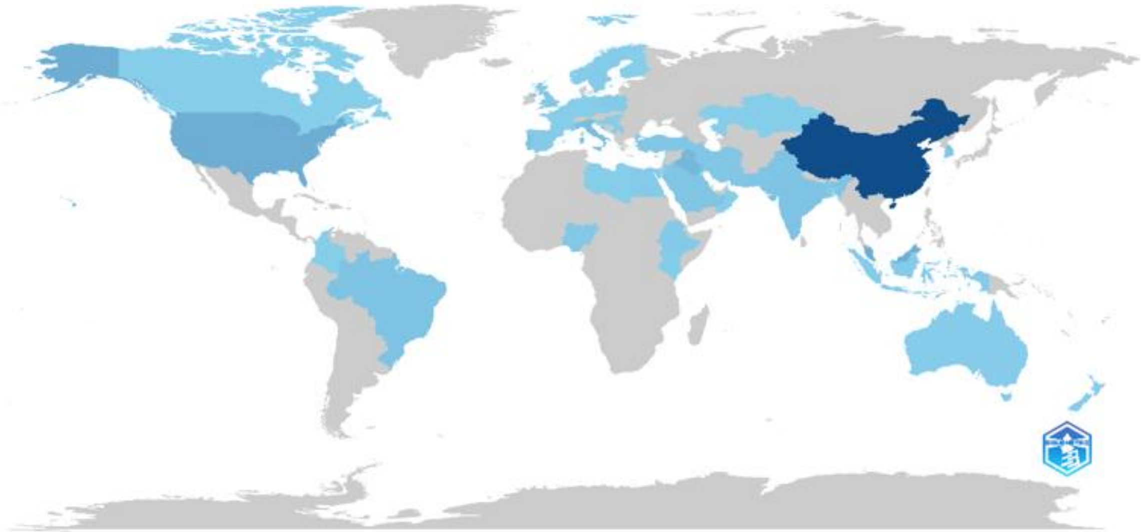

Fig 7. Countries scientific production

Beyond these leading contributors, several emerging countries, including Indonesia, Iraq, Ethiopia, and Turkey, are showing increasing participation, primarily through single-country publications. Their growing research activity reflects heightened awareness of biomass waste utilization, infrastructure sustainability challenges, and the potential of bio-based binders to support low-carbon development pathways. However, the predominance of single-country publication suggest that these emerging contributors remain relatively less integrated into global research networks. This indicates a gap in international collaboration and knowledge exchange, which may limit the scalability and broader dissemination of locally developed bio-asphalt technologies. Strengthening cross-country collaboration, particularly between established research hubs and emerging biomass-rich regions, will be critical to accelerating innovation and ensuring more equitable global development of sustainable bio-asphalt solutions.

The pronounced concentration of scientific productivity in Asia underscores the strategic role of biomass-rich regions in advancing bio-asphalt research. This pattern suggests a strong alignment between the availability of local waste resources, national sustainability priorities, and research capacity, reinforcing the development of bio-asphalt as a context-specific solution for circular and low-carbon pavement infrastructure. More importantly, this regional concentration highlights the growing importance of resource-driven innovation in shaping global research trajectories, where locally abundant biomass resources directly influence both research focus and technological development pathways.

Overall, the global distribution of scientific production and collaboration patterns demonstrates that bio-asphalt research is strongly influenced by the interplay between resource availability, national policy support, and technological capacity. Leading countries not only contribute the majority of publications but also play a central role in shaping research directions and facilitating international knowledge exchange. At the same time, the growing participation of emerging countries highlights the expanding global relevance of bio-asphalt, particularly in regions seeking sustainable and low-carbon infrastructure solutions based on locally available biomass resources. However, the observed imbalance in international collaboration suggests that further integration between established research hubs and emerging economies is necessary. These findings further emphasize the need for coordinated international research efforts to bridge regional disparities and advance performance-oriented and sustainable bio-asphalt development.

4.4 Keyword Co-Occurrence Network (VOSviewer)

Fig. 8 present-the keyword co-occurrence network generated using VOSviewer provides an essential lens for interpreting the conceptual structure of bio-asphalt research over the last three decades. By identifying clusters of frequently co-occurring terms, the analysis reveals how scientific attention is distributed across thematic domains and how these domains have evolved over time. The results indicate three dominant clusters that represent interconnected yet distinct research pathways: (1) bio-oil and rejuvenation technologies, (2) mechanical performance and durability, and (3) chemical and rheological characterization. Collectively, these clusters illustrate a clear progression from early substitution-oriented studies toward integrated performance engineering, combining material chemistry, binder rheology, and sustainable pavement design.

