
Review

Tribological performance of graphene-reinforced Al-based metal matrix composites (2015–2025): A bibliometric analysis

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Abstract: In this study, we present a bibliometric analysis of research on the tribological performance of graphene-reinforced aluminum metal matrix composites published between 2015 and 2025. Using the Scopus database and a structured search strategy focused on graphene-family reinforcements, aluminum matrix systems, composite terminology, and tribology-related terms, a cleaned corpus of 822 documents was analyzed through performance analysis and science mapping using the Bibliometrix package in R. The dataset spanned 283 publication sources and showed a strong annual growth rate of 28.56%, indicating rapid expansion of the field over the last decade. Original research articles dominated the corpus (690 documents; 83.9%), confirming the strongly experimental character of the literature. At the country level, India led in publication output (330 documents), followed by China (235 documents), whereas China showed higher average citation impact (20.3 citations per document) than India (14.3 citations per document). The most cited paper in the corpus was Tabandeh-Khorshid et al. (2016) with 236 citations. Keyword co-occurrence analysis identified graphene, wear, microstructure, and mechanical properties as the main conceptual anchors of the field. Thematic mapping revealed five principal clusters: graphene tribology, mechanical-microstructural characterization, powder-metallurgy-based hybrid systems, graphene oxide coatings and wear resistance, and self-lubricating wear mechanisms. Importantly, the analysis showed that the field remains more strongly organized around processing–microstructure–performance correlations than around interface-specific tribological mechanisms. Mechanism-oriented topics such as matrix–graphene interfacial bonding, tribofilm and transfer-layer formation, Al_4C_3 interfacial reactions, third-body behavior, and wear-mechanism transitions remain comparatively less central in the keyword and thematic

structure. Thematic evolution showed a transition from early feasibility-oriented and self-lubricating themes toward more mature emphases on microstructural interpretation, reinforcement differentiation, and performance optimization. Trend analysis indicated that the most relevant near-term research frontiers are microstructure-guided tribological design, graphene-form specificity, multifunctional property optimization, and refinement of established fabrication routes. The results also showed that mechanism-resolved tribology, standardized benchmarking, and application-relevant validation remain comparatively underdeveloped. Overall, this study provides a structured map of the field's growth, knowledge base, conceptual organization, and future research priorities.

Keywords: bibliometric analysis; graphene; aluminum matrix composites; wear; tribology; friction; graphene nanoplatelets; graphene oxide; science mapping; Bibliometrix

1. Introduction

Aluminum alloys and aluminum-based composites remain central to lightweight engineering design in aerospace, automotive, marine, and general industrial applications because they offer attractive combinations of low density, corrosion resistance, and processability [1]. The growing demand for lightweight structural and engine components has therefore continued to drive the development and optimization of aluminum-based materials that can satisfy increasingly stringent mechanical and surface-performance requirements [2]. However, the relatively modest hardness, limited wear resistance, and susceptibility to adhesive and abrasive degradation of unreinforced aluminum alloys have long motivated the development of Al-based metal matrix composites (AMMCs) reinforced with ceramic particulates, fibers, and, more recently, carbonaceous nanomaterials [3]. In parallel with these property-driven developments, practical issues such as machinability and manufacturability remain important for the broader engineering adoption of hybrid metal matrix composites [4].

Among the available nanoscale reinforcements, graphene-family materials, including single-layer graphene, graphene nanoplatelets (GNPs), graphene oxide (GO), reduced graphene oxide (rGO), and few-layer graphene (FLG), have attracted particular attention because they can address several limitations of aluminum alloys simultaneously [5,6]. The rationale for incorporating graphene into aluminum matrix composites is based on the combination of its mechanical, interfacial, and solid-lubrication functions. Mechanically, the high in-plane elastic modulus, tensile strength, and specific surface area of graphene can promote load transfer, grain refinement, and dislocation pinning, thereby increasing hardness and reducing subsurface plastic deformation during sliding contact [3,7]. The potential of graphene as a reinforcement in aluminum composites was recognized early, and subsequent studies have shown that even modest additions of graphene-family materials can produce measurable improvements in hardness, strength, and wear resistance relative to unreinforced alloys [8,9]. Tribologically, the layered structure and low interlayer shear resistance of graphene can reduce friction by facilitating easy shear at the contact interface, while graphene-derived transfer layers and tribofilms can protect the worn surface and reduce direct metal-to-metal contact [10,11]. In addition, the high thermal conductivity of graphene may assist heat dissipation at sliding interfaces, which is relevant under severe or elevated-temperature wear conditions [12,13]. Nanostructured AA2124 self-lubricating composites reinforced with graphene, for example, have shown simultaneous

improvements in mechanical and tribological behavior relative to the base alloy [14]. Similarly, the hybridization of graphene nanoplatelets with conventional ceramic reinforcements such as SiC has been shown to enhance wear performance compared with composites containing either reinforcement alone [15]. The exceptional intrinsic properties of graphene, including a high in-plane elastic modulus, very high tensile strength, low interlayer shear resistance, high thermal conductivity, and very large specific surface area, provide a strong theoretical basis for its use as a tribological modifier in metallic matrices [16]. Broader metallic-matrix evidence also supports this interpretation, since multilayer graphene reinforcement has been shown to improve mechanical strength and tribological performance in Ni₃Al-based composites [17]. In addition, studies on inorganic nanomaterial lubricant additives indicate that graphene-family materials are increasingly recognized as effective friction- and wear-reducing agents across a wide range of tribological configurations [18].

In aluminum-based systems, graphene additions at relatively low volume fractions, often within the sub-2 wt.% range, have been shown to improve hardness, reduce coefficient of friction, lower wear rates, and promote the formation of self-lubricating tribofilms at sliding interfaces [19]. The role of graphene nanoplatelets in the tribological performance of self-lubricating aluminum matrix nanocomposites has been systematically investigated, revealing that GNP addition promotes the development of a protective transfer layer on the worn surface that reduces friction and material loss [20]. The formation and stability of such graphene-derived tribofilms during dry sliding wear have been directly confirmed through detailed microstructural analysis of worn surfaces [21]. Related tribofilm evidence has also been reported outside aluminum matrices, such as in Al₂O₃-graphene nanoplatelet composites, which supports the broader solid-lubrication role of graphene at sliding interfaces [22]. Hybrid aluminum composites reinforced with alumina and graphene-family phases have likewise demonstrated notable reductions in coefficient of friction and specific wear rate compared with monolithic aluminum [23,24].

These tribological benefits arise from the synergistic combination of several strengthening and lubrication mechanisms. Load transfer from the soft aluminum matrix to the high-stiffness graphene reinforcement, combined with grain refinement caused by the pinning effect of graphene at grain boundaries, contributes to increased hardness and resistance to plastic deformation during sliding contact [25]. Orowan-type dislocation pinning, in which graphene platelets act as obstacles to dislocation motion, further enhances matrix strength and reduces subsurface deformation under tribological loading [26]. From a broader self-lubricating metal matrix composites (MMC) perspective, layered carbon reinforcements reduce friction because weak interlayer bonding facilitates easy shear at the contact surface [27]. In aluminum systems specifically, the combined action of strengthening and solid-lubrication mechanisms has been demonstrated in carbonaceous-reinforcement studies, where graphene outperformed carbon nanotubes and graphite in reducing the wear rate of friction stir processed Al6061 alloy [28]. Computational approaches, including molecular dynamics simulations, have further shown that the geometrical aspects of nanofillers, particularly the two-dimensional sheet morphology of graphene, play a critical role in determining the tribological performance of Al-based nanocomposites [29].

The dry sliding wear behavior of graphene-reinforced aluminum composites has been extensively characterized under varying loads, sliding speeds, and temperatures [30]. Reciprocating dry sliding friction and wear tests have confirmed that graphene additions reduce the severity of adhesive and abrasive wear mechanisms in cast aluminum alloy matrices [31]. Under elevated-temperature conditions, the tribological advantages of graphene reinforcement are generally maintained, although

the stability of the graphene-derived tribofilm and the onset of interfacial degradation become increasingly important above approximately 200 °C [32]. Hybrid aluminum composites reinforced with ceria and graphene nanoparticles have revealed that graphene can contribute to a transition from severe oxidative wear to milder wear regimes at elevated contact temperatures [33]. The tribological performance of SPS-consolidated aluminum-graphene composites has also been evaluated across a range of temperatures, demonstrating that graphene reinforcement is effective in maintaining low friction and wear from room temperature to moderately elevated service conditions [34].

The influence of graphene content on tribological properties has been a central focus of numerous investigations. Wear studies on graphene-reinforced AA7050-based composites indicate that an optimal graphene content exists, beyond which agglomeration degrades microstructural homogeneity and wear resistance [35]. Similar observations have been reported for hybrid aluminum composites containing graphene and ZrO₂ binary nanoparticles, where progressive increases in graphene content initially improved and then deteriorated tribological performance [36]. The tribological behavior of hybrid aluminum self-lubricating composites under dry sliding conditions has also been shown to be sensitive to graphene loading fraction and the presence of complementary ceramic phases that help anchor graphene within the matrix [37]. In addition, the combination of surface texturing with graphene nanoplatelets can further enhance the friction-reducing capability of graphene reinforcement [38].

Machine learning (ML) models have been applied to analyze the friction and wear of graphene-reinforced aluminum metal matrix composites, demonstrating that data-driven approaches can capture complex nonlinear relationships between processing parameters, reinforcement content, and tribological response [39]. Related ML studies on graphene-containing light-metal composite systems beyond aluminum, including magnesium-based composites, further indicate that predictive models can achieve high accuracy in forecasting wear rates from relatively limited experimental datasets [40]. These computational approaches represent a growing research direction within the field and now complement the predominantly experimental literature base.

Processing routes for graphene-reinforced AMMCs have diversified considerably over the past decade. Powder metallurgy (PM) combined with hot pressing or spark plasma sintering (SPS) remains the most widely reported consolidation strategy for these systems [41]. SPS-based fabrication has been employed to produce graphene-nanoplatelet-reinforced 7075 aluminum alloy composites with improved strength and wear resistance, benefiting from rapid densification and limited grain growth [42]. More broadly, microstructure and wear studies of PM and hot-press-consolidated graphene-reinforced aluminum composites have shown that consolidation conditions strongly affect graphene dispersion, densification, and structural integrity within the matrix [43]. Induction sintering followed by hot rolling has been used to fabricate nanostructured graphene/A6061 composites, yielding improvements in mechanical and tribological properties relative to conventionally sintered counterparts [44]. The fabrication of Al/Al₂O₃/SiC/graphene hybrid nanocomposites through powder metallurgy routes has further shown that multi-phase reinforcement architectures can be successfully consolidated while preserving graphene integrity [45].

Friction stir processing (FSP) has emerged as one of the most versatile solid-state routes for incorporating graphene into aluminum matrices, offering the advantages of severe plastic deformation, grain refinement, and mechanical mixing without melting [39]. Multi-pass friction stir processing has been employed to disperse graphene nanoplatelets into Al-Mg alloys, achieving more homogeneous reinforcement distribution and significant strengthening after repeated cumulative passes [9]. Friction stir alloying has likewise been used to manufacture high-strength multilayer-graphene-reinforced

aluminum composites, further demonstrating the suitability of shear-assisted solid-state processing for graphene incorporation [46]. Hybrid surface nanocomposites containing graphene and TiB_2 have been produced by multi-pass FSP, demonstrating that the combination of nano- and micro-scale reinforcements can enhance hardness and wear resistance beyond what either reinforcement achieves independently [47]. The effects of graphene nanoplatelets on the microstructural characteristics and textural development of an Al-Mg alloy during friction-stir processing have been characterized in detail, showing that GNPs promote dynamic recrystallization and grain refinement within the stir zone [48]. A combined powder metallurgy and friction stir processing strategy has also been reported to achieve high-efficiency dispersal and strengthening of graphene-reinforced aluminum alloy composites, addressing the persistent challenge of agglomeration encountered in single-step processes [49]. Surface modification of Al6061-SiC composites through the impregnation of graphene, graphite, and carbon nanotubes via FSP has been systematically compared, revealing that graphene yields the greatest tribological improvement among the three carbonaceous reinforcements [50].

Stir casting has also been explored as a liquid-state route for graphene-reinforced aluminum matrix composites, although the literature continues to emphasize challenges related to graphene wettability, flotation, and agglomeration in molten aluminum. Dry sliding wear and microstructural studies of stir-cast Al6061-based composites reinforced with cerium oxide and graphene nanoplatelets have shown that this route can yield improved wear performance when processing parameters are appropriately optimized [51]. Hybrid composites of Al7075 reinforced with B_4C and nano-graphene fabricated by stir casting have likewise exhibited enhanced mechanical and wear properties, supporting the continued relevance of this route for larger-scale production [52,53]. Squeeze casting has also been adopted for graphene-containing hybrid composites, offering superior densification and reduced porosity compared with conventional gravity casting [54].

Moreover, selective laser melting (SLM) and related additive-manufacturing techniques have been applied to the fabrication of graphene-reinforced aluminum composites. AlSi10Mg alloy nanocomposites reinforced with aluminum-coated graphene have been successfully fabricated by SLM, with interfacial microstructure analysis revealing that the nano-Al coating improves wetting and bonding between graphene and the aluminum matrix during laser processing [55]. Wear-resistance studies on GNP-reinforced AlSi10Mg composites prepared by SLM have demonstrated substantial reductions in wear rate compared with the unreinforced alloy, attributed to the combined effects of grain refinement and the formation of a graphene-enriched tribolayer [56]. Microstructure and tribological studies of graphene/Al composites produced by SLM have also reinforced the view that additive manufacturing can provide viable routes for forming tribologically relevant graphene-aluminum architectures [57]. Solid-state additive manufacturing methods for aluminum-graphene nanoplatelet composites have further been developed, offering some of the advantages of additive manufacturing without the complications of melting, such as graphene thermal degradation and undesirable carbide formation [58]. Friction stir additive manufacturing of B_4C - and graphene-reinforced aluminum matrix hybrid nanocomposites using consumable pins has also been demonstrated as a promising route for producing bulk composite structures with tailored reinforcement distributions [59]. Processing route significantly affects graphene dispersion uniformity, matrix-reinforcement interfacial bonding, and preservation of graphene structural integrity, all of which are critical to tribological performance. Under sufficiently high temperatures and/or prolonged thermal exposure, liquid-state and some high-temperature solid-state routes can promote formation of Al_4C_3 at the graphene-aluminum interface [60,61]. This phase may enhance interfacial bonding and load transfer when present in small,

finely dispersed amounts, but excessive formation or agglomeration tends to embrittle the interface, create crack-initiation sites, and degrade wear resistance. Strategies such as lowering processing temperature, shortening dwell time, and using interfacial coatings or hybrid surface modifications have been explored to limit direct graphene-aluminum reaction, with mixed success [5,62]. Friction stir processing has been particularly effective for improving graphene dispersion and refining the matrix microstructure, often leading to higher hardness and lower wear while reducing the likelihood of excessive reaction compared with more thermally severe processing routes [63,64]. Overall, careful control of processing parameters is essential to balance beneficial reinforcement effects against detrimental carbide formation in graphene-reinforced aluminum composites.

