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Research Trends of the Buckling Behaviour of Fiber-Reinforced Polymer Composites: A Bibliometric Analysis

Elyaf Takviyeli Polimer Kompozitlerin Burkulma Davranışına İlişkin Araştırma Eğilimleri: Bir Bibliyometrik Analiz

Cenap GÜVEN

Harran University Vocational School of Technical Sciences, Şanlıurfa, Türkiye

ABSTRACT

Fiber-reinforced polymer (FRP) composites are widely used in aerospace, marine, civil, mechanical, and structural engineering applications owing to their high specific strength, corrosion resistance, and design flexibility. However, buckling and post-buckling behaviour remain critical issues for thin-walled, laminated, and load-bearing composite structures. This study presents a bibliometric analysis of research trends and the knowledge structure related to the buckling behaviour of FRP composites. Bibliometric data were retrieved from the Web of Science Core Collection using a fielded search strategy in which buckling-related terms were searched in the title field and FRP composite-related terms were searched in the topic field. After filtering for English language articles and review articles, 2215 publications published between 1975 and 2026 were included in the final dataset. The dataset received 61,986 citations, with an average of 27.98 citations per item and an h-index of 98. VOSviewer was used to perform keyword co-occurrence, country co-authorship, author co-authorship, and institutional co-authorship analyses. The keyword co-occurrence network included 106 keywords grouped into 8 clusters, indicating that the field is mainly structured around buckling, post-buckling, thermal buckling, finite element analysis, vibration, delamination, laminated composites, and FRP structural applications. The country collaboration network consisted of 49 countries, while the author and institutional networks included 18 authors and 54 organizations, respectively. The results show that research in this field has developed through several specialized thematic clusters and internationally connected collaboration networks.

Keywords: Fiber-reinforced polymer composites; Buckling behaviour; Post-buckling; Bibliometric analysis; VOSviewer

ÖZ

Elyaf takviyeli polimer (FRP) kompozitler, yüksek özgül mukavemetleri, korozyon dirençleri ve tasarım esneklikleri nedeniyle havacılık, denizcilik, inşaat, makine ve yapı mühendisliği uygulamalarında yaygın olarak kullanılmaktadır. Bununla birlikte, burkulma ve burkulma sonrası davranış, ince cidarlı, lamine ve yük taşıyan kompozit yapılar için kritik sorunlar olmaya devam etmektedir. Bu çalışma, FRP kompozitlerin burkulma davranışı ile ilgili araştırma eğilimlerinin ve bilgi yapısının bibliyometrik bir analizini sunmaktadır. Bibliyometrik veriler, burkulma ile ilgili terimler ve konu alanında FRP kompozit ile ilgili terimler aranarak, alan bazlı bir arama stratejisi kullanılarak Web of Science Core Collection'dan elde edilmiştir. İngilizce makaleler ve derleme makaleleri filtrelendikten sonra, 1975 ile 2026 yılları arasında yayınlanan 2215 yayın nihai veri setine dahil edilmiştir. Veri seti 61.986 atıf almış, makale başına ortalama 27.98 atıf ve 98'lik bir h-endeksi elde edilmiştir. Anahtar kelime eşdizimliliği, ülke ortak yazarlığı, yazar ortak yazarlığı ve kurumsal ortak yazarlık analizleri VOSviewer kullanılarak gerçekleştirilmiştir. Anahtar kelime eşdizimliliği ağı, 8 kümeye gruplandırılmış 106 anahtar kelimeyi içermektedir. Bu da alanın esas olarak burkulma, burkulma sonrası, termal burkulma, sonlu eleman analizi, titreşim, delaminasyon, lamine kompozitler ve FRP yapısal uygulamaları etrafında yapılandırıldığını göstermektedir. Ülke işbirliği ağı 49 ülkeden oluşurken, yazar ve kurumsal ağlar sırasıyla 18 yazar ve 54 kuruluşu içermektedir. Sonuçlar, bu alandaki araştırmaların çeşitli uzmanlaşmış tematik kümeler ve uluslararası bağlantılı işbirliği ağları aracılığıyla geliştiğini göstermektedir.