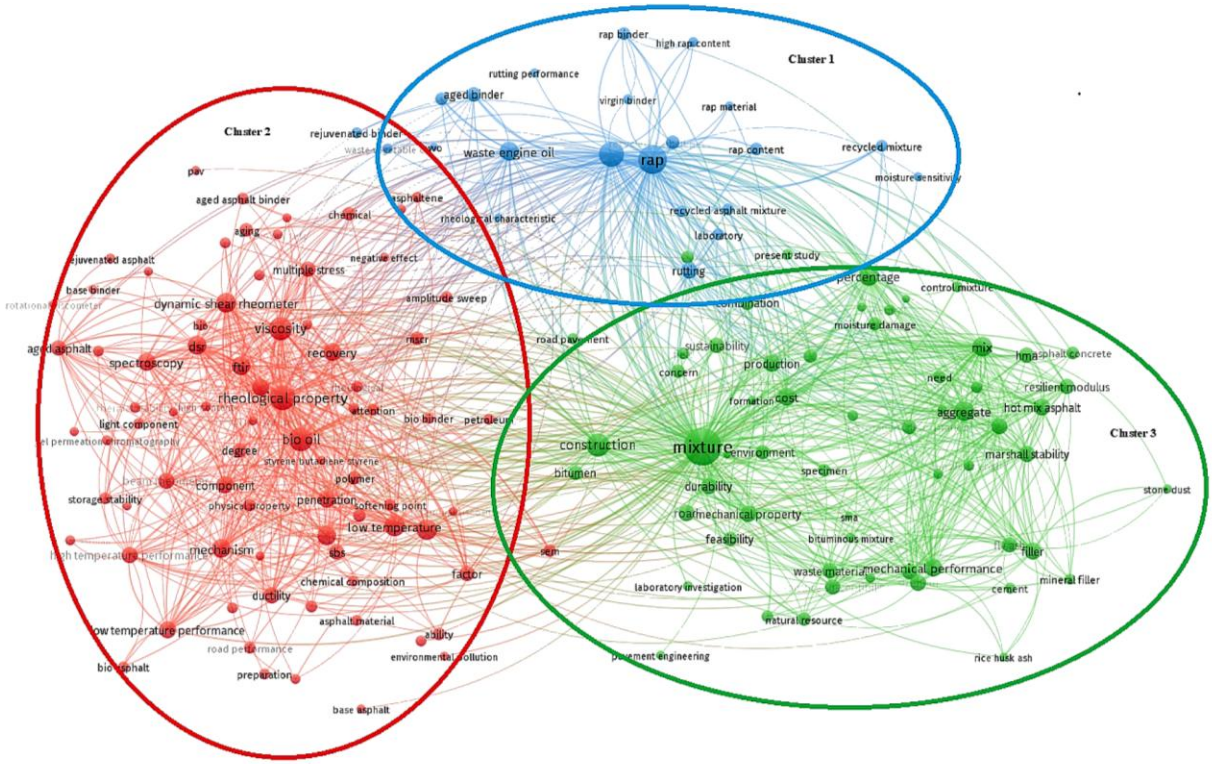

Fig. 8. Present the keyword co-occurrence network (using VOSviewer)

Cluster 1: Bio-Oil and Rejuvenation Technologies

The first thematic cluster, represented by keyword such as bio-oil, waste cooking oil, and rejuvenation, reflects the central role of rejuvenation technologies in both early and contemporary bio-asphalt research. This cluster captures the scientific focus on restoring aged binders and improving mixture workability, particularly within the broader context of circular economy strategies and sustainable pavement engineering.

Studies within this cluster explore the capacity of bio-oils-derived from waste cooking oil, palm oil residues, lignocellulosic biomass, or pyrolysis liquids-to soften oxidized asphalt binders and restore colloidal balance by redistributing maltene and asphaltene fraction [27], [28]. A significant portion of this research is associated with reclaimed asphalt pavement (RAP), highlighting its growing importance in infrastructure recycling. High RAP-content mixtures often suffer from brittleness and cracking susceptibility due to aged binder stiffness; bio-oil-based rejuvenators can mitigate these effects by enhancing ductility and improving fatigue resistance [29]–[31].

The prominence of the term recycling within this cluster indicates a strong alignment with global sustainability goals. RAP utilization is not only economically beneficial but also environmentally significant, as it reduces the demand for virgin bitumen and lowers lifecycle emissions [32]–[34]. Researchers have also investigated optimal blending strategies, dosage levels, and compatibility issues associated with different bio-oil sources[35], [36]. More importantly, this cluster highlights the strategic role of bio-oil technologies in enabling circular pavement systems, where waste materials are effectively reintegrated into infrastructure applications. Therefore, this cluster represents a critical intersection of waste valorization, material rejuvenation, and circular-economy-driven innovation.

Cluster 2 : Mechanical Performance and Durability

The second major cluster encompasses keywords such as rutting, moisture damage, stiffness, tensile strength, fatigue, permanent deformation, and durability. These terms reflect the mechanical and performance-driven dimension of bio-asphalt research, focusing on how modified binders and mixtures behave under traffic loading, environmental stresses, and long-term aging. More importantly, this cluster highlights the fundamental engineering challenge in bio-asphalt development: achieving a balanced performance between rutting resistance at high temperatures and cracking resistance under intermediate and low-temperature conditions.

Bio-asphalt materials, especially those modified with bio-oils, lignin, bio-polymers, or nano-additives, must satisfy rigorous performance criteria to be considered viable substitutes or enhancers for conventional bitumen. This cluster reflects the analytical efforts to evaluate how such modifications influence key performance indicators, including rutting resistance at high temperatures, fatigue performance under repeated loading, stiffness modulus, and resistance-induced stripping [37]–[40].

The observed clustering of rutting and moisture damage indicates that these performance issues remain primary constraints in the widespread adoption of bio-modified binders. Bio-oils tend to reduce viscosity and stiffness, which improves workability but may compromise high-temperature rutting resistance if not properly balanced with other modifiers. This highlights the inherent challenge in bio-asphalt design: achieving a balance between enhanced flexibility and adequate structural stability. To address this issue, numerous studies have explored hybrid modification strategies, including combinations of lignin, nano-materials, and polymer additives, to achieve improved performance across multiple distress modes [41]–[43].

Durability is another core theme in this cluster. Aging susceptibility, oxidative hardening, and moisture weakening collectively dictate the long-term reliability of asphalt pavements. The frequent co-occurrence of fatigue and tensile strength also signifies an increasing emphasis on mixture-level behavior, which is often studied using tests such as SCB, HMA fatigue tests, indirect tensile strength, and modulus-based evaluations [44]–[46]. More importantly, this trend highlights the critical need to translate binder-level modifications into reliable pavement performance, reinforcing the importance of linking rheological properties with mixture-scale mechanical behavior. The mechanical cluster therefore represents a growing scientific commitment to understanding how material modification influences real-world pavement performance.

Cluster 3 : Chemical and Rheological Characterization

The third cluster comprises keywords such as FTIR, DSR, rheology, thermal analysis, viscoelasticity, and microstructure, reflecting the fundamental analytical dimension of bio-asphalt research. This domain emphasizes the molecular, chemical, and rheological foundations that govern binder behavior and performance. More importantly, this cluster highlights the growing reliance on advanced characterization techniques to understand the interactions between bio-based modifiers and the bitumen matrix, enabling more rational material design and performance prediction.