The rapid growth of experimental literature on graphene-reinforced AMMCs with tribological focus has generated a substantial body of knowledge spanning fabrication methods, microstructural characterization, tribological testing configurations, wear-mechanism analysis, and, increasingly, computational and machine learning approaches to property prediction. Several narrative and systematic reviews have addressed subsets of this domain, such as general graphene metal matrix composites [5], friction stir processed graphene-reinforced aluminum systems [64], or solid-processing routes for graphene-aluminum composites [41]. A broader overview of recent developments in graphene-reinforced metal matrix nanocomposites has also contributed to the understanding of this rapidly growing field [6]. Complementary work has extended the methodological and materials scope to electrodeposited Al-graphene composite coatings [65], powder-metallurgy Al/Al₂O₃/rGO hybrids [66], and solid-state processed Al-1100/GNP surface nanocomposites [67]. Bibliometric review work on carbon nanostructure-reinforced composites confirms that bibliometric methods are now being applied to adjacent composite domains, but no dedicated bibliometric study was identified that quantitatively maps the intellectual structure, collaborative landscape, thematic architecture, and emerging research frontiers specific to the intersection of graphene reinforcement, aluminum matrix systems, and tribological performance [68]. Tribological studies on graphene-hybridized metallic systems outside aluminum matrices, such as Cu-Al₂O₃/GNP composites, further illustrate the breadth of graphene-enabled tribology research while underscoring the need for a field-specific map of the aluminum-based literature [69]. Authoritative tribology and green-tribology references also provide important context for the present analysis. Davim's Tribology for Engineers summarizes the engineering fundamentals of friction, wear, lubrication, surface topography, and micro/nanotribology, while Progress in Green Tribology extends these principles toward environmentally sustainable tribological materials, lubricants, and design approaches [70,71]. In parallel, bibliometric analyses by Davim on tribology and composite materials demonstrated the value of bibliometric mapping for identifying productivity patterns, dominant sources, leading contributors, and disciplinary trends [72,73]. However, these researchers addressed either the broad field of tribology or composite materials in general; they did not map the intersection of graphene-family reinforcements, aluminum matrix composites, and tribological performance examined in this study.

Bibliometric analysis offers a quantitative, reproducible, and scalable methodology for analyzing large scholarly corpora, enabling the identification of publication trends, influential works, research communities, knowledge clusters, and thematic trajectories that narrative reviews cannot systematically capture. When applied to a well-defined research domain, bibliometric mapping can reveal not only which topics dominate the literature, but also which areas remain underexplored, which collaboration networks are strongest, and how the conceptual structure of the field has evolved over time.

Despite the availability of bibliometric tools and the substantial volume of publications on graphene-reinforced aluminum matrix composites, a targeted bibliometric investigation that combines performance analysis with science mapping and focuses on tribological performance has not been identified in the literature to the best of our knowledge. Reviews are predominantly narrative, covering either graphene-reinforced metal matrix composites broadly or aluminum composites without an explicit tribological focus [1,62]. The absence of a field-level bibliometric map limits the ability of researchers to identify dominant paradigms, detect emerging research fronts, recognize underrepresented methodological approaches, and avoid redundant investigations.

In this study, we aim to address this gap by conducting a comprehensive bibliometric analysis of the scientific literature on the tribological performance of graphene-reinforced AMMCs published between 2015 and 2025. For the analytical framework, we integrate performance analysis, quantifying productivity, citation impact, and leadership at the author, institution, journal, and country levels, with science mapping, revealing intellectual structure through co-authorship, keyword co-occurrence, and thematic evolution analyses. We draw on a rigorously cleaned Scopus dataset of 822 documents, analyzed using the Bibliometrix R package.

The study is guided by four research questions (RQ): (RQ1) How has the literature on graphene-reinforced aluminum matrix tribology evolved quantitatively from 2015 to 2025? (RQ2) Who are the most influential authors, institutions, countries, journals, and documents shaping this field? (RQ3) What intellectual and thematic structures define the knowledge base of graphene-aluminum tribology? (RQ4) What emerging topics and future research directions are identifiable from the bibliometric evidence? By answering these questions, we provide a structured, evidence-based overview of the current state of the field and identify critical directions for future investigation.

2. Methodology

2.1. Study design and bibliometric rationale

We adopted a quantitative bibliometric design combining performance analysis with science mapping, following established best-practice recommendations for bibliometric research in applied sciences. Performance analysis quantified the productivity and impact of scholarly actors (authors, institutions, journals, and countries), while science mapping revealed the intellectual and conceptual relationships among documents, references, and keywords within the corpus. This dual-framework approach was appropriate for the graphene-aluminum tribology domain because the field has grown sufficiently large (exceeding 800 documents over a decade) to warrant quantitative analysis rather than manual narrative review, yet remains thematically coherent enough to support meaningful clustering and trend identification.

2.2. Data source and search strategy

A comprehensive literature search was conducted in the Scopus database on 16 March 2026 to identify publications related to the tribological performance of graphene-reinforced aluminum matrix composites. Scopus was selected as the sole data source owing to its extensive coverage of peer-reviewed journals, conference proceedings, and review literature in materials science, manufacturing, nanomaterials, and tribology. This choice was consistent with scientometric practice, as Scopus is

widely recognized as one of the principal databases for rigorous bibliometric studies and is particularly valued for its subject coverage and export functionality [74,75]. The search was performed in the TITLE-ABS-KEY field and covered the publication period from 2015 to 2025.

The search strategy was structured around four concept blocks combined with Boolean operators: (i) graphene-family materials, including graphene, graphene nanoplatelets, graphene oxide, reduced graphene oxide, graphene nanosheets, graphite nanoplatelets, few-layer graphene, multilayer graphene, functionalized graphene, and related abbreviations (GNP, rGO, GO, FLG, MLG, TRGO, CRGO, GQD); (ii) aluminum matrix systems, including aluminum/aluminium, aluminum alloys, Al-based systems, Al matrix, Al-MMC, pure aluminum, wrought and cast aluminum, major wrought and cast alloy designations (1xxx through 8xxx series), and related alloy codes; (iii) composite and reinforcement terminology, including composite, nanocomposite, metal matrix composite, metal matrix nanocomposite (MMNC), aluminum matrix composite, reinforced, hybrid composite, surface composite, self-lubricating composite, and related MMC/MMNC terms; and (iv) tribology and wear terminology, including tribology, wear, friction, abrasion, erosion, dry sliding, sliding wear, wear rate, wear mechanism, coefficient of friction, pin-on-disc, ball-on-disc, tribofilm, transfer layer, surface roughness, and related tribological descriptors. Documents indexed as errata were excluded. This strategy returned 1053 records, which formed the raw bibliographic corpus before data cleaning.

2.3. Data cleaning and preprocessing

The Scopus export was cleaned prior to bibliometric analysis following standard bibliometric data-preparation principles, which recommend removing duplicates and erroneous entries before running performance and science-mapping analyses. The cleaning workflow comprised text normalization of the title, abstract, and keyword fields; year-range verification; document-type screening; scope screening; and duplicate checking using DOI, Scopus EID, and title + year + first author rules.

Explicit inclusion and exclusion criteria were applied to ensure that only records relevant to the intersection of graphene-family reinforcement, aluminum matrix systems, composite terminology, and tribological performance were retained. A record was included only when all four relevance pillars were identifiable in the title, abstract, or keyword fields: (i) a graphene-family material, such as graphene, graphene nanoplatelets, graphene oxide, reduced graphene oxide, few-layer graphene, or related abbreviations; (ii) an aluminum/aluminium matrix, aluminum alloy, Al-based composite, or aluminum surface-composite context; (iii) a composite, reinforcement, nanocomposite, metal matrix composite, hybrid composite, or surface-composite context; and (iv) tribology-related relevance, such as wear, friction, sliding wear, abrasion, erosion, coefficient of friction, wear rate, tribofilm, transfer layer, surface roughness, or wear mechanism.

Records were excluded according to the following criteria: (i) publication year outside the 2015–2025 study period; (ii) excluded document type, including errata and conference reviews; (iii) duplicate record identified by DOI, Scopus EID, or title + year + first author; (iv) absence of a graphene-family reinforcement or graphene-derived material; (v) absence of an aluminum/aluminium matrix, aluminum alloy, Al-based composite, or aluminum surface-composite context; (vi) absence of a composite or reinforcement context; (vii) absence of tribology, wear, friction, or sliding-contact relevance; and (viii) insufficient evidence, after title–abstract–keyword inspection, that the record belonged to the target intersection of graphene reinforcement, aluminum matrix composites, and

tribological performance. Coating-focused, machining-focused, non-English, and keyword-only scope-signal records were retained only when the four relevance pillars could be confirmed; otherwise, they were excluded from the final corpus.

The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA)-style data screening workflow is presented in Figure 1. The cleaning procedure applied a triage strategy that classified records as KEEP, REVIEW, or REMOVE. Records were classified as KEEP when the four relevance pillars were present. Records were classified as REMOVE when they met one or more of the exclusion criteria. Records classified as REVIEW were conservatively excluded from the final analytical corpus when the required four-pillar intersection could not be confirmed with sufficient clarity from the available bibliographic metadata. Applied to the initial 1053 Scopus records, this procedure removed 79 records because of excluded document type, detected no duplicate records by DOI, EID, or title + year + first author, and excluded 152 records after review because they did not unambiguously satisfy the full scope criteria. The final dataset used for bibliometric analysis therefore consisted of 822 cleaned records. The resulting dataset covered the period 2015 to 2025, with 24 records lacking DOI identifiers, 61 records lacking author keywords, no missing abstracts, and usable cited-reference, affiliation, and country metadata for bibliometric mapping.

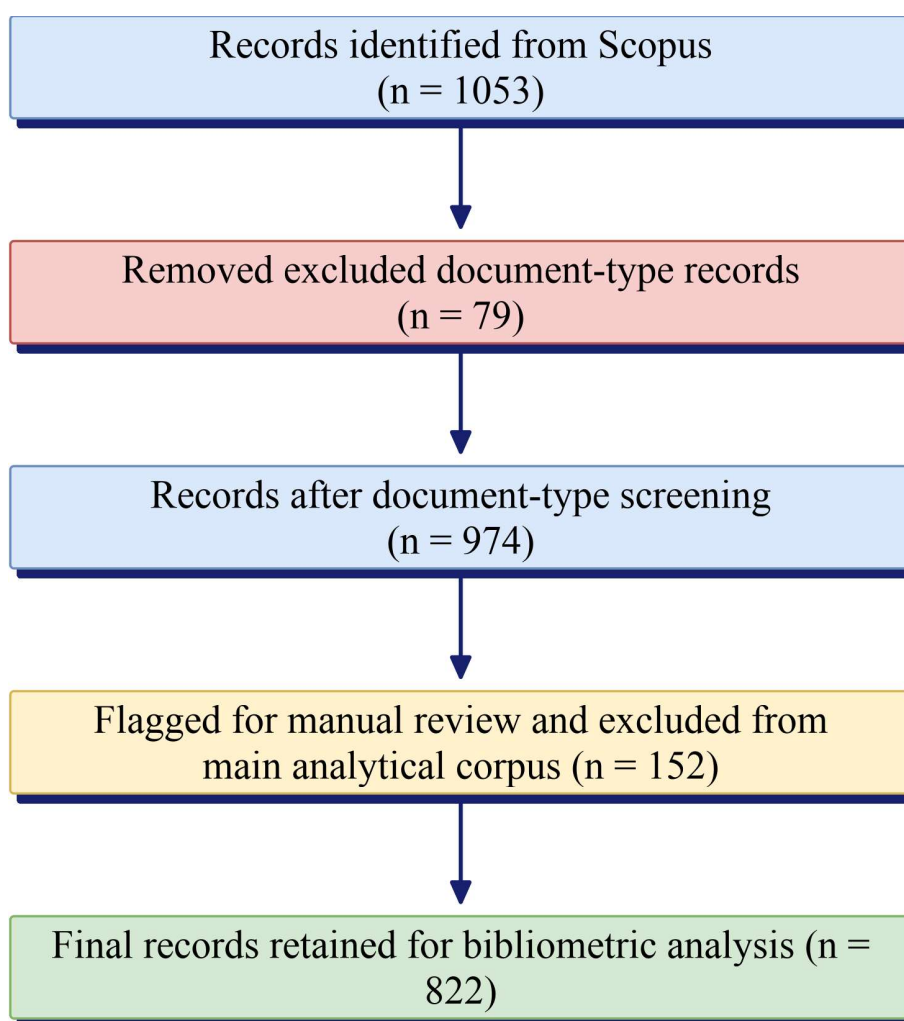


Figure 1. PRISMA-style data screening workflow illustrating the identification, cleaning, and final selection of 822 records from the initial Scopus export of 1053 documents.