Anahtar Kelimeler: Elyaf takviyeli polimer kompozitler; Burkulma davranışı; Burkulma sonrası davranış; Bibliyometrik analiz; VOSviewer

Cenap Güven, Harran University, Vocational School of Technical Sciences, Şanlıurfa, Türkiye

E-mail: cenap_guven@harran.edu.tr / **ORCID ID:** 0000-0001-9868-3249

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INTRODUCTION

Fiber-reinforced polymer (FRP) composites have become increasingly important engineering materials because they combine low density with high specific strength, high specific stiffness, corrosion resistance, fatigue resistance, and considerable design flexibility. These features make FRP composites attractive for aerospace, marine, automotive, civil infrastructure, transportation, and energy-related applications, where lightweight and durable structural components are required (De et al., 2024; Guo et al., 2024; Ahmed et al., 2023). In these materials, the reinforcing fibers mainly provide load-bearing capacity, whereas the polymer matrix transfers stresses between fibers, protects the reinforcement, and contributes to the environmental durability of the composite system (De et al., 2024; Mittelstedt, 2020). However, the mechanical response of FRP composites is highly dependent on fiber type, matrix chemistry, fiber volume fraction, stacking sequence, interfacial bonding, manufacturing route, structural geometry, and environmental exposure conditions (De et al., 2024; Ahmed et al., 2023; Reddy, 2004). Therefore, understanding their structural behaviour requires not only material-level characterization but also systematic evaluation of geometry-dependent failure and instability mechanisms.

Among these mechanisms, buckling is one of the most critical design concerns for thin-walled and load-bearing FRP composite structures. Composite plates, shells, columns, stiffened panels, pultruded profiles, sandwich structures, and laminated beam-column systems are often designed with reduced thickness to maximize weight efficiency, which makes them susceptible to local, global, distortional, thermal, and post-buckling instabilities under compressive, shear, bending, or thermo-mechanical loading (Mittelstedt, 2020; Reddy, 2004; Turvey and Marshall, 1995; Szklarek and Gajewski, 2020; Lee and Park, 2007). Unlike isotropic metallic structures, laminated FRP composites exhibit anisotropic and lay-up-dependent stiffness, so their buckling behaviour is strongly influenced by fiber orientation, boundary conditions, geometric imperfections, shear deformation, lamination parameters, and temperature-dependent material properties (Reddy, 2004; Szklarek and Gajewski, 2020; Kim and Hong, 1997). For this reason, analytical, semi-analytical, numerical, and experimental methods have been widely used to predict critical buckling loads, post-buckling paths, failure modes, and load-carrying capacity of composite structural members (Reddy, 2004; Turvey and Marshall, 1995; Lee and Park, 2007; Wang et al., 2010).

In addition to classical stability problems, damage-related instability has become a major research direction in FRP composite structures. Delamination, matrix cracking, impact-induced defects, manufacturing imperfections, adhesive layer degradation, and local material discontinuities can significantly reduce buckling resistance and modify post-buckling behaviour (Kim and Hong, 1997; Wang et al., 2010; Mekonnen et al., 2020; Muc, 2022; Xia et al., 2024). Delamination is particularly important because it may remain hidden inside laminated composites while promoting local buckling, delamination growth, stiffness degradation, and premature compressive failure (Wang et al., 2010; Mekonnen et al., 2020; Muc, 2022; Xia et al., 2024). Recent studies have also emphasized the role of optimization, finite element modeling, cohesive zone approaches, experimental validation, and advanced laminate design in improving the stability performance of thin-walled composite members (Szklarek and Gajewski, 2020; Lee and Park, 2007; Mekonnen et al., 2020; Jones, 1999). As a result, the literature on FRP composite buckling has expanded into a multidisciplinary research field covering structural mechanics, polymer composites, damage mechanics, aerospace structures, civil engineering applications, optimization, and computational modeling.

Given this rapid expansion, it is increasingly difficult to capture the evolution and intellectual structure of the field through traditional narrative reviews alone. Bibliometric analysis offers a systematic and quantitative approach for evaluating large-scale scientific literature by identifying publication trends, influential contributors, citation patterns, collaboration networks, and conceptual relationships among research topics (Donthu et al., 2021; Zupic and Cater, 2015; Aria and Cuccurullo, 2017). In particular, science

mapping tools such as VOSviewer and Bibliometrix enable the visualization of co-authorship networks, keyword co-occurrence patterns, institutional collaboration, and country-level research structures (Zupic and Cater, 2015; Aria and Cuccurullo, 2017; van Eck and Waltman, 2010). Although numerous experimental and numerical studies have investigated the buckling and post-buckling behaviour of FRP composites, a focused bibliometric mapping of this field remains necessary. Therefore, this study aims to map the research trends and knowledge structure of the buckling behaviour of fiber-reinforced polymer composites using bibliometric data retrieved from the Web of Science Core Collection. The study evaluates publication growth, citation characteristics, country collaboration, author and institutional co-authorship, and keyword co-occurrence patterns to provide a systematic overview of the development, current structure, and emerging directions of this research field.