Rheological and chemical analyses have become indispensable tools for understanding how bio-based modifiers interact with the bitumen matrix. Fourier Transform Infrared Spectroscopy (FTIR) is widely used to identify functional groups and oxidation characteristics, providing insight into chemical changes during modification and aging [47]. Dynamic Shear Rheometer (DSR) testing evaluates viscoelastic properties across temperature ranges, enabling the assessment rutting resistance (G*/sin δ), fatigue susceptibility (G*sin δ), and non-recoverable creep compliance (J_nr). Thermal analysis methods, including Differential Scanning Calorimetry (DSC), Thermogravimetric Analysis (TGA), and Bending Beam Rheometer (BBR), further provide insight into glass transition behavior, thermal stability, and low-temperature cracking potential [48]. Collectively, these techniques enable a mechanistic understanding of binder behavior, linking chemical composition and microstructure to performance-related properties.

The clustering of chemical and rheological keywords indicates that the field increasingly relies on molecular-level characterization to guide material design. This trend represents a strategic departure from the traditional reliance on empirical tests, such as penetration and softening point, toward more mechanistic and performance-oriented evaluation approaches. The integration of chemical analysis, rheology, and microstructural evaluation demonstrates a clear methodological shift toward establishing structure-performance relationships. This approach enables more rational modification strategies, improves understanding of bio-molecular interactions, and supports the development of predictive frameworks for binder behavior. More importantly, this shift facilitates the translation of laboratory-scale findings into performance-based pavement design, strengthening the linkage between material characterization and real-world engineering applications.

Critical Insight: Evolution Toward Multi-Dimensional Performance Engineering

The combined patterns observed across the three clusters reveal a critical insight: bio-asphalt research has evolved from early-stage material substitution toward a sophisticated, multi-dimensional performance engineering framework. Early studies primarily focused on the use of bio-oils and biomass-derived materials as softening agents or partial substitutes for conventional binders. However, the contemporary research landscape reflects a much deeper integration of material chemistry, mechanical behavior, sustainability considerations, and advanced characterization techniques , as consistently highlighted in recent studies [49]–[52]. This evolution is driven by several converging factors, including the increasing global emphasis on decarbonization and circular economy principles, the recognition of the fundamental role of binder chemistry in governing pavement performance, and the widespread adoption of rheological and chemical analytical frameworks. In addition, growing interest in hybrid material systems-combining lignin, polymers, and nanomaterials-has further accelerated the development of more robust and performance-balanced bio-asphalt systems. More importantly, the keyword co-occurrence network highlights a clear transition toward integrative and performance-oriented research approaches, where sustainability, chemistry, rheology, and mechanics are no longer treated as isolated domains but as interconnected components of material design. This integrated perspective provides a structured foundation for subsequent performance-based analysis presented in Section 5.

4.5 Science Mapping and Thematic Evolution (SciMAT)

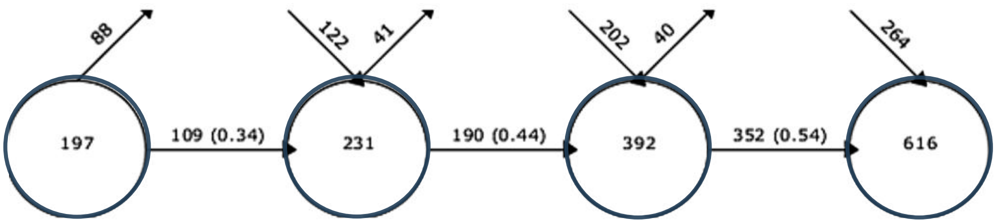

Fig. 9. Evolution map

Fig. 9 present the science mapping using SciMAT, providing a comprehensive understanding of how scientific themes in bio-asphalt research have emerged, evolved, strengthened, declined, and converged over time. By examining thematic network across sequential periods, this approach identifies conceptual cores, structural importance, and inter-theme relationships within the global knowledge system. The thematic evolution across four temporal segments (1995-2010, 2011-2015, 2016-2020, and 2021-2025) reflects a clear and logical progression from exploratory studies to interdisciplinary, sustainability-oriented engineering frameworks. More importantly, this evolution illustrates the transformation of bio-asphalt research from basic material substitution toward integrated performance engineering, encompassing rheological design, hybrid modification strategies, and comprehensive environmental evaluation.

Period 1 (1995-2010): Primitive and Isolated Themes

The earliest period of bio-asphalt research is characterized by relatively underdeveloped and weakly connected thematic structures, often lacking strong conceptual or methodological cohesion. The recurring themes during this period include vegetable oils, softening, viscosity, and modifiers. These keywords reflect the exploratory nature of early research, which primarily focused on assessing whether oils derived from soybean, rapeseed, palm, or waste cooking streams could function as partial substitutes for petroleum-based bitumen [53]–[55]. This stage represents a low-maturity phase of the field, where research efforts were largely fragmented and driven by material feasibility rather than performance-oriented engineering considerations.

Research output during this phase was sporadic, and the scientific community had not yet established standardized protocols, performance metrics, or rheological frameworks for evaluating bio-modified binders. Most studies relied on empirical testing methods, including penetration, softening point, and viscosity measurement, to assess binder softening potential. Advanced characterization techniques, such as FTIR, TGA, and DSR, were not yet widely adopted. As a result, the thematic structure of this period is characterized by low density, limited interconnectivity, and minimal integration with pavement engineering performance or environmental sustainability considerations. This reflects a fundamental limitation of the early research phase, where empirical evaluation dominated and mechanistic understanding of binder behavior remained largely undeveloped.

This thematic underdevelopment is consistent with the technological and academic landscape of the time. Bio-asphalt research had not yet established a solid theoretical foundation in areas such as binder chemistry, oxidative aging, or interaction mechanisms between bio-oil components and bitumen. Moreover, global policy frameworks related to renewable materials and waste valorization were still limited. As result, this early stage represents an initial phase of bio-asphalt research, characterized by fragmented efforts and a primary focus on material substitution rather than performance-oriented engineering.

Period 2 (2011-2015): emerging Structural Themes and Foundation Building

The second period marks the emergence of more structured thematic clusters, reflecting a significant increase in scientific interest and methodological sophistication. Dominant motor themes include lignin, bio-binder, rejuvenation, and chemical modification. These themes clearly indicate a transition phase in bio-asphalt research, shifting from exploratory material substitution toward systematic investigation of chemical interactions, performance enhancement, and binder rejuvenation mechanism. This period represents the initial integration of material chemistry with performance-oriented considerations.