2.4. Software and analysis environment

All data processing, bibliometric analysis, and figure generation were carried out in the R environment using a scripted workflow rather than the Biblioshiny graphical interface. The analytical pipeline was based on the Bibliometrix 5.2.1 package for bibliographic data import, performance analysis, and science mapping, together with standard R packages for data manipulation, visualization, network construction, and reporting, including ggplot2, dplyr, stringr, readr, tibble, tidyr, igraph, and openxlsx [76]. The workflow was organized as a reproducible analysis environment with structured configuration settings, automated logging, standardized output directories, and export of tables, figures, cleaned datasets, and summary reports. The workflow also incorporated topic-specific text-mining and heuristic classification procedures to assist interpretation of processing routes, reinforcement types, tribological conditions, wear-related outcomes, and other domain-relevant features within the retained corpus.

2.5. Analytical framework

2.5.1. Performance analysis

Performance analysis was used to quantify the productivity, impact, and relative leadership of the principal research constituents within the cleaned corpus. In line with established bibliometric practice, for the analysis, we focused on annual scientific production, annual citation intensity, the productivity of authors and source titles, the citation impact of documents and authors, and the contribution profiles of institutions and countries. Publication counts were interpreted as indicators of productivity, whereas citation-based measures were used to reflect impact and influence. In addition to total publications and total citations, average citations per document and author- and source-level impact indices were examined where available. This component of the analytical framework addressed RQ1 by mapping the temporal evolution of the literature and RQ2 by identifying the most productive and influential authors, journals, institutions, countries, and documents in the field.

2.5.2. Science mapping

Science mapping was employed to reveal the social, intellectual, and conceptual structure of the research field. Co-authorship analysis was used to examine collaboration patterns among authors and countries. Citation analysis was used to identify the most influential publications in the corpus. Co-word analysis, implemented through keyword co-occurrence mapping, was used to explore the conceptual structure of the literature through the frequency and co-occurrence patterns of author keywords, with index keywords used only as a fallback where necessary. In addition, thematic mapping and thematic evolution analysis were used to identify major research themes and to trace their continuity and transformation across the three subperiods 2015 to 2018, 2019 to 2021, and 2022 to 2025. Together, these techniques addressed RQ3 by revealing the intellectual and conceptual organization of the field and RQ4 by identifying emerging and developing research directions.

2.6. Indicators and thresholds

To ensure interpretable and visually coherent outputs, the bibliometric workflow applied explicit thresholds and display constraints during network construction and thematic mapping. Ranking-based performance tables reported the top authors, documents, source titles, and countries. For collaboration and science-mapping networks, the workflow retained a maximum of 50 nodes in most maps, with thresholding based on network link strength rather than only on publication frequency. The author co-authorship network was generated from the collaboration matrix using an initial edge-weight threshold of 2, with dynamic adjustment to maintain an interpretable edge density. The country collaboration network used an initial threshold of 1 and a maximum of 30 nodes. Keyword co-occurrence analysis was based primarily on author keywords, using an initial threshold of 3 for co-occurrence links; when author keywords were unavailable or insufficient, index keywords were used with an initial threshold of 4. Thematic mapping was computed on the keyword field with $n = 100$, minimum frequency = 2, and two labels per cluster. Thematic evolution analysis used the same keyword basis with break points set at 2018 and 2021, thereby defining the three analytical phases of emergence (2015 to 2018), consolidation (2019 to 2021), and expansion (2022 to 2025). The three thematic-evolution periods were selected using a combined empirical and domain-based rationale rather than by visual convenience alone. First, annual publication counts were inspected as a short time series and first-difference changes in annual output were considered as an exploratory change-point indicator. The early period culminated in a marked rise to 50 documents in 2018, after which the field entered a higher-output but comparatively stable interval of approximately 80–86 documents per year during 2019–2021. A second output-regime shift occurred after 2021, with annual production increasing to 108 documents in 2022 and reaching 148 documents in 2025. Because the study period contained only eleven annual observations, this procedure was treated as an exploratory breakpoint assessment rather than as a stand-alone formal statistical proof. Second, the same breakpoints aligned with identifiable technological maturation in the field. The 2015–2018 period captured early feasibility studies centered on graphene addition, graphene nanoplatelets, graphene oxide, spark plasma sintering, powder metallurgy, and self-lubricating behavior. The 2019–2021 period reflected consolidation around friction stir processing, graphene oxide, hardness, wear resistance, and systematic property evaluation. The 2022–2025 period captured expansion toward reinforcement-form differentiation, microstructure-centered interpretation, hybrid and graded systems, additive or solid-state processing, elevated-temperature conditions, and initial machine-learning-assisted analysis. Therefore, the three windows used for thematic evolution reflected publication-growth behavior and technological development in graphene-reinforced aluminum matrix tribology.

3. Results and discussion

3.1. Descriptive overview of the dataset

Table 1 summarizes the major characteristics of the bibliographic dataset. The analyzed corpus consists of 822 documents published between 2015 and 2025 across 283 sources, including journals, conference proceedings, and book series. This distribution indicates that the topic has developed within a diverse publication landscape rather than being concentrated in only a few specialized outlets. The field also exhibits a strong growth trajectory, with an annual growth rate of 28.56%, confirming that

research on the tribological performance of graphene-reinforced AMMCs has expanded rapidly over the last decade. The document-type composition shows that the field is dominated by original research articles, which account for 690 records (83.9%), followed by 75 conference papers (9.1%), 41 review articles (5.0%), and 16 book chapters (1.9%). This pattern indicates that the literature is primarily driven by experimental and application-oriented studies, while review and synthesis contributions remain comparatively limited. The relatively small share of review articles suggests that, despite the growth of the field, opportunities still exist for integrative and critical synthesis of accumulated findings. From an authorship perspective, the corpus includes 2453 authors and 3876 author appearances, indicating a broad and active research community. The average of 4.72 co-authors per document and the presence of only 9 single-authored documents confirm that research in this area is overwhelmingly collaborative. Such a pattern is consistent with the interdisciplinary and laboratory-intensive nature of advanced materials and tribology research, where expertise in powder processing, microstructural characterization, mechanical testing, and tribological evaluation is often combined within multi-author teams. The citation profile further indicates that the field has achieved meaningful scholarly visibility. The average document age is 4.28 years, the mean citation count is 18.64 citations per document, and the average citation rate is 3.25 citations per year per document. These values suggest that the corpus is not only relatively recent, but also sufficiently mature to support citation-based analyses of impact and knowledge structure. In addition, the dataset contains 75,707 cited references, providing a substantial bibliographic foundation for citation-based mapping. The keyword structure also reflects breadth and thematic richness. The corpus includes 1732 author keywords and 4402 keywords plus terms, indicating a diverse conceptual vocabulary and a sufficiently dense textual basis for co-word and thematic-evolution analyses. Furthermore, the larger number of keywords plus terms relative to author keywords suggests that the field spans a wider semantic space than authors alone explicitly declare, which is typical of developing and interdisciplinary research areas. Finally, the rate of international co-authorship (21.05%) indicates a moderate level of cross-border collaboration. This suggests that, although international partnerships are present and meaningful, a substantial proportion of the literature is still produced within national or regionally concentrated research networks. Overall, the descriptive profile of the dataset portrays a fast-growing, collaborative, experimentally driven, and increasingly visible research field with a sufficiently large and structured corpus to support robust bibliometric analysis.

Table 1. Major characteristics of the bibliographic dataset.

Description	Value
Timespan	2015–2025
Sources (journals, books, etc.)	283
Documents	822
Annual growth rate (%)	28.56
Document average age (years)	4.28
Average citations per document	18.64
Average citations per year per document	3.25

Continued on next page

Description	Value
References	75,707
Document types: articles	690
Document types: conference papers	75
Document types: reviews	41
Document types: book chapters	16
Keywords plus	4402
Author keywords	1732
Authors	2453
Author appearances	3876
Single-authored documents	9
Co-authors per document	4.72
International co-authorships (%)	21.05

3.2. Performance analysis of the field

3.2.1. Annual scientific production

The annual publication trend, presented in Figure 2, indicates an upward trajectory in research output between 2015 and 2025. Three broad developmental phases can be identified when the annual output is interpreted together with the breakpoint rationale described in Section 2.6. The emergence and early-acceleration phase (2015–2018) increases from 12 documents in 2015 to 50 documents in 2018, indicating that the field moves from isolated early studies to a recognizable research topic. The consolidation phase (2019–2021) remains at a higher but relatively stable production level of approximately 80–86 documents per year, suggesting that the field develops a sustained publication base. The expansion phase (2022–2025) begins with 108 documents in 2022, shows a temporary decline to 94 documents in 2023, and then increases to 120 documents in 2024 and 148 documents in 2025. This pattern supports the use of 2018 and 2021 as practical breakpoints for thematic-evolution analysis. Although publication output declines temporarily from 108 documents in 2022 to 94 documents in 2023, this decrease should be interpreted cautiously as a short-term fluctuation rather than as evidence of field contraction. A plausible explanation is that the 2023 decline reflects changes in journal submission and indexing patterns, temporary redistribution of studies between proceedings-based and journal-based outlets, or a shift in research focus from broad graphene-addition feasibility studies toward more specialized microstructural, interfacial, and service-condition-oriented investigations. The subsequent rise to 120 documents in 2024 and 148 documents in 2025 indicates that the overall growth trend remains strong. Consistent with this pattern, the dataset-level annual growth rate of 28.56% confirms the rapid development of research on the tribological performance of graphene-reinforced AMMCs over the study period.

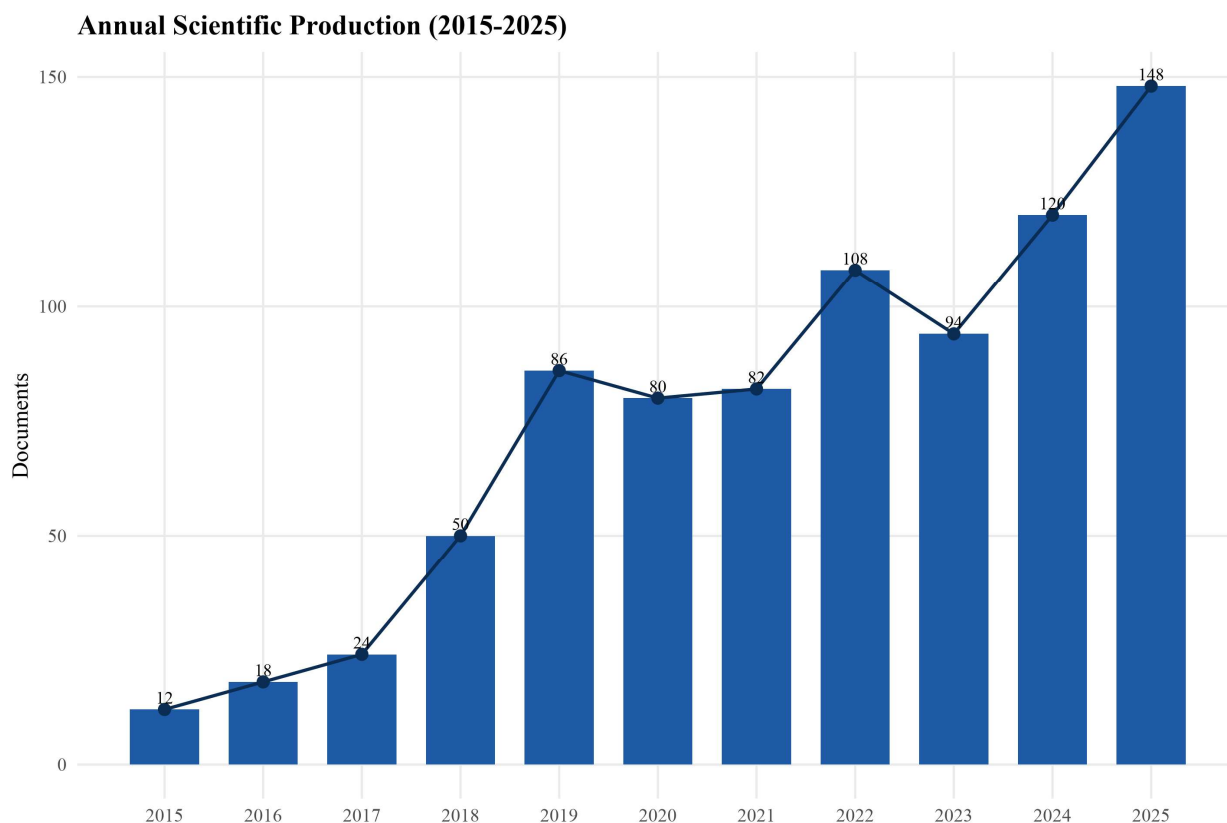


Figure 2. Annual scientific production from 2015 to 2025, showing the number of documents published per year with a trend line overlay.

3.2.2. Annual citation structure

The average article citations per year, shown in Figure 3, reveal a pattern that differs from the annual publication growth trend. Moreover, while annual output increases strongly over the study period, citation intensity is comparatively higher for older publication years and lower for more recent ones. The highest average citation rate is observed for publications from 2016, at approximately 4.7 citations per year per document, indicating the continued influence of early studies published during the formative stage of the field. A second citation peak is visible for 2020, with an average of approximately 4.3 citations per year per document, suggesting that papers published during this period also achieve relatively strong citation visibility. Between 2017 and 2023, the annual citation rate fluctuates within a relatively narrow band of roughly 3.1 to 4.0 citations per year per document, indicating a fairly stable intermediate-impact zone across much of the corpus. This pattern suggests that, although the field expands rapidly in publication volume, citation impact remains concentrated in selected year cohorts rather than increasing uniformly over time. In other words, growth in the number of publications do not translate directly into proportionate growth in average citation intensity. From 2022 onward, the average citation rate declines progressively, falling to approximately 3.8 in 2022, 3.6 in 2023, 3.0 in 2024, and approximately 1.7 citations per year per document for publications from 2025. This decline is expected and is consistent with the well-known citation lag effect, whereby published documents have had less time to accumulate citations than older publications. Accordingly, the lower citation averages observed for the most recent years should not be interpreted

as evidence of weaker scientific value, but rather as a temporal effect inherent to citation-based indicators. Field-normalized citation indicators would provide a stronger correction for cross-year and cross-field differences than raw citation counts or citations per year alone. In particular, the Field-Weighted Citation Impact (FWCI) compares the observed citation performance of a publication with the expected citation performance of publications of similar field, publication year, and document type. However, document-level FWCI values are not available in the standard Scopus bibliographic export used for this analysis, and their calculation requires access to SciVal or an equivalent source of expected-citation baselines. Therefore, FWCI is not reported directly in this study. To reduce temporal bias with the available metadata, our analysis reports average citations per year and interprets the lower citation rates of 2022–2025 publications cautiously as a citation-lag effect rather than as evidence of lower scientific quality. Future extensions of this work could supplement this citation analysis with FWCI, citation percentiles, or other field-normalized indicators.