MATERIALS AND METHODS

Data source and search strategy

The bibliometric data used in this study were retrieved from the Web of Science Core Collection database. Web of Science was selected because it provides structured bibliographic metadata, citation information, author affiliations, and indexed records suitable for bibliometric mapping and network-based science visualization. The search was conducted on 25 April 2026 using the Fielded Search option. To increase the relevance of the dataset, buckling-related terms were searched in the Title field, while fiber-reinforced polymer composite-related terms were searched in the Topic field. The search strategy was designed to capture studies directly focused on buckling, post-buckling, and related instability behaviour in FRP composite structures. This fielded search strategy was adopted to balance specificity and coverage: searching buckling-related terms in the Title field ensured that the retrieved records had buckling or post-buckling as a central research focus, whereas searching FRP composite-related terms in the Topic field allowed the inclusion of relevant studies using different composite terminology in the title, abstract, author keywords, or Keywords Plus.

The search query was structured as follows:

- Title: buckl* OR postbuckl* OR "post-buckl*"
- Topic: "fiber reinforced polymer*" OR "fibre reinforced polymer*" OR FRP OR CFRP OR GFRP OR AFRP OR "carbon fiber reinforced polymer*" OR "carbon fibre reinforced polymer*" OR "glass fiber reinforced polymer*" OR "glass fibre reinforced polymer*" OR "polymer matrix composite*" OR "composite laminate*" OR "laminated composite*"

This initial search yielded 2424 records. The dataset was then refined by document type and language. Only articles and review articles written in English were included. No Web of Science category filter was applied in order to avoid excluding relevant publications indexed under different subject categories, such as mechanics, materials science, polymer science, civil engineering, aerospace engineering, and mechanical engineering. After applying these criteria, 2215 records were included in the final bibliometric dataset. The complete data selection process is summarized in Figure 1.

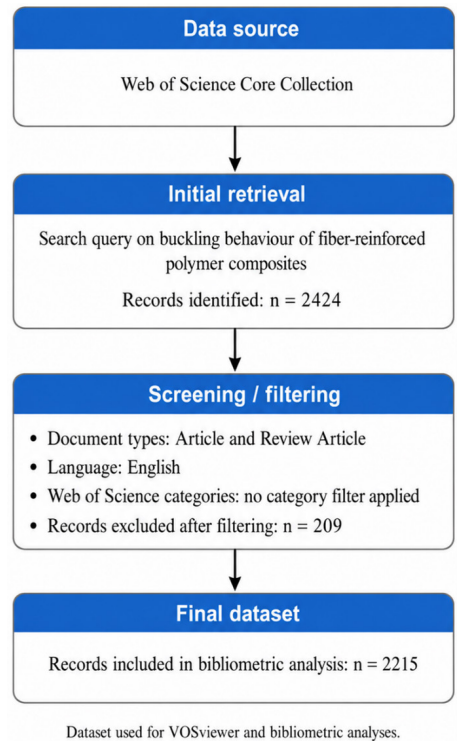

Figure 1. Flow diagram of the data selection process used to construct the bibliometric dataset

Inclusion and exclusion criteria

The inclusion criteria were defined to ensure that the final dataset represented scientific literature on the buckling behaviour of fiber-reinforced polymer composites. Publications were included if they contained buckling-related terms in the title and FRP composite-related terms in the topic field. The topic field included title, abstract, author keywords, and Keywords Plus. Only English language articles and review articles were retained for analysis. Other document types, including proceedings papers, editorial materials, meeting abstracts, book chapters, corrections, and non-English records, were excluded from the final dataset.

The final dataset covered publications from 1975 to 2026. It should be noted that the publication and citation data for 2026 were incomplete at the time of data retrieval. According to the Web of Science Citation Report, the final dataset of 2215 publications received 61,986 citations, with an average of 27.98 citations per item and an h-index of 98. When self-citations were excluded, the total number of citations decreased to 51,825.

Data cleaning and preprocessing

The bibliographic records were exported from Web of Science as plain text files using the Full Record and Cited References option. Since the number of records exceeded the export limit, the data were downloaded in multiple parts and then imported together into VOSviewer. Before analysis, the exported files were checked for formatting consistency. Non-standard fundName rows generated during Web of Science export were removed because these rows caused file-reading errors in VOSviewer. This cleaning step did not alter the core bibliometric information, such as authors, titles, abstracts, keywords, sources, publication years, citations, affiliations, or cited references. Therefore, the removal of these non-standard fundName rows did not affect the country or institutional co-authorship analyses, because these analyses were based on the author address and affiliation fields rather than funding-name metadata. The number of records in the dataset remained unchanged after this formatting correction.