This transition phase is characterized by two major developments that significantly shaped the direction of bio-asphalt research. First, lignin emerged as a promising bio-binder, particularly due to its aromatic and phenolic structure, which closely resembles the aromatic fractions of conventional bitumen. Derived from agricultural residues such as empty fruit bunches (EFB), sugarcane bagasse, and wood waste, lignin demonstrated the potential to enhance binder stiffness, improve oxidative stability, and increase resistance to high-temperature rutting [56]–[58]. Second, the increasing adoption of reclaimed asphalt pavement (RAP) led to growing interest in bio-oils as rejuvenating agents. Bio-oils derived from waste cooking oil, palm oil residues, pyrolysis processes, and tall oil were extensively studied for their ability to restore, ductility, reduce stiffness, and improve fatigue resistance in aged binders [59]–[61]. Together, these developments reflect a shift toward integrating chemical modification strategies with pavement performance considerations, laying the conceptual foundation for more advanced and performance-driven research in subsequent periods.

The thematic evolution map for 2011-2015 shows significantly stronger interconnectivity, indicating that researchers begam linking chemical modification themes with pavement engineering performance considerations. Unlike the first period, research during this phase is no longer isolated but instead forms more cohesive and structured thematic networks. This increasing connectivity reflects a growing level of scientific maturity, where material chemistry and engineering performance are increasingly integrated. As such, this period establishes the conceptual and methodological foundation for more advanced, performance-oriented bio-asphalt research in subsequent phases.

Period 3 (2016-2020): Consolidation, Diversification, and Technological Advancement

The third period (2016-2020) represents a phase of significant conceptual consolidation and technological diversification, during which bio-asphalt research became more systematized, multidimensional, and strongly performance-oriented. The motor themes identified by SciMAT include nanoparticles, aging resistance, warm mix asphalt (WMA), rheology, rheological performance (DSR-based), and viscoelasticity. This period marks a critical turning point in bio-asphalt innovation, characterized by the integration of advanced materials, improved characterization techniques, and increasing alignment with performance-based pavement engineering principles.

This phase is characterized by several key technological advancements that collectively transformed the direction of bio-asphalt research. One of the most significant developments is the emergence of nano-modified bio-asphalt systems, where nanomaterials such as nano-silica, nano-clay, graphene oxide, carbon nanotubes (CNTs), and nano-calcium carbonate are incorporated into bio-binders. These nano-additives enhance rutting resistance, improve microstructural stability, reduce temperature susceptibility, and mitigate the softening effects associated with bio-oil modification [62], [63]. In parallel, there is a substantial expansion in the use of advanced rheological and chemical characterization techniques. Methods such as multiple stress creep recovery (MSCR), linear amplitude sweep (LAS), bending beam rheometer (BBR), Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), and scanning electron microscopy (SEM) enable a deeper understanding of viscoelastic behavior, molecular structure, and aging mechanisms [64]. Additionally, bio-asphalt research increasingly integrates sustainability considerations through the adoption of Warm Mix Asphalt (WMA) technologies. Bio-oils are utilized as viscosity-reducing agents, allowing lower mixing and compaction temperatures, reduced energy consumption, and decreased emissions. Together, these developments reflect a shift toward more engineered, performance-driven, and environmentally conscious material design.

The thematic network for 2016-2020 exhibits high density, strong centrality, and well-defined thematic boundaries, indicating a mature and intellectually cohesive research phase. This structural consolidation reflects the increasing integration of material science, rheology, and pavement engineering within the field. Studies during this period provide the theoretical and methodological foundation necessary to translate laboratory-scale findings into practical engineering applications, marking a critical step toward implementation-oriented bio-asphalt technologies.

Period 4 (2021-2025): Sustainability, Circular Economy, and Implementation Readiness

The final period (2021-2025) reveals a strong shift toward environmental performance, large-scale implementation, and circular economy integration. Motor themes include circular economy, life cycle assessment (LCA), low-carbon materials, high-RAP utilization, and bio-based polymers. This phase represents the highest level of maturity in bio-asphalt research, characterized by the integration of sustainability metrics, advanced material engineering, and real-world implementation strategies. It reflects a transition from laboratory-scale innovation toward systems-level evaluation and practical application in sustainable pavement infrastructure.

This phase is characterized by a comprehensive integration of sustainability metrics into bio-asphalt research. While earlier studies primarily focused on material feasibility and performance, recent research increasingly incorporates life cycle assessment (LCA), life cycle cost analysis (LCCA), carbon reduction potential, and energy consumption into evaluation frameworks. This reflects a shift toward system-level sustainability assessment, where bio-asphalt is evaluated not only as a material but as part of a broader infrastructure system. At the same time, the growing adoption of high reclaimed asphalt pavement (RAP) content, often exceeding 50%, highlights the increasing importance of circular economy approaches. Bio-oils play a crucial role as rejuvenating agents, restoring aged binders and extending pavement service life, thereby enabling multiple recycling cycles. In addition, recent developments in bio-based polymers, including natural rubber latex, lignin-polymer blend, and recycled polymer systems, indicate a move toward more advanced hybrid material design. These systems aim to enhance both performance and durability while maintaining environmental compatibility. Collectively, these developments demonstrate a strong convergence between sustainability, material engineering, and implementation-oriented innovation.

Compared to previous periods, the thematic evolution map for 2021-2025 shows highly interconnected clusters with strong cross-linkages between environmental science, pavement engineering, rheology and material chemistry. This indicates the highest level of research maturity observed to date, where disciplinary boundaries are increasingly blurred and integrated. Such integration reflects a paradigm shift toward holistic and system-oriented research approaches, where material performance, environmental impact, and engineering design are simultaneously considered. This level maturity underscores the readiness of bio-asphalt technologies for real-world implementation within sustainable and circular infrastructure systems.