Overall, the citation structure suggests that the intellectual influence of the field is anchored partly in publications from the 2016 to 2020 period, while the rapidly growing body of more recent literature has not reached comparable citation maturity. This pattern is typical of expanding research areas, where publication output can rise faster than citation accumulation. As a result, the citation profile of the field should be interpreted dynamically, with older publications reflecting established influence, and more recent publications representing developing impact that may become clearer over time.

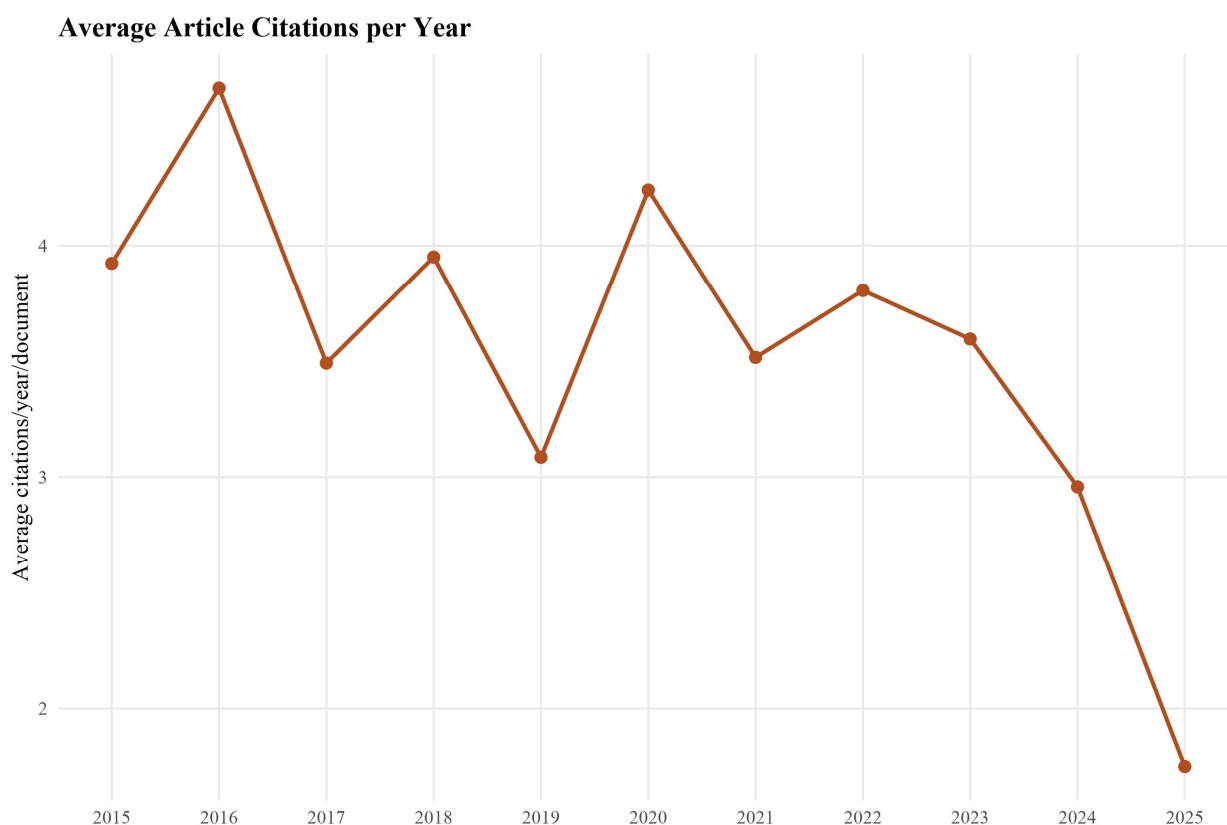


Figure 3. Average citations per year per document for publications from 2015 to 2025, illustrating the higher citation maturity of older publications and the citation-lag effect for recent years.

3.2.3. Most influential documents

Table 2 presents the top 10 most cited documents in the analyzed corpus, ranked by total citations. The most cited publication is the study by Tabandeh-Khorshid et al. [9], with 236 total citations, indicating its central role in the development of tribological research on graphene-reinforced aluminum-based composites. The upper citation tier also includes Zhao et al. [55] with 194 citations and two equally cited papers, Zhang et al. [49] and Dixit et al. [46], each with 173 citations. Other highly cited contributions include Khodabakhshi et al. [77] with 158 citations, Gutierrez-Gonzalez et al. [78] with 143 citations, Wu et al. [56] with 138 citations, Alam et al. [8] with 134 citations, Khodabakhshi et al. [48] with 133 citations, and Maurya et al. [28] with 132 citations. Several patterns emerge from the top-cited set. First, the most influential papers are dominated by experimental studies, indicating that the field has been shaped primarily by processing- and performance-oriented investigations rather than by purely theoretical work. Second, highly cited contributions are strongly associated with major fabrication and microstructure-control routes, particularly powder metallurgy and friction stir processing, as reflected by the prominence of papers such as Zhang et al. [49], Dixit et al. [46], and Khodabakhshi et al. [77]. Third, the journals represented in the top-cited list, including *Engineering Science and Technology, an International Journal*, *Journal of Alloys and Compounds*, *Carbon*, *Composites Part B*, *Materials Characterization*, *Applied Surface Science*, *Ceramics International*, *Materials Science and Engineering A*, *Surface and Coatings Technology*, and *Materials & Design*, suggest that the field draws influence from both tribology-oriented and broader materials-engineering publication venues. Overall, the citation profile indicates that the intellectual influence of the field is concentrated in a relatively small group of publications that combine strong tribological relevance, material innovation, and clear processing-performance relationships. These highly cited papers form an important knowledge base for understanding how graphene-based reinforcement has been studied in aluminum matrix systems and which experimental approaches have attracted the most scholarly attention.

Table 2. Top 10 most cited documents in the corpus, ranked by total citations.

First author	Year	Source	Total Cit.	Cit./Year
Tabandeh-Khorshid M	2016	<i>Engineering Science and Technology, an International Journal</i>	236	21.5
Zhao Z	2019	<i>Journal of Alloys and Compounds</i>	194	24.3
Zhang ZW	2018	<i>Carbon</i>	173	19.2
Dixit S	2018	<i>Composites Part B</i>	173	19.2
Khodabakhshi F	2017	<i>Materials Characterization</i>	158	15.8
Gutierrez-Gonzalez CF	2015	<i>Ceramics International</i>	143	11.9
Wu L	2020	<i>Applied Surface Science</i>	138	19.7
Alam SN	2016	<i>Materials Science and Engineering A</i>	134	12.2
Khodabakhshi F	2018	<i>Surface and Coatings Technology</i>	133	14.8
Maurya R	2016	<i>Materials & Design</i>	132	12

3.2.4. Leading journals ranked by article count

Table 3 presents the leading publication sources ranked by article count. The distribution of documents across sources indicates that research on the tribological performance of graphene-reinforced AMMCs is dispersed across a broad range of materials, manufacturing, surface engineering, and tribology journals rather than being concentrated in a single dominant outlet. *Ceramics International* leads the field with 34 articles, followed by *Materials Today: Proceedings* with 32 articles, and the *Journal of Materials Engineering and Performance* with 31 articles. Other highly productive sources include *Materials Research Express* (23 articles), the *Journal of Materials Research and Technology* (21 articles), *Surface and Coatings Technology* (18 articles), and *Journal of Alloys and Compounds* and *Tribology International* with 17 articles each. This source profile suggests that the field is positioned at the intersection of several research communities. On the one hand, materials-processing and composite-focused journals such as *Journal of Materials Engineering and Performance*, *Journal of Materials Research and Technology*, and *Journal of Alloys and Compounds* serve as major publication platforms for studies emphasizing powder metallurgy, friction stir processing, sintering, alloy design, and microstructure-property relationships. On the other hand, tribology-oriented journals such as *Tribology International* and *Wear* provide an outlet for studies that more explicitly foreground friction behavior, wear mechanisms, transfer layers, and tribological performance metrics. The presence of *Surface and Coatings Technology* and *Applied Surface Science* further indicates that part of the literature is closely connected to surface modification, coating-assisted approaches, and interfacial engineering. A notable feature of the source distribution is the important role of conference-linked publication channels, particularly *Materials Today: Proceedings*, which reflects the strong contribution of conference-driven dissemination in this area. This pattern is common in rapidly developing engineering fields, where emerging results are often first communicated through proceedings-based outlets before later appearing in more specialized journals. Furthermore, the coexistence of proceedings-heavy sources with well-established high-impact journals indicates that the field has an active short-cycle dissemination culture and a maturing archival literature. Journals with the largest number of published articles are not necessarily the same journals that exert the strongest citation influence. Although *Ceramics International*, *Materials Today: Proceedings*, and the *Journal of Materials Engineering and Performance* lead in publication volume, journals such as *Tribology International*, *Wear*, *Carbon*, and *Progress in Materials Science* contribute fewer papers but tend to host more influential and citation-intensive studies. This pattern suggests that volume leadership is associated primarily with broad-access materials and conference-oriented outlets, whereas influence leadership is concentrated in journals with stronger specialization in tribology, carbon nanomaterials, and high-visibility review publishing. The source structure therefore reflects a field that is multidisciplinary and unevenly stratified. High-output journals provide the main publication infrastructure for the growing volume of studies, while a smaller group of specialized and high-impact journals shapes much of the field's intellectual visibility. This separation between publication quantity and citation influence is characteristic of applied materials science domains, where experimental productivity is distributed widely across engineering journals, but the most influential conceptual and synthesis contributions are concentrated in a more selective set of sources.

Table 3. Leading journals ranked by article count.

Source	Articles
<i>Ceramics International</i>	34
<i>Materials Today: Proceedings</i>	32
<i>Journal of Materials Engineering and Performance</i>	31
<i>Materials Research Express</i>	23
<i>Journal of Materials Research and Technology</i>	21
<i>Surface and Coatings Technology</i>	18
<i>Journal of Alloys and Compounds</i>	17
<i>Tribology International</i>	17
<i>Materials</i>	16
<i>Wear</i>	15
<i>Transactions of the Indian Institute of Metals</i>	13
<i>Materials Today Communications</i>	12
<i>International Journal of Advanced Manufacturing Technology</i>	11
<i>Applied Surface Science</i>	10
<i>Carbon</i>	8

3.2.5. Most productive authors and collaboration patterns

The top 20 most productive authors are presented in Table 4. Shi X leads with 21 publications, followed by Zhang L with 20 publications and Zhang Y with 16 publications. Other highly productive contributors include Liu Y, Sharma A, and Zhang J, each with 15 publications, as well as Chen Z with 14 publications. Overall, the upper productivity tier is composed of a relatively small group of recurring contributors who appear prominently across the publication record of the field. A notable pattern in Table 4 is the strong presence of author groups associated with institutions from China and India, which is consistent with the broader country-level publication profile of the dataset. Authors such as Shi X, Zhang L, Zhang J, Chen Z, Wu H, and Huang Y represent one major group of recurrent contributors, while Charoo MS, Srivivas PD, Anthony Xavier M, and Paul J are among the most productive authors in the corpus. This distribution suggests that the field is driven by a limited number of highly active research groups rather than by a uniformly dispersed authorship structure.

Table 4. Top 20 most productive authors ranked by publication count.

Author	Articles	Share of corpus (%)
Shi X	21	2.55
Zhang L	20	2.43
Zhang Y	16	1.95
Liu Y	15	1.82
Sharma A	15	1.82
Zhang J	15	1.82
Chen Z	14	1.70
Charoo MS	13	1.58
Li X	13	1.58
Liu X	13	1.58
Srivyas PD	13	1.58
Chen Y	12	1.46
Huang Y	12	1.46
Wang X	12	1.46
Wu H	12	1.46
Anthony Xavior M	11	1.34
Kumar D	11	1.34
Paul J	11	1.34
Singh S	11	1.34
Yang K	11	1.34

The co-authorship network shown in Figure 4 further clarifies the collaborative organization of the field. The most productive authors are embedded in distinct collaboration clusters rather than functioning as isolated contributors. One dense cluster includes Shi X, Liu X, Huang Y, Yang K, Xu Z, and Zhai W, while another prominent cluster is centered around Zhang L, Zhang J, Chen Z, Jiang Z, and Wu H. These patterns indicate that publication output is strongly associated with established research teams characterized by repeated co-authorship links. Furthermore, the network is segmented into seven community clusters, with relatively limited links between several of the larger groups. This suggests that the field is collaborative at the team level, but not fully integrated across all major author communities. In other words, the literature is being advanced by multiple productive research clusters, although cross-cluster collaboration appears more limited than intra-cluster collaboration.