The cleaned Web of Science files were then used for network visualization. The final dataset included five cleaned bibliographic files corresponding to the complete set of 2215 records.

Bibliometric analysis and visualization

Bibliometric analysis was performed to identify the publication characteristics, conceptual structure, and collaboration patterns of the literature on the buckling behaviour of FRP composites. Bibliometric methods are useful for systematically evaluating large scientific datasets and revealing publication trends, influential contributors, and knowledge structures within a research field (Donthu et al., 2021; Zupic and Cater, 2015; Aria and Cuccurullo, 2017). Network visualization was conducted using VOSviewer 1.6.20, which is widely used for constructing and visualizing bibliometric networks such as co-authorship, keyword co-occurrence, and institutional collaboration maps (van Eck and Waltman, 2010).

The following analyses were performed:

- Keyword co-occurrence analysis
- Country co-authorship analysis
- Author co-authorship analysis
- Institutional co-authorship analysis

For the keyword co-occurrence analysis, author keywords were used as the unit of analysis, and the full counting method was applied. A minimum occurrence threshold of 10 was selected. The resulting keyword network included 106 items, grouped into 8 clusters, with 1113 links and a total link strength of 2698. This analysis was used to identify the main thematic structure of the research field.

For the country co-authorship analysis, countries were used as the unit of analysis, and only countries with at least 5 publications were included. The country collaboration network consisted of 49 countries, grouped into 8 clusters, with 272 links and a total link strength of 739. This analysis was used to evaluate international collaboration patterns.

For the author co-authorship analysis, authors with at least 5 publications were included in the network. The resulting author collaboration map consisted of 18 authors, grouped into 5 clusters, with 26 links

and a total link strength of 62. This analysis was used to identify active author groups and collaboration structures.

For the institutional co-authorship analysis, organizations with at least 5 publications were included. The institutional collaboration network consisted of 54 organizations, grouped into 10 clusters, with 79 links and a total link strength of 164. This analysis was used to determine the leading institutions and their collaborative relationships in the field.

Interpretation of network maps

In the VOSviewer maps, each node represents an analytical unit, such as a keyword, country, author, or institution. The size of a node indicates the weight of that item, such as the number of publications or keyword occurrences. Links between nodes represent relationships, such as co-authorship or keyword co-occurrence. The thickness of a link reflects the strength of the relationship. The total link strength value represents the cumulative strength of the connections of an item with all other items in the network. Cluster colours indicate groups of closely related items, reflecting thematic or collaborative structures within the research field.

Together, these analyses provided a systematic overview of the evolution, conceptual structure, and collaboration patterns of research on the buckling behaviour of fiber-reinforced polymer composites.

RESULTS AND DISCUSSIONS

General characteristics of the dataset

The final bibliometric dataset consisted of 2215 English language articles and review articles indexed in the Web of Science Core Collection. The records covered the period from 1975 to 2026, indicating that research on the buckling behaviour of fiber-reinforced polymer composites has developed over a long-time span. The initial search yielded 2424 records, and after applying the document type and language filters, 209 records were excluded. Therefore, 2215 publications were retained for the final bibliometric analysis. The data selection procedure is presented in Figure 1.

According to the Web of Science Citation Report, the final dataset received 61,986 citations in total. When self-citations were excluded, the total number of citations decreased to 51,825. The average number of citations per item was 27.98, and the h-index of the dataset was 98. These values indicate that the buckling behaviour of fiber-reinforced polymer composites has attracted considerable scientific attention and has generated a substantial citation impact within the broader fields of composite materials, structural mechanics, and engineering applications.

The wide time span of the dataset suggests that the research field has evolved from early theoretical and analytical studies on composite plates and shells toward more diversified topics involving finite element modeling, post-buckling response, delamination, thermal buckling, optimization, and structural applications of FRP systems. The relatively high h-index also indicates that the field contains a considerable number of influential publications rather than being dominated by only a few highly cited studies. This reflects the multidisciplinary nature of the topic, which combines material-level composite behaviour with structural-level stability analysis.

It should be noted that the publication and citation data for 2026 were incomplete at the time of data retrieval. Therefore, the number of publications and citations for 2026 should not be interpreted as representing a full publication year. Nevertheless, the dataset provides a comprehensive basis for identifying the main research trends, collaboration patterns, and conceptual structure of the literature on the buckling behaviour of fiber-reinforced polymer composites.