Critical Insight: Evolution Toward Sustainability -Driven and Implementation-Oriented Bio-Asphalt Research

Across all four periods, the thematic evolution reveals a clear and progressive transition in the focus of bio-asphalt research. The field has evolved from early-stage feasibility studies centered on material substitution, toward structured binder modification approaches, followed by the integration of advanced characterization techniques and hybrid material engineering, and ultimately into a holistic sustainability and implementation-oriented research framework. This progression reflects a steady increase in scientific depth, interdisciplinary integration, and practical relevance. In the early stages, research was primarily driven by the need to identify viable bio-based alternatives to petroleum binders. However, as the field matured, emphasis shifted toward understanding the fundamental interactions between bio-based modifiers and bitumen, optimizing rheological performance, and addressing durability challenges. More recently, the integration of sustainability assessment tools, such as life cycle analysis, carbon reduction evaluation, and circular economy frameworks, has redefined the research landscape. Bio-asphalt is no longer evaluated solely as a material, but as a component of a broader infrastructure system that must balance performance, environmental impact, and economic feasibility[2], [6]. Overall, the SciMAT-based thematic evolution confirms that bio-asphalt research has transitioned into a multi-dimensional and performance-oriented discipline. This evolution provides a critical conceptual foundation for the subsequent analysis presented in Section 5, where the engineering performance implication of these development-particularly in terms of rutting resistance, cracking behavior, aging, and sustainability-are examined in detail.

4.6 Integration of Performance Themes

The bibliometric and thematic analyses presented in Section 4.4 and 4.5 collectively reveal that bio-asphalt research has evolved toward a multi-dimensional, performance-oriented framework. The convergence of key research themes-including bio-oil rejuvenation, mechanical performance evaluation, and advanced chemical and rheological characterization-highlights a growing emphasis on linking material composition with engineering performance[62]–[65]. Across the identified thematic clusters, several critical performance domains consistently emerge as central research priorities, namely rutting resistance, cracking behavior, aging susceptibility, and moisture damage. These performance indicators are inherently interconnected and are strongly influenced by the type, dosage, and interaction mechanisms of biomass-derived modifiers within the asphalt binder system[66]–[68]. The evolution of these themes demonstrates that bio-asphalt performance cannot be adequately understood through isolated property evaluation. A key insight from this integration is the existence of a fundamental performance balance requirement in bio-asphalt design. Bio-oil incorporation typically reduces viscosity and enhances workability and fatigue resistance, but may simultaneously decrease stiffness and compromise rutting resistance at elevated temperatures[69]–[71]. Conversely, lignin-rich materials, polymers, and nano-additives tend to improve stiffness and high-temperature performance, but may increase brittleness and susceptibility to cracking under low-temperature or fatigue loading conditions. This inherent trade-off underscores the necessity of adopting integrated modification strategies, where hybrid systems are designed to achieve balanced performance across multiple distress modes. The increasing prominence of hybrid bio-binders, combining bio-oil, lignin, polymers, and nanomaterials, reflects a shift toward engineered material systems that simultaneously address rheological behavior, durability, and environmental sustainability[53], [71], [72]. Therefore, a comprehensive understanding of bio-asphalt performance requires a systematic evaluation of these interdependent properties within a unified framework. Building upon this integrated perspective, Section 5 provides a detailed performance-based analysis of bio-asphalt materials, focusing on the fundamental mechanisms governing rutting, cracking, aging, and moisture-related behavior under varying loading and environmental conditions.

5 Performance-Oriented Analysis of Bio-Asphalt

Building upon the bibliometric and thematic analyses presented in Section 4, this section provides a comprehensive performance-oriented synthesis of bio-asphalt research. The keyword clustering and thematic evolution analyses reveal a clear transition toward multi-dimensional performance engineering, where material composition, rheological behavior, and sustainability considerations are increasingly integrated. Accordingly, this section translates these conceptual insights into a technical perspective by examining the key performance characteristics of bio-asphalt materials, including rutting resistance, cracking behavior, aging susceptibility, and moisture-related performance. These properties are critically influenced by the incorporation of bio-based modifiers such as bio-oil, lignin, polymers, and nanomaterials, which alter the viscoelastic behavior and structural stability of asphalt binders. More importantly, the analysis emphasizes the fundamental challenge in bio-asphalt design: achieving a balanced performance across multiple distress modes. While bio-oils tend to improve workability and fatigue resistance, they may reduce stiffness and compromise rutting resistance. Conversely, lignin-based and nano-modified systems enhance stiffness and high-temperature performance but may increase brittleness and cracking susceptibility. Therefore, understanding and optimizing this performance trade-off is essential for the development of durable and sustainable bio-asphalt materials.

5.1 Rutting Resistance (High-Temperature Performance)

Rutting resistance is a critical performance parameter in asphalt pavements, particularly under high-temperature conditions and repeated traffic loading. As identified in the performance-oriented cluster in Section 4, rutting behavior is primarily governed by the viscoelastic properties of asphalt binders, especially their stiffness and resistance to permanent deformation. Bio-oil modification generally leads to reduction in binder viscosity and stiffness, which improves workability and mixing efficiency. At low moderate dosages ($\leq$10-15% by binder weight), bio-oils enhance flexibility and facilitate rejuvenation of aged binders by redistributing oxidized asphaltenes and restoring viscoelastic balance [59],[60],[73]. However, excessive bio-oil incorporation (>15%) results in over-softening, which significantly reduces high-temperature stiffness and increase susceptibility to rutting [74], [75]. To compensate for this limitation, hybrid modification strategies are widely adopted. Lignin-rich materials, due to their aromatic and phenolic structures, contribute to increased binder stiffness and improved rutting resistance[3], [76], [77]. Similarly, nanomaterials such as nano-SiO_2, nano-$CACO_3$, and graphene oxide enhance microstructural stability, reduce temperature susceptibility, and improve load-bearing capacity [78]–[81]. Rheological evaluation using Dynamic Shear Rheometer (DSR) and Multiple Stress Creep Recovery (MSCR) test further confirms that hybrid-modified bio-asphalt systems exhibit improved rutting performance, characterized by higher rutting factors ($G^*/\sin\delta$), lower non-recoverable creep compliance (Jnr), and higher elastic recovery[82], [83]. These findings indicate that the negative impact of bio-oil softening can be effectively mitigated through the incorporation of stiffening modifiers.