Author Co-authorship Network

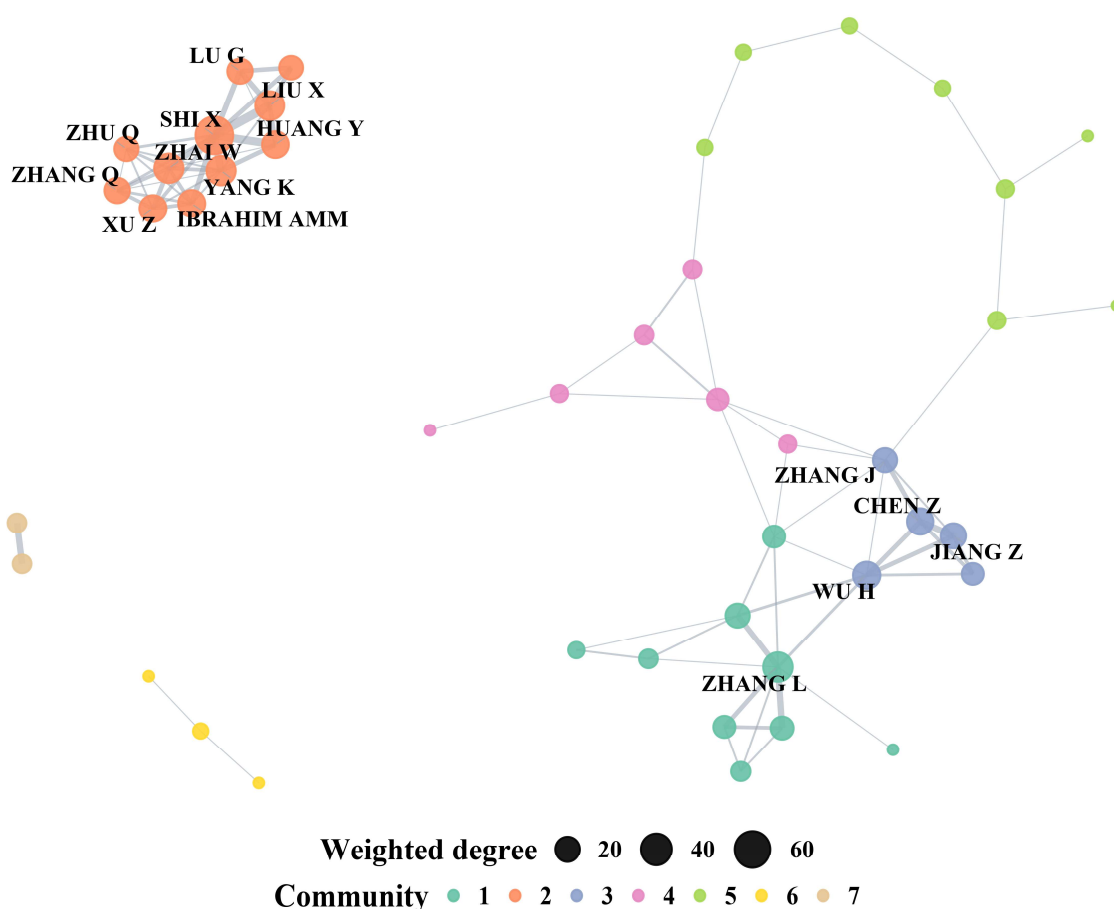


Figure 4. Author co-authorship network of the analyzed corpus. Node size is proportional to weighted degree, edge thickness reflects collaboration strength, and node colors indicate modularity-based author communities. Colors identify collaboration communities only and do not represent productivity or citation impact.

3.2.6. Leading institutions

Table 5 presents the leading institutional affiliations ranked by publication count. The National Institute of Technology (NIT) system in India leads with 27 publications, followed by the School of Mechanical Engineering with 16 publications and Wuhan University of Technology with 16 publications. Other prominent contributors include the Indian Institute of Technology (IIT) system and King Abdulaziz University, each with 12 publications, followed by King Saud University and NIT Rourkela with 11 publications each. Institutions such as Nanchang Hangkong University, Ondokuz Mayis University, Saveetha School of Engineering, Tsinghua University, and the University of Science and Technology Beijing each contribute 10 publications, indicating that the field is supported by a relatively broad institutional base rather than a single dominant center. Institutional productivity was calculated from Scopus affiliation metadata associated with the retained records. Affiliation strings were normalized for spelling variants, abbreviations, and direct institutional-name variants, but no manual reassignment was made on the basis of author career movement. Therefore, a publication was

attributed to King Abdulaziz University only when the Scopus affiliation field for that publication contained “King Abdulaziz University” or an obvious direct spelling variant of that institutional name. Researchers who moved between institutions during 2015–2025 were credited according to the affiliation recorded on each publication, not according to their current or most recent affiliation. The 12 articles attributed to King Abdulaziz University therefore reflect publication-level Scopus affiliation metadata after institutional-name normalization, not manual author-based merging. A notable pattern in Table 5 is the strong representation of institutions from India and China, which is consistent with the author- and country-level productivity patterns observed elsewhere in the dataset. The prominence of the NIT and IIT systems suggests that graphene-reinforced aluminum matrix composite research has become well embedded within India’s engineering and applied materials research infrastructure. Similarly, the presence of Wuhan University of Technology, Tsinghua University, Nanchang Hangkong University, and the University of Science and Technology Beijing indicates that Chinese technical universities also play a major role in shaping the field’s publication output. Furthermore, the appearance of King Abdulaziz University and King Saud University among the leading affiliations indicates that the field is not limited to South and East Asia. These institutions highlight the growing contribution of Saudi Arabian research networks to advanced tribological and composite-materials research. The inclusion of Ondokuz Mayıs University also points to a meaningful contribution from Turkey, reinforcing the international character of the field even though productivity remains concentrated in a few national systems. One point that should be interpreted cautiously is the appearance of the generic affiliation label “School of Mechanical Engineering.” Because this designation may correspond to departments in multiple universities, it likely reflects an affiliation-aggregation artifact rather than a single institution in the strict sense. Nonetheless, its prominence is informative because it indicates that a substantial share of the literature is being produced within mechanical-engineering departments, emphasizing the applied, manufacturing-oriented, and tribology-centered nature of the field. Overall, the institutional profile suggests that research on the tribological performance of graphene-reinforced AMMCs is concentrated in publicly supported technical universities and engineering-focused research systems. The field appears to be driven less by isolated elite laboratories and more by clusters of productive institutions embedded in national materials-engineering ecosystems, particularly in India and China.

Table 5. Leading institutions ranked by article count.

Affiliation	Articles
National Institute of Technology (India)	27
School of Mechanical Engineering	16
Wuhan University of Technology	16
Indian Institute of Technology	12
King Abdulaziz University	12
King Saud University	11
NIT Rourkela	11
Nanchang Hangkong University	10

Continued on next page

Affiliation	Articles
Ondokuz Mayıs University	10
Saveetha School of Engineering	10
Tsinghua University	10
University of Science and Technology Beijing	10

3.2.7. Leading countries and international collaboration

Table 6 presents the country-level distribution of publications and citations. India leads decisively in publication output with 330 articles and 4733 total citations, followed by China with 235 articles and 4763 total citations. Although India produces the largest number of publications, China records a slightly higher total citation count and a higher average citation rate, with 20.3 citations per document compared with 14.3 citations per document for India. This suggests that Chinese publications, on average, have achieved greater citation visibility within the field. The United States ranks third in publication output with 53 articles, but it records a notably high average citation impact of 34.3 citations per document, placing it among the most influential contributors on a per-document basis. Other countries with strong average citation performance include Canada (45.6 citations per document), Australia (29.3), the United Kingdom (27.9), Iran (27.1), and Egypt (27.0). These data indicate that productivity and impact are not distributed uniformly: Some countries dominate in volume, whereas others achieve greater visibility through a smaller number of highly cited contributions. The country profile therefore reveals two complementary patterns. First, the field is anchored in Asia, particularly in India and China, which together account for the largest share of publications. Second, several countries with lower total output exert disproportionate citation influence, suggesting that publication quantity alone does not determine intellectual visibility. In particular, the strong citation performance of the United States, Canada, the United Kingdom, and Australia implies that their contributions often appear in higher-visibility journals or address themes with broader cross-disciplinary relevance. The international collaboration structure, shown in Figure 5, further clarifies the geographic organization of the field. The country collaboration network is divided into three major community clusters rather than a single densely integrated global network. One cluster is centered on India, with strong links to Saudi Arabia, Egypt, Ethiopia, Pakistan, and Malaysia, reflecting a South Asian and Middle Eastern collaboration axis. A second cluster is centered on China, with visible links to the United Kingdom, Australia, Germany, and France, indicating a broader East Asian-European research interface. A third cluster includes the United States, Canada, Iran, and Korea, representing another significant but comparatively more compact collaboration community. Although international collaboration is present, the overall structure suggests that much of the research activity remains concentrated within national or regionally aligned research systems, with stronger collaboration inside clusters than between them. This pattern is consistent with the broader descriptive statistics of the dataset, which shows a moderate but not dominant share of international co-authorship. Taken together, the country-level results indicate that the field is globally distributed but unevenly organized, with leadership in publication output concentrated in India and China, while higher per-paper citation influence is more dispersed across countries.

Table 6. Leading countries ranked by article count, with total and average citations.

Country	Articles	Total Cit.	Avg. Cit.
India	330	4733	14.3
China	235	4763	20.3
USA	53	1820	34.3
Turkey	52	693	13.3
Saudi Arabia	49	1014	20.7
Iran	37	1001	27.1
Egypt	33	892	27.0
United Kingdom	23	641	27.9
Japan	20	434	21.7
Canada	17	775	45.6
Australia	16	469	29.3
Malaysia	16	298	18.6

Country Collaboration Network

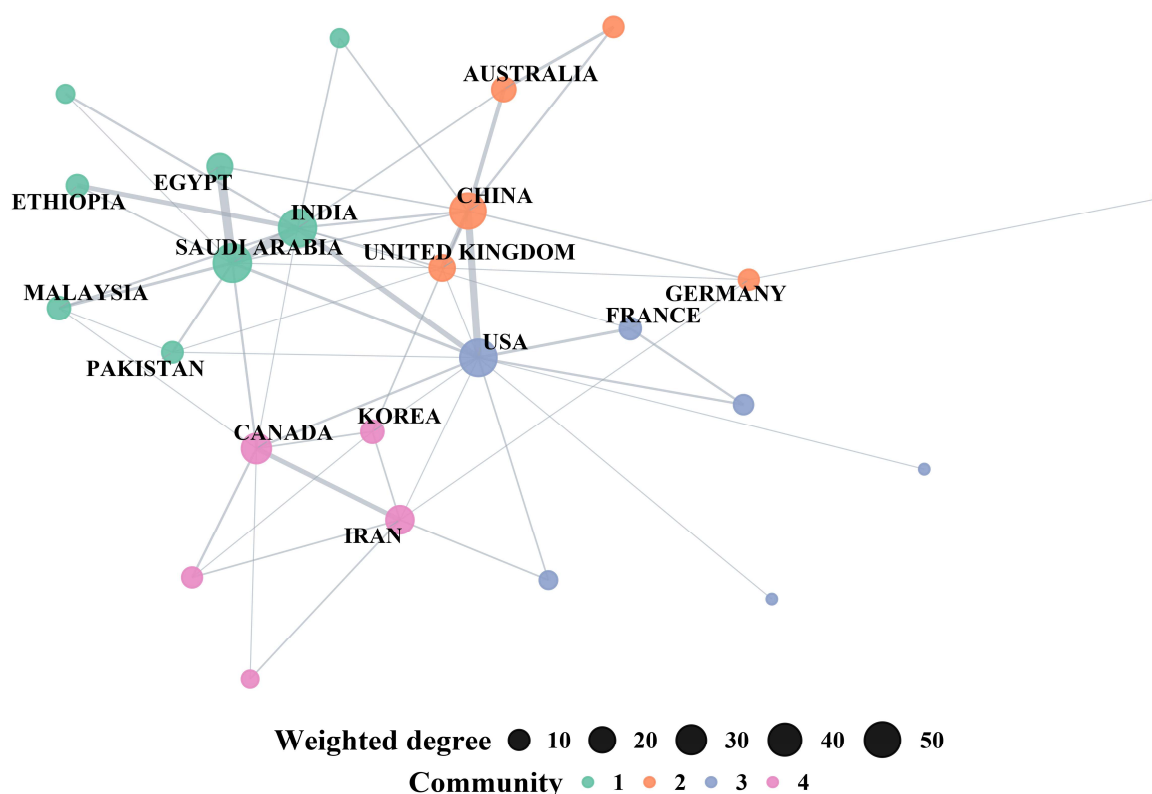


Figure 5. Country collaboration network. Node size is proportional to weighted degree, edge thickness reflects international strength, and node colors indicate modularity-based country communities.

3.3. Conceptual and thematic structure

3.3.1. Keyword co-occurrence analysis

The keyword co-occurrence network, presented in Figure 6, maps the conceptual structure of the field on the basis of author-keyword frequency and co-occurrence strength. The network is organized around three major thematic communities, with graphene, wear, and microstructure/mechanical properties forming the principal conceptual anchors. In node-frequency terms, graphene is the dominant keyword in the corpus, with a frequency of 37 and a weighted degree of 403, followed by microstructure (24, weighted degree 151), wear (23, weighted degree 230), and mechanical properties (20, weighted degree 130). Other highly connected keywords include powder metallurgy (15, weighted degree 72), hardness (10, weighted degree 68), nanocomposites (12, weighted degree 66), friction stir processing (10, weighted degree 65), and aluminum (9, weighted degree 63). Together, these terms indicate that the field is conceptually organized around the interrelationship between reinforcement type, processing route, microstructural development, and tribological performance.

Keyword Co-occurrence Network

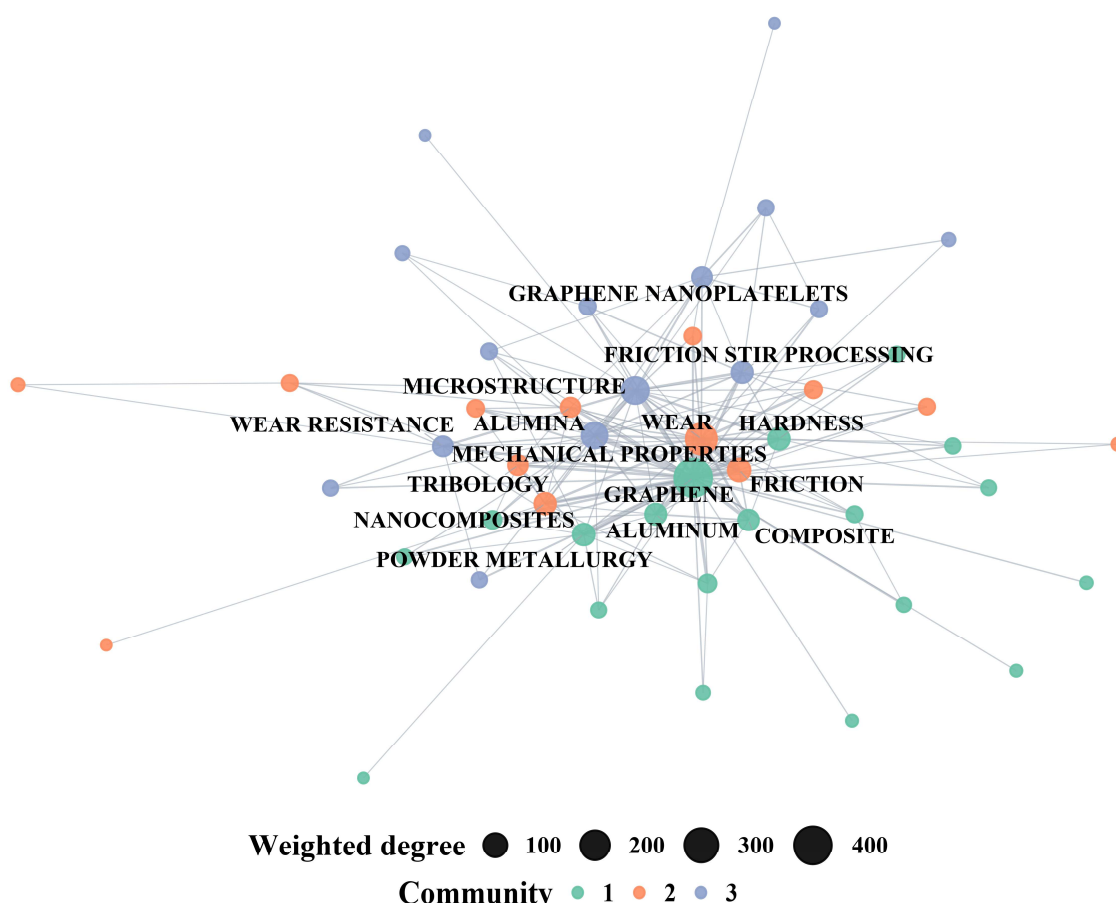


Figure 6. Keyword co-occurrence network based on author keywords. Node size is proportional to keyword frequency, edge thickness reflects co-occurrence strength, and node colors indicate thematic communities identified by modularity optimization.

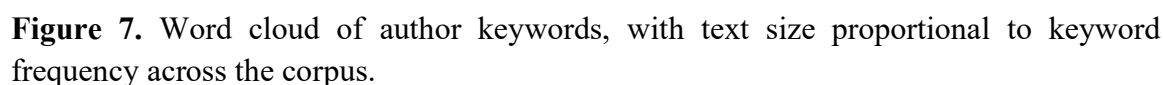
The first major community, centered on graphene, represents the broad material-design and composite-development axis of the field. This cluster includes terms such as composite, aluminum, aluminium, powder metallurgy, hardness, metal matrix composites, sintering, hybrid composites, and silicon carbide, indicating that graphene is most often discussed in relation to matrix design, reinforcement architecture, and fabrication route selection. The strongest links in the network further confirm this centrality: graphene-wear has the highest co-occurrence weight (48), followed by graphene-mechanical properties (25), graphene-aluminum (23), graphene-microstructure (21), graphene-powder metallurgy (19), graphene-composite (17), graphene-friction (17), and graphene-hardness (17). These high-weight connections show that graphene functions not as an isolated materials keyword, but as the conceptual hub linking processing, structure, and tribological response.

The second community is organized around wear and friction, and captures the tribological characterization axis of the literature. Within this cluster, wear has a weighted degree of 230 and is strongly linked to friction (33), hardness (12), composite (12), nanocomposites (11), aluminum (10), mechanical properties (10), tribology (8), and microstructure (8). Additional links such as wear-corrosion (13), wear-alumina (6), wear-carbon nanotubes (6), wear-powder metallurgy (5), and wear-spark plasma sintering (4) indicate that tribological performance is often investigated together with corrosion behavior, hybrid reinforcement systems, and fabrication-dependent surface responses. This cluster therefore reflects the field's strong emphasis on measurable performance outputs, especially wear resistance, friction behavior, and related durability indicators.

The third community is centered on microstructure and mechanical properties and reflects the structure-property-processing dimension of the field. Particularly strong links in this cluster include mechanical properties-microstructure (22), microstructure-hardness (11), microstructure-wear resistance (10), microstructure-friction stir processing (12), and mechanical properties-friction stir processing (7). Keywords such as graphene nanoplatelets, microhardness, tribological properties, spark plasma sintering, and AMMCs also appear in this community, showing that the literature frequently connects processing routes to microstructural evolution and then to mechanical and tribological performance. The prominence of friction stir processing, powder metallurgy, stir casting, and spark plasma sintering within the network confirms that the conceptual structure of the field is strongly shaped by manufacturing and consolidation strategies. The keyword network also highlights the importance of specific graphene forms and hybrid reinforcement concepts. Terms such as graphene nanoplatelets, graphene oxide, carbon nanotubes, hybrid composite, and hybrid composites appear as meaningful but secondary nodes. Their links to aluminum matrix composites, spark plasma sintering, tribology, and wear resistance suggest that the field has diversified beyond single-reinforcement systems and increasingly explores hybrid or multifunctional material designs. However, these topics remain less central than the dominant graphene-wear-microstructure-processing nexus.

The keyword cloud shown in Figure 7 provides a complementary visual summary of the conceptual landscape. The most prominent terms include graphene, wear, mechanical properties, microstructure, hardness, graphene nanoplatelets, powder metallurgy, tribology, friction, and friction stir processing, which broadly mirrors the structure of the network map. Furthermore, the word cloud should be interpreted as a descriptive supplement rather than an analytical substitute for the co-occurrence network because it reflects frequency prominence but not the relational strength between terms.

Overall, the conceptual structure suggests that the field remains primarily organized around materials processing, microstructural control, and property characterization, with tribological performance most often framed through measurable outputs such as wear, friction, hardness, and wear



While Figure 6 reports the filtered author-keyword co-occurrence network, Table 7 presents a complementary thematic mapping output based on keyword clustering and strategic-diagram metrics; accordingly, cluster counts and occurrence values are not expected to match exactly across the two analyses. Table 7 presents the five thematic clusters identified through keyword-based thematic mapping, together with their representative keywords, cluster size, centrality, and density metrics. Collectively, these clusters indicate that the field is organized around a small number of interrelated themes spanning graphene-enabled tribology, processing and microstructural control, hybrid reinforcement systems, graphene-oxide-based surface engineering, and self-lubricating wear mechanisms.

Cluster 2, “mechanical-microstructural characterization,” includes mechanical properties (91), microstructure (89), hardness (55), friction stir processing (50), graphene nanoplatelets (49), tribological properties (26), stir casting (25), metal matrix composites (22), spark plasma sintering (21),

and microhardness (20). This is the largest cluster by keyword count ($n = 38$) and shows the highest centrality (1.01) with moderate density (15.0). These characteristics indicate a well-developed and highly central theme that occupies a methodological core position in the field. The cluster reflects the strong emphasis placed on linking fabrication route, microstructural evolution, and the resulting mechanical and tribological performance of graphene-reinforced aluminum systems.

Cluster 3, “powder metallurgy and hybrid systems,” groups powder metallurgy (46), hybrid composites (14), machinability (12), reduced graphene oxide (12), aluminum matrix composite (8), surface roughness (8), wear properties (8), machine learning (6), mechanical and tribological properties (6), and tool wear (6). This cluster combines a relatively low centrality (0.30) with high density (15.8), which suggests a specialized but internally cohesive niche. It appears to represent a focused line of research centered on fabrication-intensive studies, especially powder-metallurgy-based systems and hybrid reinforcements. The inclusion of machine learning is noteworthy because it suggests that data-driven and predictive approaches are beginning to intersect with more traditional materials-processing research.

Cluster 4, “graphene oxide coatings and wear resistance,” contains graphene oxide (45), wear resistance (44), composites (23), corrosion resistance (20), coating (12), wear rate (11), Al_2O_3 (10), wear mechanism (10), composite coating (9), and tribological behavior (9). With low centrality (0.32) and relatively high density (15.7), this cluster can be interpreted as another specialized but well-developed theme. It captures a distinct body of literature focused on graphene-oxide-based coatings, surface modification, and protective wear-resistant systems. Although related to the broader graphene-composite field, this cluster appears more strongly aligned with surface engineering and corrosion-wear performance than with bulk aluminum matrix composite design.

Cluster 5, “self-lubricating composites and wear mechanisms,” includes metal matrix composite (14), wear mechanisms (11), sliding wear (9), interface (8), solid lubricants (8), and self-lubricating composites (7). This is the smallest cluster ($n = 6$) and has the lowest centrality (0.11), together with moderate density (14.1). These characteristics indicate a relatively isolated but conceptually coherent niche focused on mechanism-oriented tribology, interfacial behavior, and self-lubrication phenomena. Since the five thematic clusters in Table 7 contain 100 leading mapped terms in total, Cluster 5 represents 6% of the mapped leading thematic vocabulary; however, this should not be interpreted as the percentage of documents containing mechanistic keywords. In addition, mechanism-specific descriptors such as tribofilm, transfer layer, third-body behavior, and mechanically mixed layer do not appear among the strongest keyword nodes or leading trend terms. These results indicate that mechanism-specific vocabulary is much less prominent than broad processing and performance descriptors such as graphene, wear, microstructure, mechanical properties, hardness, powder metallurgy, and friction stir processing. A precise document-level percentage of mechanistic papers and its correlation with journal tier or citation impact would require an additional document-level keyword screen and a journal-ranking dataset, which were outside the scope of the present analysis. This is therefore identified as a useful future extension.

Taken together, the thematic structure suggests that the field is anchored by two broad and central themes, namely graphene-centered tribology and mechanical-microstructural characterization, while three smaller clusters reflect more specialized directions related to powder-metallurgy-based hybrid systems, graphene oxide coatings, and self-lubricating wear mechanisms. This distribution indicates that the field remains strongly driven by processing, characterization, and performance evaluation, while more focused mechanistic and surface-engineering themes are developing as specialized subdomains.

Table 7. Thematic clusters identified through keyword-based thematic mapping, with centrality and density metrics.

Cluster	Label	Top keywords	n	Centrality	Density
1	Graphene tribology	Graphene (233), wear (128), friction (46), nanocomposites (41), tribology (33)	25	0.95	10.8
2	Mechanical-microstructural characterization	Mechanical properties (91), microstructure (89), hardness (55), FSP (50), GNPs (49)	38	1.01	15.0
3	Powder metallurgy and hybrid systems	Powder metallurgy (46), hybrid composites (14), machinability (12), rGO (12), machine learning (6)	12	0.30	15.8
4	Graphene oxide coatings and wear resistance	Graphene oxide (45), wear resistance (44), composites (23), corrosion resist. (20)	19	0.32	15.7
5	Self-lubricating composites and wear mechanisms	Metal matrix composite (14), wear mechanisms (11), sliding wear (9), interface (8)	6	0.11	14.1

3.3.3. Thematic evolution

The thematic evolution map shown in Figure 8 traces the development of the field across three subperiods: 2015 to 2018 (emergence), 2019 to 2021 (consolidation), and 2022 to 2025 (expansion). During the emergence phase, the most prominent themes were graphene, wear, solid lubricants, graphene nanoplatelets, graphene oxide, and spark plasma sintering. This profile suggests that early research was primarily concerned with establishing the feasibility of graphene-based reinforcement for tribological improvement, especially through conventional consolidation and self-lubrication-oriented approaches. In the consolidation phase (2019 to 2021), the thematic structure becomes more focused around graphene, wear, graphene oxide, hardness, and wear resistance. Compared with the emergence phase, this pattern indicates a shift from early proof-of-concept studies toward more systematic evaluation of performance-related properties. In particular, the continued visibility of graphene oxide across the first two periods suggests strong thematic continuity, while the growing prominence of hardness and wear resistance indicates that the literature increasingly emphasized measurable structure-property-performance relationships rather than only material novelty. In the expansion phase (2022 to 2025), the thematic structure becomes more differentiated. Although graphene remains the most prominent term, the appearance of microstructure, graphene nanoplatelets, graphene oxide, hardness, and microhardness as distinct high-prominence themes suggest a more specialized and mature research landscape. This development implies that the field has moved beyond broad tribological validation and toward finer-grained analysis of how reinforcement form, processing route, and microstructural evolution influence wear-related performance. Representative article-level examples from the consolidation and expansion periods support this interpretation and help connect the keyword-level evolution to specific materials-processing trajectories. During the consolidation period, FSP-fabricated AA7075/SiC-BN hybrid nanocomposite surfaces demonstrated that combined hard ceramic and solid-lubricant nanoparticle reinforcement can substantially refine grains and improve microhardness and wear resistance, while Al2024-graphene nanocomposites produced by mechanical alloying and sintering showed that graphene content and sintering temperature strongly influence density, thermal and electrical response, corrosion behavior, and mechanical strengthening [79,80].

Moreover, work on functionally graded Al-based graphene and graphene/vanadium carbide (VC) nanocomposites further illustrates the expansion-stage shift toward architecture-controlled and microstructure-sensitive design, where layered reinforcement gradients are correlated with coefficient of thermal expansion (CTE), conductivity, Young's modulus, and compressive strength [81]. These examples should therefore be understood not as a separate narrative review, but as targeted evidence that the thematic evolution detected bibliometrically reflects a broader movement toward processing-specific, reinforcement-sensitive, and mechanism-aware interpretation of aluminum matrix nanocomposite performance. A notable feature of the late-stage thematic structure is the increased prominence of microstructure relative to earlier periods. This indicates that studies are more frequently linking tribological outcomes to microstructural characterization, suggesting a gradual transition from largely phenomenological reporting of wear and friction behavior toward more mechanism-aware interpretation. Furthermore, the continued persistence of graphene, graphene oxide, and graphene nanoplatelets across periods shows that the field remains anchored in reinforcement-type optimization, even as its analytical focus becomes more sophisticated.