5.2 Cracking Resistance (Fatigue and Low-Temperature Performance)

Cracking resistance is a critical performance parameter in asphalt pavement, particularly under repeated loading and low-temperature conditions. As identified in the thematic evolution and performance-oriented clusters in Section 4, increasing research attention has been directed toward fatigue resistance, tensile behavior, and crack mitigation mechanisms in bio-asphalt systems. The incorporation of bio-oils generally enhances cracking resistance by reducing binder viscosity and increasing molecular mobility. This softening effect improves stress relaxation capacity, allowing the binder to dissipate strain energy more effectively under cyclic loading. As a result, bio-modified binders exhibit improved fatigue life and delayed crack initiation and propagation. In particular, bio-rejuvenators derived from plant-based oils have been shown to restore ductility and tensile strain capacity in aged binders, significantly enhancing fatigue performance [61], [84]. Furthermore, bio-asphalt systems demonstrate enhanced self-healing capabilities due to increased molecular diffusion and improved crack wetting behavior. Reduced viscosity facilitates the flow of binder molecules into micro-cracks, while rest periods under intermittent loading conditions promote molecular interdiffusion across crack interfaces, enabling partial recovery of mechanical integrity[3], [85]. Compared to conventional petroleum-based binders, bio-modified asphalt generally exhibits improved resistance to embrittlement during long-term aging, maintaining greater flexibility and relaxation capacity under cyclic loading[86], [87] However, excessive bio-oil incorporation may adversely affect fatigue performance by excessively reducing stiffness, leading to insufficient load-bearing capacity and accelerated damage accumulation. To address this limitation, hybrid modification strategies are increasingly employed. The incorporation of polymers such as styrene-butadiene-styrene (SBS) and crumb rubber enhances elasticity, improves energy dissipation capacity, and maintains structural integrity under repeated loading. These hybrid systems enable a more balanced response between flexibility and stiffness, thereby improving overall cracking resistance[88]. At the mechanistic level, cracking resistance in bio-asphalt systems is governed by the interplay between viscosity, molecular mobility, and viscoelastic relaxation behavior. Reduced stiffness enhances flexibility and crack resistance, while sufficient structural integrity is required to sustain repeated loading. This highlights the importance of optimizing bio-asphalt formulations to achieve enhanced cracking resistance without compromising other critical performance properties.

5.3 Aging Behavior (Short-Term and Long-Term Aging)

Aging behavior is a critical determinant of asphalt binder durability and long-term pavement performance. As identified in the chemical and rheological characterization cluster in Section 4, the aging susceptibility of bio-asphalt is strongly influenced by binder composition, oxidation mechanisms, and the interaction between bio-based modifiers and the bitumen matrix. In bio-asphalt systems, aging behavior can be either enhanced or impaired depending on the origin, chemical composition, and dosage of the bio-based modifier. Lignin-rich components have consistently demonstrated improved aging resistance due to their aromatic structure and high phenolic content, which provide natural antioxidant effects and inhibit oxidative hardening of the [3], [83], [84]. These phenolic compound act as radical scavengers, slowing down oxidation reactions and stabilizing the binder microstructure during aging. Similarly, bio-oils derived from lignocellulosic biomass and wood waste have been reported to reduce carbonyl index growth and restore colloidal balance in aged binders, thereby improving durability under long-term aging conditions[4], [85]. The rejuvenation effect of bio-oils facilitates the redistribution of oxidized asphaltenes and enhances the viscoelastic properties of aged asphalt systems. Nanomaterial additives, including nano-SiO_2, nano-$CaCO_3$, and TiO_2, further enhance aging resistance by forming micro-barriers within the binder matrix. These barriers reduce oxygen diffusion, improve thermal stability, and delay oxidative degradation[86]. The synergistic combination of bio-oil, lignin, and nanomaterials has been shown to provide superior aging performance through both chemical stabilization and structural reinforcement mechanisms. However, not all bio-oil modifications lead to improved aging performance. Highly oxygenated bio-oils may accelerate oxidative reactions due to the presence of reactive functional groups, while excessive bio-oil content (>15% by binder weight) can increase volatile fractions and exacerbate short-term aging during mixing and compaction processes[4], [78]. At the mechanistic level, aging behavior in bio-asphalt is governed by the balance between oxidation kinetics, molecular structure, and binder microstructure. Phenolic compounds inhibit free radical propagation, polymeric and lignin networks provide structural stability, and nano-fillers reduce oxygen permeability. Therefore, optimizing binder composition through hybrid modification strategies is essential to achieve enhanced durability and long-term aging resistance in bio-asphalt systems.

5.4 Moisture Susceptibility (Stripping and Water Damage Resistance)

Moisture susceptibility is a critical durability issue in asphalt pavement, as it governs the resistance of asphalt mixture to stripping, cohesion loss, and long-term performance degradation under wet conditions. As identified in the performance and chemical interaction clusters in Section 4, moisture-related damage in bio-asphalt systems is strongly influenced by binder polarity, chemical composition, and adhesion characteristics between binder and aggregate. The incorporation of bio-oils can significantly affect moisture resistance due to their high oxygen content and polar functional groups. These characteristics tend to increase binder hydrophilicity, weakening the adhesion between asphalt binder and aggregate surfaces. As a result, bio-oil modified binders may exhibit increased susceptibility to moisture-induced stripping, particularly at higher dosages[4], [78]. However, at moderate dosages, bio-oils can improve binder dispersion and coating ability, leading to more uniform aggregate coverage and potentially mitigating moisture damage. Additionally, rejuvenation of aged binders through bio-oil incorporation can restore binder flexibility and reduce micro-cracking, indirectly improving resistance to moisture penetration. To address the inherent moisture susceptibility of bio-based binders, hybrid modification strategies are widely employed. The addition of polymers, anti-stripping agents, and nanomaterials enhances adhesion strength and improves moisture resistance. Nanomaterials such as nani-SiO_2, and nano-$CaCO_3$, improve binder-aggregate bonding by increasing surface interaction and reducing permeability[89]–[91] Similarly, polymer modified systems enhance cohesion and elastic recovery, contributing to improved resistance against moisture-induced damage. At the mixture level, moisture susceptibility is commonly evaluated using tests such as indirect tensile strength (ITS), retained ITS, and tensile strength ratio (TSR). These tests indicate that hybrid-modified bio-asphalt systems generally demonstrate improved moisture resistance compared to bio-oil-only systems, confirming the importance of integrated material design. Overall, moisture susceptibility in bio-asphalt systems is governed by the balance between chemical polarity and adhesive properties. While bio-oils introduce hydrophilic components that may weaken binder-aggregate bonding, the incorporation of complementary modifiers can effectively restore adhesion and enhance resistance to moisture damage.