Thematic Evolution

Break points: 2018, 2021

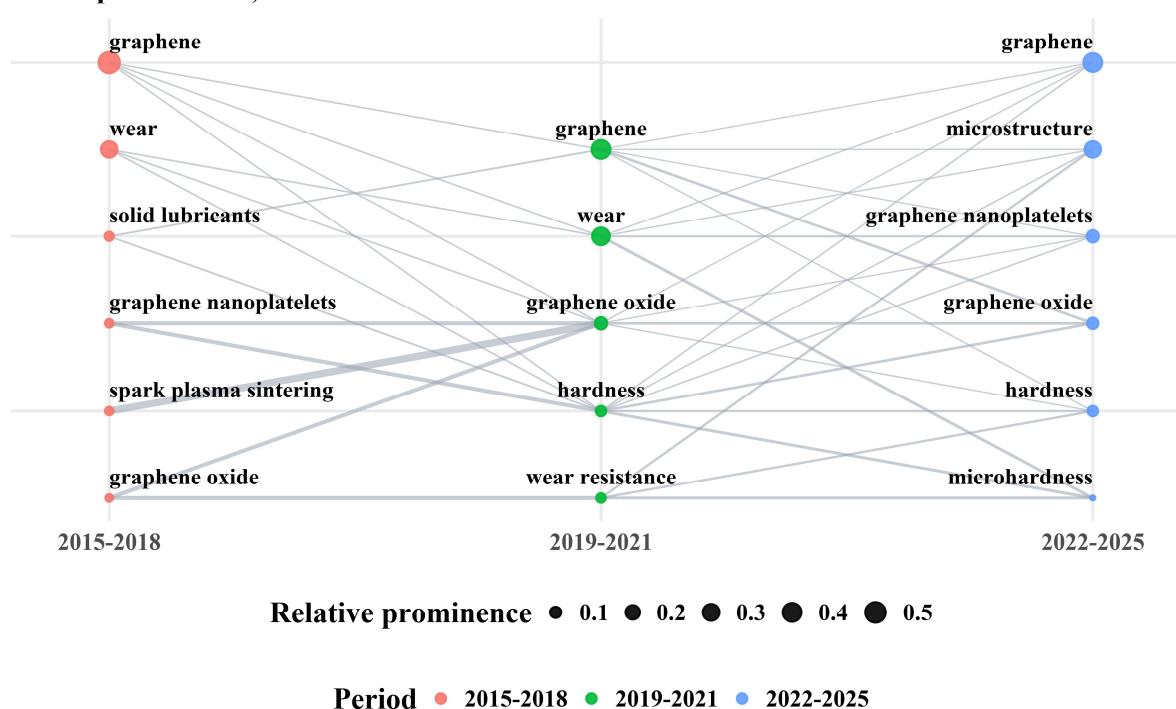


Figure 8. Thematic evolution map across three subperiods (2015 to 2018, 2019 to 2021, and 2022 to 2025). Node size is proportional to relative thematic prominence, connecting lines indicate thematic continuity across periods, and colors distinguish thematic streams.

Overall, the thematic evolution map suggests that the field has progressed from an early emphasis on feasibility and self-lubricating concepts, through a period of property-centered consolidation, into a more mature stage characterized by microstructural interpretation, reinforcement differentiation, and more specialized tribological analysis.

3.4. Emerging directions and research frontiers

Table 8 presents the emerging topics and keyword trends in the corpus, ranked by trend slope. At first glance, the strongest upward trajectories are associated with graphene (trend slope = 3.47), microstructure (1.97), mechanical properties (1.73), wear (1.47), graphene nanoplatelets (0.88), wear resistance (0.85), and graphene oxide (0.72). However, these trends require careful interpretation. The continued dominance of graphene should not be read as an “emerging” theme in the strict sense, because it functions as the umbrella concept of the field rather than a newly developing research direction. Instead, its strong slope indicates that the literature continues to expand around graphene-centered materials systems without moving decisively toward a narrower set of advanced subtopics. A more meaningful signal of thematic development is the strong rise of microstructure and mechanical properties, which now rank immediately behind graphene in trend slope. This pattern suggests that the field is becoming increasingly focused on linking tribological response to microstructural evolution and structure-property relationships. In practical terms, the literature appears to be shifting from simple proof-of-concept demonstrations of graphene addition toward more detailed investigation of how dispersion quality, interfacial bonding, defect structure, and reinforcement morphology affect hardness, wear resistance, and related performance indicators. The growing prominence of graphene nanoplatelets further reinforces this interpretation, suggesting that the field is increasingly converging on specific reinforcement forms rather than treating graphene as a generic carbon nanofiller. Furthermore, the trend structure also reveals an important limitation. The strongest positive slopes are associated primarily with processing-sensitive and property-sensitive keywords, such as microstructure, mechanical properties, wear resistance, hardness, powder metallurgy, and friction stir processing, rather than with deeper mechanistic tribology descriptors. Terms such as tribofilm, transfer layer, third-body behavior, mechanically mixed layer, or more advanced interfacial and contact-mechanics concepts do not appear among the leading trending topics. This suggests that, despite the maturation of the field, the dominant research trajectory remains centered on optimizing fabrication routes and reporting resulting performance metrics rather than on resolving the fundamental mechanisms governing friction and wear at the contact interface.

The behavior of wear and friction also deserves a nuanced reading. Although both remain among the most frequent and persistent keywords, their trend slopes are modest relative to their total occurrence and their peak years occur comparatively early, especially for wear and friction, both of which peak in 2019. This indicates that these terms remain foundational to the field but are not, by themselves, markers of frontier development. In other words, the research front is no longer defined merely by showing that graphene affects wear or friction, but increasingly by how that effect is interpreted through microstructure, reinforcement architecture, and process-dependent performance pathways.

Among the more specific topics, graphene oxide and wear resistance show continued upward movement, indicating that graphene-oxide-based systems and durability-oriented studies remain active directions. The persistence of graphene oxide suggests continued interest in oxygen-functionalized graphene derivatives, likely because of their processing versatility, dispersion behavior, and compatibility with hybrid or surface-engineered systems. Likewise, the positive slope of wear resistance suggests that long-term performance optimization remains a central applied goal of the literature. By contrast, powder metallurgy and friction stir processing show only moderate positive slopes, which may indicate that these fabrication routes are becoming established methodological platforms rather than frontier topics in their own right. Although a separate reinforcement-subtype-stratified

bibliometric network was not generated in this study, the thematic and trend results indicate increasing differentiation among graphene-family reinforcements. Graphene remains the umbrella keyword of the field, but graphene nanoplatelets, graphene oxide, and reduced graphene oxide appear in distinct thematic contexts. Graphene nanoplatelets are associated mainly with the mechanical-microstructural characterization cluster, graphene oxide appears in the coatings and wear-resistance cluster, and reduced graphene oxide appears within the powder-metallurgy and hybrid-systems cluster. Few-layer graphene does not emerge as a separate leading thematic or trend term in this mapping, suggesting that it remains less visible than GNPs, GO, and rGO within the mapped leading keyword structure. These results suggest that graphene-family subtypes are beginning to support different application-oriented directions, although a full subtype-specific network analysis would require additional document-level classification. Future extensions of this work could therefore stratify the corpus by GNP, GO, rGO, FLG, and related forms to determine whether these reinforcement subtypes constitute separate research subcommunities.

A second critical insight from Table 8 is that the research front appears to be evolutionary rather than disruptive. The rising terms do not point to a dramatic conceptual shift toward entirely new paradigms, but rather to a gradual deepening of established themes. The field is expanding through finer differentiation of graphene form, better microstructural control, and more systematic coupling of processing and performance. This is a sign of disciplinary maturation, but it also suggests that much of the literature may be incremental in character. The persistence of broad terms such as graphene, wear, and mechanical properties as the most active trends implies that the field has not fully transitioned toward highly specialized frontier topics such as data-driven inverse design, real-time tribological monitoring, tribocorrosion-dominated multifunctional systems, or multiscale interfacial modeling.

From this perspective, the most credible near-term research frontiers appear to lie in four directions. First, the increasing prominence of microstructure indicates that researchers are likely to place greater emphasis on correlating tribological performance with dispersion state, grain refinement, defect population, interfacial phases, and reinforcement distribution. Second, the upward trend of graphene nanoplatelets suggests that reinforcement-form specificity will become increasingly important, particularly in distinguishing the tribological roles of nanoplatelets, graphene oxide, reduced graphene oxide, and hybrid graphene-based systems. Third, the continued relevance of wear resistance, hardness, and mechanical properties suggests that multifunctional optimization, rather than wear reduction alone, will remain a key design objective. Fourth, the persistence of powder metallurgy and friction stir processing indicates that process innovation is likely to emerge through refinement of existing routes rather than wholesale replacement by entirely new manufacturing paradigms.

Overall, the trend analysis indicates that the field is moving toward a more mature and differentiated phase, but not toward a fully mechanism-driven or computationally transformed research landscape. The emerging front is characterized less by radical topical novelty than by increasing specialization within established themes, especially those linking graphene form, processing route, microstructure, and tribological performance. This suggests that future high-impact work will likely come not from repeating conventional wear-comparison studies, but from integrating advanced microstructural analysis, mechanistic tribology, and more rigorous process-structure-property modeling.

ML and data-driven methods represent a small but strategically important emerging direction in the field. In the thematic map, “machine learning” appears within the powder-metallurgy and hybrid-systems cluster with six keyword occurrences rather than as an independent thematic cluster. This indicates that ML/artificial intelligence (AI) studies are embedded within conventional

processing–property research rather than forming a mature autonomous subfield. ML-oriented studies differ from traditional experimental studies in several respects. First, their methodological focus is not limited to fabricating and testing a single composite system; instead, they use compiled datasets to model nonlinear relationships between processing parameters, reinforcement content, load, hardness, sliding speed, sliding distance, coefficient of friction, and wear rate. Second, the quality of the dataset, feature selection, model validation, and interpretability become central methodological issues. Third, ML studies can support prediction and optimization across a wider parameter space than is feasible through trial-and-error experiments alone. At present, however, the low keyword frequency and absence of a distinct ML community in the keyword network indicate that data-driven research remains at an early stage. Collaboration patterns are also likely to differ from conventional experimental work because ML studies require integration of tribology, materials processing, statistics, and computational modeling expertise. Future high-impact work should therefore entail combining standardized tribological datasets, uncertainty-aware regression or classification models, physically meaningful features, open data reporting, and experimental validation of ML-predicted processing–structure–property relationships. In this sense, ML/AI is not a dominant research front in graphene-reinforced AMMC tribology, but it is a promising pathway toward accelerated materials design and reduced experimental trial-and-error.

Table 8. Emerging topics and keyword trend analysis, ranked by trend slope.

Keyword	Total occ.	Active years	Peak year	Peak occ.	Trend slope
Graphene	233	11	2024	43	3.47
Microstructure	89	9	2023	19	1.97
Mechanical properties	91	9	2025	17	1.73
Wear	128	11	2019	19	1.47
Graphene nanoplatelets	49	10	2023	10	0.88
Wear resistance	44	9	2025	10	0.85
Graphene oxide	45	9	2022	8	0.72
Hardness	55	8	2023	11	0.49
Nanocomposites	41	11	2025	7	0.38
Friction	46	9	2019	9	0.38
Powder metallurgy	46	10	2024	8	0.38
Friction stir processing	50	7	2023	10	0.18

3.5. Bibliometric synthesis of developmental trajectory and current research status

Although this study was designed as a bibliometric analysis rather than a conventional narrative review, the combined results of the annual production analysis, citation analysis, keyword co-occurrence network, thematic mapping, and thematic evolution map enable the development history and current research status of graphene-reinforced aluminum matrix tribology to be reconstructed at the field level. From a developmental perspective, the literature can be interpreted as progressing through three broad

stages. The first stage, from 2015 to 2018, represents an emergence period in which the field was mainly concerned with demonstrating the feasibility of graphene-family reinforcements for improving aluminum-based tribological performance. The most visible themes in this period were graphene, wear, solid lubricants, graphene nanoplatelets, graphene oxide, and spark plasma sintering. This indicates that researchers focused on establishing whether graphene addition could reduce friction, improve wear resistance, and support self-lubricating behavior in aluminum-based systems.

The second stage, from 2019 to 2021, represents a consolidation period. During this stage, the thematic structure became more focused around graphene, wear, graphene oxide, hardness, and wear resistance. This suggests that the field moved from material novelty and proof-of-concept demonstrations toward more systematic evaluation of processing–structure–property relationships. In this period, fabrication routes such as powder metallurgy, spark plasma sintering, stir casting, and friction stir processing became recurring methodological platforms, while hardness, coefficient of friction, wear rate, and microstructural characterization became central performance descriptors.

The third stage, from 2022 to 2025, represents an expansion and differentiation period. In this stage, the thematic structure became more specialized, with increased prominence of microstructure, graphene nanoplatelets, graphene oxide, hardness, and microhardness. This indicates that the field has moved beyond broad confirmation that graphene can improve tribological behavior and is now increasingly concerned with how reinforcement form, dispersion quality, interfacial bonding, processing route, and microstructural evolution affect wear-related response. The growing importance of microstructure and graphene nanoplatelets also suggests a gradual shift from treating graphene as a generic reinforcement toward distinguishing between graphene-family subtypes and their specific tribological functions.

The current research status can therefore be summarized as follows: first, the field is a rapidly expanding and experimentally driven research area, supported by 822 cleaned Scopus records from 2015 to 2025 and dominated by original research articles. Second, the conceptual core of the field is organized around graphene, wear, microstructure, mechanical properties, hardness, powder metallurgy, friction stir processing, graphene nanoplatelets, and graphene oxide. Third, the most mature research directions are processing–microstructure–performance studies, particularly those involving powder metallurgy, spark plasma sintering, friction stir processing, stir casting, and graphene-oxide-related surface or coating approaches. Fourth, the field has begun to differentiate into more specialized subdomains, including graphene nanoplatelet systems, graphene oxide coatings, hybrid reinforcement architectures, self-lubricating composites, and early machine-learning-assisted property prediction. Fifth, despite this growth, mechanism-resolved tribology remains less developed than processing and property reporting. Terms related to tribofilm formation, transfer-layer evolution, third-body behavior, interfacial reactions, tribochemistry, and service-condition-dependent wear do not occupy central positions in the keyword and thematic structures. This bibliometric synthesis shows that the field has moved from early feasibility studies toward a more mature stage of microstructure-centered and reinforcement-specific tribological research. However, it has not fully transitioned into a mechanism-driven or application-validated research paradigm. Therefore, researchers should place greater emphasis on standardized tribological benchmarking, detailed worn-surface and interface characterization, transfer-layer and tribofilm stability, tribocorrosion, elevated-temperature wear, counterface effects, durability under realistic service conditions, and predictive process–structure–property modeling. In this sense, the present bibliometric analysis does not merely quantify publication volume, collaboration relationships, and research hotspots; it also organizes the

development trajectory and current scientific status of graphene-reinforced aluminum matrix tribology at the field level.

3.6. Critical discussion

The bibliometric results indicate that research on the tribological performance of graphene-reinforced AMMCs has moved from an emerging niche to a rapidly expanding and increasingly structured field. The annual growth rate, the high share of multi-authored publications, and the broad distribution of output across journals all suggest that the topic has achieved substantial research momentum. However, the results also show that expansion in publication volume has not been matched by an equally strong deepening of conceptual and mechanistic maturity. In this respect, the field appears to be growing quickly, but not always evenly.

A first important pattern is the imbalance between publication growth and citation maturity. Annual output rose sharply after 2018 and accelerated further after 2022, yet average citation intensity remains concentrated in earlier year cohorts, especially between 2016 and 2020. This pattern is partly explained by citation lag, but it also suggests that the most influential intellectual contributions were made during a period when the field was defining its central processing routes, reinforcement strategies, and tribological performance benchmarks. By contrast, the recent surge in publications may reflect a transition toward higher-volume but not always equally high-impact output. In fast-growing materials fields, this often corresponds to an increase in incremental studies that vary reinforcement loading, fabrication route, or test conditions without necessarily advancing the conceptual understanding of wear and friction behavior to the same extent.

A second key finding is that the field remains strongly processing-centered. The top cited papers, the dominant journals, the author keyword structure, and the thematic clusters all converge on a common core consisting of powder metallurgy, friction stir processing, spark plasma sintering, microstructure, hardness, wear resistance, and related performance descriptors. This indicates that the field has been driven primarily by the optimization of fabrication parameters and the characterization of resulting property improvements. Such a trajectory is understandable, because graphene-reinforced aluminum systems pose major challenges related to dispersion, interfacial bonding, agglomeration control, and structural integrity. Nevertheless, the bibliometric evidence also suggests a limitation: the literature is more focused on demonstrating that a processing route can improve tribological metrics than on explaining in depth why particular reinforcement architectures alter contact mechanics, transfer-layer stability, third-body behavior, tribochemical evolution, or interface-controlled wear transitions.

The conceptual mapping results reinforce this concern. The keyword co-occurrence network is dominated by broad performance and structure terms such as graphene, wear, microstructure, mechanical properties, hardness, and powder metallurgy, while more mechanism-specific tribology descriptors remain relatively weak. The thematic mapping and thematic evolution analyses show that the field has progressed from early feasibility and self-lubrication concepts toward microstructural interpretation and reinforcement differentiation, but not toward a fully mechanism-driven paradigm. This means that the field has matured in a materials-engineering sense but remains only partially mature in a tribological science sense. In other words, the literature has become more sophisticated in correlating process, structure, and performance, but it appears less advanced in resolving the fundamental interfacial mechanisms that govern wear and friction under different sliding and loading conditions.

A third issue concerns the organization of research activity. The productivity analysis shows that publication output is concentrated in a relatively small number of countries, institutions, and author clusters, especially in India and China. These national systems have acted as the major engines of field expansion. Furthermore, the co-authorship and country-collaboration networks reveal a field that is collaborative within clusters but only moderately integrated across clusters. This structure suggests that much of the literature is being produced within relatively stable regional or institutional ecosystems rather than through broadly distributed international research coalitions. Such concentration can accelerate productivity, but it may also encourage thematic repetition and methodological convergence, particularly when the same fabrication routes, material systems, and testing configurations are used across many related studies. The dominance of India and China should also be interpreted in relation to broader research-system and industrial contexts rather than only as a bibliometric outcome. At the global level, both countries are major contributors to science and engineering output. China is one of the world's largest producers of science and engineering publications, particularly in engineering, while India has become one of the leading global producers of science and engineering literature. This broad publication capacity is reflected in this graphene–aluminum tribology corpus. In China, the high output is consistent with the country's strong engineering-publication base, large manufacturing sector, and sustained emphasis on advanced materials, lightweight structures, surface engineering, and high-value manufacturing. In India, the concentration of output in the National Institute of Technology and Indian Institute of Technology systems suggests that the field is embedded in a large public technical-university network and in national priorities related to manufacturing modernization, automotive components, defense applications, aerospace materials, and lightweight engineering. The relatively accessible experimental infrastructure required for many AMMC tribology studies, including powder metallurgy, stir casting, friction stir processing, hardness testing, and pin-on-disc wear testing, may further support high publication rates in countries with large mechanical-engineering and materials-engineering communities. Thus, India and China dominate not only because of isolated author productivity, but because the topic aligns with their engineering education systems, manufacturing priorities, and applied materials research ecosystems.

The journal structure points to a similar tension between quantity and influence. High-output sources such as *Ceramics International*, *Materials Today: Proceedings*, and the *Journal of Materials Engineering and Performance* provide the main publication infrastructure for the field, whereas specialized tribology and high-visibility materials journals appear to concentrate a larger share of the most influential papers. This separation suggests that the field is supported by a broad and active dissemination base, but that its highest-impact contributions emerge from a more selective subset of outlets. From a critical standpoint, this may indicate that publication growth alone should not be taken as evidence of scientific consolidation. A maturing field should not only produce more papers, but also increase the proportion of studies that are methodologically rigorous, mechanistically informative, and broadly relevant across subcommunities.

The thematic-cluster and trend analyses further indicate that the current research frontier is evolutionary rather than disruptive. The strongest upward trends are associated with microstructure, mechanical properties, graphene nanoplatelets, wear resistance, and graphene oxide, while broader terms such as graphene and wear remain persistent anchors rather than frontier signals. This pattern suggests that progress is occurring mainly through refinement of established themes, especially through better control of reinforcement form, dispersion state, and process-structure-property

relationships. This is a legitimate mode of scientific development, but it also implies that the field has not yet fully transitioned toward the next stage of maturity, namely one characterized by standardized benchmarking, mechanism-resolved tribology, predictive modeling, and stronger connection to real engineering service conditions.

From a practical perspective, the results also raise questions about translation and comparability. The dominance of fabrication and property keywords, together with the centrality of powder metallurgy and friction stir processing, shows that the field is heavily laboratory-oriented. However, bibliometric prominence does not automatically imply technological readiness. Many researchers appear to focus on improvements in hardness, wear rate, or coefficient of friction under specific test conditions, but the broader literature structure suggests that fewer contributions address issues such as reproducibility across processing scales, long-term durability, environmental sensitivity, counterface effects, or the transferability of laboratory findings to realistic component applications. This gap between demonstrative performance and engineering translation may become increasingly important as the field grows.

Taken together, the results suggest that the field is now at an intermediate stage of scientific maturity. It has passed the early phase of isolated proof-of-concept work and has developed a stable body of influential literature, recognizable collaboration networks, and well-defined thematic cores. However, it has not fully resolved several of the issues that typically distinguish a quantitatively large field from a conceptually mature one. Future progress is likely to depend less on repeating conventional comparisons between graphene additions and unreinforced matrices, and more on advancing three areas simultaneously: mechanistic tribology, process-structure-property standardization, and application-oriented validation. In this sense, the bibliometric evidence does not merely show what the field has studied most often, as it also reveals where the field remains underdeveloped.

4. Implications

4.1. Scientific implications

This bibliometric analysis clarifies the knowledge base of research on the tribological performance of graphene-reinforced AMMCs by identifying dominant and underexplored themes, mapping the intellectual and conceptual structure of the field, and quantifying the contributions of authors, institutions, journals, and countries. The identification of five thematic clusters and their centrality-density profiles provides a structured conceptual framework that can help researchers position new studies relative to existing knowledge, recognize underdeveloped niches, and reduce thematic redundancy. In addition, the thematic evolution analysis provides a temporal perspective on how research priorities have shifted over the past decade, thereby supporting more informed planning of future experimental, analytical, and computational work.

4.2. Methodological implications

The study demonstrates how bibliometric mapping, through the integration of performance analysis and science-mapping techniques, can organize a large and rapidly growing tribology-related corpus into interpretable structural, relational, and temporal patterns. The analytical workflow, based on Scopus-derived bibliographic data, systematic data cleaning, Bibliometrix-based analysis, and

multilevel network visualization, provides a transparent and reproducible template that can be adapted to related domains, including graphene-reinforced copper systems, graphene-based ceramic tribology, and broader metal matrix nanocomposite research. More broadly, the study shows that combining descriptive bibliometric indicators with thematic and network-based mapping can generate a more informative overview than simple publication counting alone. A further methodological extension would be to perform route-stratified bibliometric mapping. In this study, we identify the prominence of powder metallurgy, friction stir processing, stir casting, spark plasma sintering, and selective laser melting within the global conceptual structure, but do not construct separate keyword networks or citation-impact profiles for each processing route. Researchers could address this by assigning records to route-specific categories and then comparing their keyword networks, citation patterns, source distributions, and temporal trajectories. Such an analysis would help determine whether powder metallurgy, FSP, stir casting, SLM, and hybrid routes constitute distinct research subcommunities or whether they remain strongly integrated within the broader processing–microstructure–performance literature.

4.3. Practical implications

From a practical standpoint, we identify the material systems and processing routes that attract the greatest research attention, particularly GNP-reinforced aluminum systems, graphene-oxide-related surface approaches, powder metallurgy, friction stir processing, and stir casting. This provides a useful orientation for material engineers and developers seeking to understand which combinations of reinforcement type and fabrication route have been most intensively investigated in the literature. Furthermore, the results highlight several underdeveloped areas, including tribocorrosion, elevated-temperature wear, in situ tribofilm analysis, machine learning assisted optimization, and manufacturing scalability. These gaps point to an important disconnect between laboratory-centered tribological research and the broader requirements of engineering deployment, suggesting that researchers should place greater emphasis on mechanism-resolved analysis, reproducibility, and application-relevant operating conditions.

5. Conclusions

We set out to provide a field-specific bibliometric mapping of research on the tribological performance of graphene-reinforced AMMCs over the period 2015 to 2025, with the aim of clarifying the field's growth trajectory, identifying its leading contributors, revealing its intellectual and conceptual structure, and highlighting emerging research directions. On the basis of a cleaned Scopus corpus of 822 documents, the results show that the field has developed into a rapidly expanding and increasingly structured research area, with an annual growth rate of 28.56% and a publication profile dominated by experimental studies.

First, the field has expanded rapidly. Publication output increased from 12 documents in 2015 to 148 documents in 2025, and the overall corpus showed an annual growth rate of 28.56%. The distribution across 283 publication sources and the dominance of original research articles (690 documents; 83.9%) show that the topic has moved from an early exploratory area to a broad, experimentally-driven research field.

Second, citation influence is concentrated in earlier influential publication cohorts. The strongest average citation intensity appears in publications from 2016 and 2020, while papers published from 2022 to 2025 show lower citation averages because of normal citation-lag effects. The most cited document in the corpus is Tabandeh-Khorshid et al. (2016), with 236 citations, confirming the importance of early work on self-lubricating aluminum matrix nanocomposites reinforced with graphene nanoplatelets.

Third, research leadership is geographically concentrated, but citation impact is more widely distributed. India leads in publication volume with 330 documents, followed by China with 235 documents. However, China has a higher average citation impact than India, and countries such as the United States, Canada, Australia, the United Kingdom, Iran, and Egypt show strong per-document citation performance. This indicates that productivity and influence do not fully coincide.

Fourth, the conceptual core of the field is strongly processing-structure-performance oriented. Keyword co-occurrence analysis identifies graphene, wear, microstructure, and mechanical properties as the dominant conceptual anchors. Thematic mapping reveals five major clusters: graphene tribology, mechanical-microstructural characterization, powder-metallurgy-based hybrid systems, graphene oxide coatings and wear resistance, and self-lubricating wear mechanisms. These clusters show that most studies connect graphene form and processing route to hardness, friction, wear resistance, and microstructural development.

Fifth, the field is maturing, but its research front remains evolutionary rather than disruptive. The strongest positive trends are associated with microstructure, mechanical properties, graphene nanoplatelets, wear resistance, and graphene oxide. This suggests a shift from simple proof-of-concept reinforcement studies toward reinforcement-form differentiation, microstructure-guided interpretation, and multifunctional property optimization.

Finally, several important gaps remain. Mechanism-resolved tribology, tribofilm, and transfer-layer analysis, standardized benchmarking, tribocorrosion, elevated-temperature wear, data-driven process optimization, manufacturing scalability, and application-relevant validation remain less developed than fabrication and property-reporting studies. Future high-impact work should therefore integrate advanced microstructural characterization, interface-level wear-mechanism analysis, process-structure-property modeling, and realistic service-condition testing.

Overall, the bibliometric evidence shows that graphene-reinforced aluminum matrix composite tribology has reached an intermediate stage of scientific maturity. It has a large and rapidly growing literature base, identifiable research leaders, and stable thematic cores, but further progress will require moving beyond incremental wear-rate comparisons toward reproducible, mechanism-based, and application-oriented research.

Use of AI tools declaration

The author declares AI-assisted tools were used solely to enhance grammar, spelling, and readability. No AI tool was used for data generation, analysis, or interpretation. All intellectual and scientific contributions are the author's original work.

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Conflict of interest

The author declares no conflict of interest.

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