5.5 Hybrid Modification Strategies

Hybrid modification has emerged as key approach in bio-asphalt research to overcome the inherent limitations of single bio-based modifiers. As identified in the thematic evolution and integration analyses in Section 4, the development of hybrid bio-asphalt systems reflects a shift toward engineered materials designed to achieve balanced performance across multiple distress modes. The incorporation of nanomaterials has demonstrated significant improvements in binder performance. Nanoparticles such as graphene oxide, nano-SiO_2, nano-$CaCO_3$, and ZnO enhance stiffness, improve rutting resistance, and increase aging stability by reinforcing the binder microstructure and reducing temperature susceptibility[92]–[95]. These materials act as nano-scale fillers and interaction enhancers, improving load transfer and resistance to deformation. Polymeric modifiers also play a crucial role in hybrid systems. Styrene-butadiene-styrene (SBS) significantly enhances elasticity, elastic recovery, and high-temperature stability, enabling improved resistance to rutting while maintaining flexibility under repeated loading conditions[81]. Ethylene-vinyl acetate (EVA) improves thermal stability and binder cohesion, while crumb rubber contributes to enhanced elasticity and resistance to permanent deformation, particularly in high-RAP mixtures[96]. Lignin integration represents another effective strategy in hybrid modification. Due to its aromatic structure, lignin increases binder stiffness, improve high-temperature performance, and enhances resistance to oxidative aging. Partial substitution of bitumen with lignin, typically within the range of 10-30% by binder weight, has been shown to reduce thermal susceptibility and improve mixture durability[3], [97], [98]. The combination of bio-oil with these modifiers enables the development of hybrid systems that simultaneously improve workability, stiffness, durability, and environmental performance. Bio-oil provides flexibility and rejuvenation capability, while polymers, lignin, and nanomaterials compensate for the loss of stiffness and structural stability. This synergistic interaction between modifiers is essential for achieving balanced performance across multiple engineering criteria. Overall, hybrid modification strategies represent a critical advancement in bio-asphalt technology, transforming bio-asphalt from a simple material substitution approach into a sophisticated, multi-functional engineered system capable of meeting modern pavement performance requirements.

5.6 Performance Balance (Rutting-Cracking Trade-off)

A fundamental challenge in bio-asphalt design lies in achieving a balanced performance between rutting resistance and cracking resistance. As consistently identified across the thematic clusters and performance analyses in Sections 4 and 5, the incorporation of bio-based modifiers introduces competing effects on the viscoelastic behavior of asphalt binders. Bio-oils, which act primarily as softening and rejuvenating agents, reduce binder viscosity and enhance molecular mobility. This leads to improved workability, enhanced fatigue resistance, and increased resistance to thermal cracking. However, this softening effect also reduces high-temperature stiffness, thereby increasing susceptibility to permanent deformation and rutting, particularly at higher dosages[73][74]. Conversely, lignin, polymeric modifiers, and nanomaterials tend to increase binder stiffness and improve high-temperature performance. These materials enhance rutting resistance by strengthening the internal structure of the binder and improving load-bearing capacity. However, excessive stiffening may reduce flexibility and increase brittleness, leading to a higher risk of fatigue and low-temperature cracking. This inherent trade-off highlights the importance of adopting a performance-based design approach in bio-asphalt systems. Rather than optimizing a single property, effective material design requires achieving a balance response across multiple distress modes, Hybrid modification strategies, combining, bio-oil with lignin, polymers, and nanomaterials, have been shown to provide the most effective solution by simultaneously enhancing flexibility, stiffness, durability, and resistance to environmental damage[81], [96], [98], [99]. At the mechanistic level, this performance balance is governed by the interplay between viscosity, molecular mobility, and structural rigidity. Bio-oil enhances molecular diffusion and stress relaxation, while lignin and nano-modifiers reinforce the binder matrix and improve resistance to deformation. The optimal balance is achieved when sufficient flexibility is maintained to resist cracking, while adequate stiffness is preserved to prevent rutting. Overall, the concept of performance balance provides a unifying framework for understanding bio-asphalt behavior and guiding material design. This perspective shifts the focus from single-property optimization toward integrated performance engineering, aligning bio-asphalt development with modern performance-based pavement design principles. **Table 2** summarizes the comparative performance trends of various bio-based modifiers discusses in this section, highlighting their effects on key engineering properties, including rutting resistance, cracking behavior, fatigue performance, moisture susceptibility, aging resistance, and stiffness characteristics.

As shown in **Table 2**, no single bio-based material consistently optimizes all performance aspects. While certain modifiers enhance flexibility and cracking resistance, other improve stiffness and rutting resistance. This reinforces the importance of hybrid modification strategies and performance-balanced design approaches, as discussed in Section 5.6. Despite the significant advancements discussed in this study, several limitations should be acknowledged. First, the performance of bio-asphalt materials is highly dependent on the variability of bio-oil composition, which is influenced by feedstock type, biomass source, and conversion processes such as pyrolysis or transesterification. This variability introduces challenges in generalizing performance outcomes across different studies. Second, the lack of standardized testing protocols and modification procedures limits the comparability of results reported in the literature. Variations in binder preparation methods, dosage levels, and testing conditions may lead to inconsistencies in reported performance characteristics. Third, the majority of existing studies are conducted at the laboratory scale, with limited long-term field validation under real traffic and environmental conditions. This gap restricts the ability to fully assess the practical performance and durability of bio-asphalt systems in real-world applications. Finally, much of the current research relies on qualitative or semi-quantitative performance evaluation, which may not fully capture the complex interactions governing bio-asphalt behavior. Therefore, future research should focus on developing standardized evaluation frameworks, improving reproducibility, and validating performance through large-scale field studies.

Table 2 Comparative Performance Evaluation of Bio-Based Modifiers in Asphalt Systems Based on Literature Synthesis

Bio-Based Material	Dosage (%)	Rutting Resistance (High-Temp)	Cracking Resistance (Low-Temp)	Fatigue Resistance	Moisture Susceptibility	Aging Resistance	Stiffness Modulus	Key Noted	References
Waste Cooking Oil	3-10	Moderate ↓	Strong ↑	Strong ↑↑	Neutral ●	Moderate ↑	Low ↓	Effective rejuvenator; requires hybrid modification for high-temperature stability	[59], [60], [73], [100]
Palm Oil	5-20	Low ↓↓	Low ↓	Moderate ↑	Low ↓	Weak ↓	Low ↓↓	High softening effect; limited suitability for-high-temperature applications	[73], [101]
Sugarcane Baggasse	2-8	High ↑	Good ●	High ↑	Very High ↑↑	High ↑	Medium ↑	Strong reinforcement due to lignin-rich structure; improves durability and stiffness	[82], [102]
Pine Oil	5-20	Low ↓↓	Low ↓	Moderate ↑	Low ↓	Very Low ↓↓	Low ↓	Limited suitability for high-stress pavement conditions	[74]
Soybean Oil	5-20	Neutral ●	Strong ↑	Moderate ↑	High ↑↑	Neutral ●	Medium ●	Provides good flexibility; improved performance when combined with polymers	[61], [84]
Cottonseed Oil	5-20	Moderate ●	Strong ↑	Strong ↑	Moderate ↑	Stable ●	Medium ●	Enhances workability and fatigue performance; compatible with hybrid systems	[61], [84]
Peanut Husk Extract	2-8	Very High↑↑	Very High ↑↑	High ↑	High ↑	Very High ↑↑	High ↑	Promising multi-performance characteristics; requires further validation	[97], [98]

Notes: Performance ratings summarize general trends reported in the literature and may vary depending on biomass source, production pathway, base binder grade, modifier dosage, aging condition, and test method. Representative dosage values indicate commonly reported ranges in published studies rather then fixed optimum contents. High or low performance classifications should therefore be interpreted as comparative qualitative indicators within the reviewed literature, not as absolute rankings, Hybrid systems require case-specific optimization due to possible synergistic or antagonistic interactions among modifiers.

5 Conclusion

This study presents a comprehensive bibliometric and performance-oriented synthesis of bio-asphalt research, integrating 343 Scopus-indexed publications from 1995 to 2025. The analysis reveals a clear and progressive evolution of the field, from early-stage exploratory studies focused on material substitution toward a multi-dimensional, performance-driven, and sustainability-oriented research framework. The bibliometric findings highlight a significant increase in scientific output after 2015, accompanied by a shift toward interdisciplinary research integrating material science, rheology, nanotechnology, and environmental engineering. Thematic evolution analysis using SciMAT demonstrates that bio-asphalt research has transitioned through distinct developmental stages, characterized by increasing methodological sophistication and conceptual integration. Early studies primarily focused on feasibility and basic material characterization, while recent research emphasizes advanced hybrid modification strategies, performance-based evaluation, and sustainability considerations such as life cycle assessment and circular economy implementation.

From a performance perspective, the findings indicate that the behavior of bio-asphalt is governed by complex interactions between material composition, viscoelastic properties, and environmental conditions. Bio-oils play a critical role in improving workability, rejuvenation capability, and cracking resistance, but may reduce high-temperature stiffness and increase rutting susceptibility at higher dosages. In contrast, lignin, polymers, and nanomaterials enhance stiffness, rutting resistance, and aging performance, but may increase brittleness if not properly optimized. A key contribution of this study is the identification of a fundamental performance balance framework in bio-asphalt design. Rather than optimizing individual properties, effective material design requires achieving a balanced response between rutting resistance and cracking resistance. Hybrid modification strategies, combining bio-oil with lignin, polymers, and nanomaterials, provide the most promising pathway to achieving this balance by integrating flexibility, stiffness, durability, and environmental performance. The comparative analysis presented in Table 2 further confirms that no single bio-based material consistently optimizes all performance aspects, reinforcing the importance of integrated material design approaches. Despite these advancements, several challenges remain, including variability in bio-oil composition, lack of standardized testing protocols, and limited long-term field validation. Overall, this study provides a structured and integrative framework for understanding bio-asphalt behavior, bridging bibliometric insights with engineering performance analysis. The findings highlight the potential of bio-asphalt as a viable and sustainable alternative to conventional petroleum-based binders, while emphasizing the need for standardized methodologies and large-scale implementation strategies. Future research should focus on optimizing hybrid systems, developing performance-based specifications, and validating long-term field performance under diverse environmental and traffic conditions.

Novelty Statement

(1) This study integrates bibliometric mapping with performance-oriented engineering analysis in bio-asphalt research.
(2) A performance balance framework is proposed to explain the trade-off between rutting resistance and cracking behavior
(3) Hybrid modification strategies are identified as the most promising pathway for achieving multi-dimensional performance and sustainability

Acknowledgement

We are grateful to our anonymous reviewers and the Language Awareness editor for their invaluable feedback. We also wish to thank the Directorate of Research and Community Service at Universitas Lancang Kuning for the generous support and access to Turnitin and Grammarly, which greatly facilitated the preparation of this manuscript. We also extend our appreciation to Universitas Gadjah Mada for providing access to the Scopus database, which significantly enriched the research and references for this study.

Funding Statement

This work was supported by the Center for Higher Education Funding and Assessment (PPAPT/ Pusat Pembiayaan dan Asesmen Pendidikan Tinggi) and the Indonesian Endowment Fund for Education (LPDP/Lembaga Pengelola Dana Penelitian) under the Indonesian Education Scholarship (BPI/Beasiswa Pendidikan Indonesia) program (Contract No. 02041/BPPT/BPI.06/9/2023)

CRediT authorship contribution statement

Alfian Saleh: Conceptualization, Writing-original draft, Writing-review & editing. **Latif Budi Suparma:** Methodology, Supervision**. Taqia Rahman:** Supervision, Visualization.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the present study.

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