Publication growth and temporal evolution

The annual publication trend reflects the development and maturity of the research field. In bibliometric studies, publication growth is commonly used to identify the emergence and expansion of a scientific topic (Donthu et al., 2021; Zupic and Cater, 2015). The final dataset covered publications from 1975 to 2026, indicating that research on the buckling behaviour of fiber-reinforced polymer composites has developed over a long period. The annual distribution of publications is shown in Figure 2.

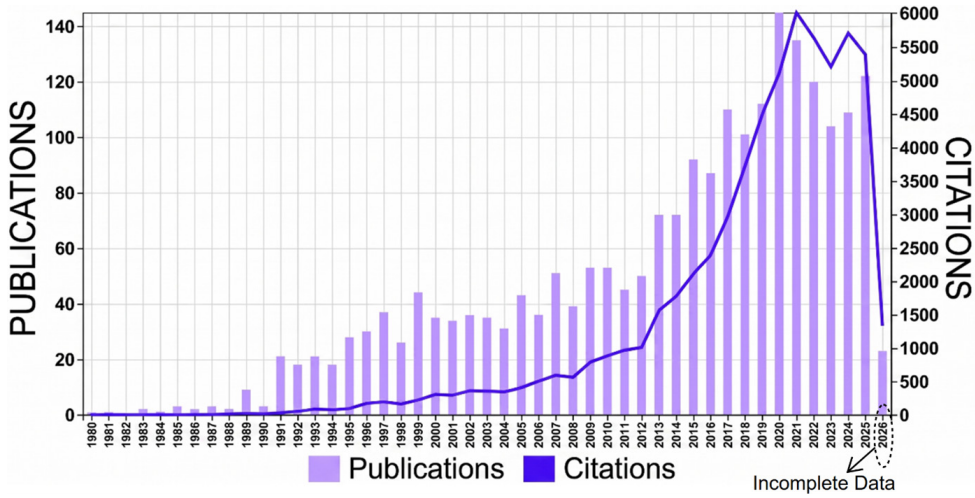

Figure 2. Annual publication trend on the buckling behaviour of fiber-reinforced polymer composites

The early studies were mainly focused on the theoretical and analytical buckling behaviour of laminated composite plates, shells, and beam-type structures. Over time, the field expanded with the increasing use of FRP composites in aerospace, civil infrastructure, marine, automotive, and mechanical engineering applications (De et al., 2024; Ahmed et al., 2023; Mittelstedt, 2020). This growth also reflects the increasing importance of thin-walled and lightweight composite structures, where buckling and post-buckling behaviour are critical design concerns.

The rise in publication activity can also be linked to the development of finite element analysis, nonlinear stability modeling, optimization methods, and damage-based approaches. These methods have enabled more detailed investigation of post-buckling response, thermal buckling, delamination-induced instability, and local-global buckling interactions in laminated FRP structures (Mittelstedt, 2020; Szklarek and Gajewski, 2020). Since the year 2026 was incomplete at the time of data retrieval, publication data for this year should be interpreted with caution.

Keyword co-occurrence analysis and conceptual structure

Keyword co-occurrence analysis was performed to reveal the conceptual structure and dominant research themes of the field (Figure 3). This type of analysis is widely used in bibliometric studies because frequently co-occurring keywords indicate closely related research topics and thematic clusters (van Eck and Waltman, 2023; Cobo et al., 2011). In this study, author keywords were analysed using VOSviewer with a minimum occurrence threshold of 10.

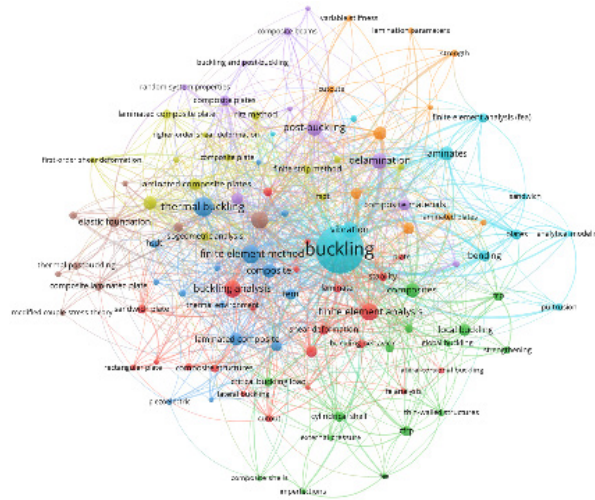

Figure 3. Keyword co-occurrence analysis: network visualization

The keyword network included 106 items grouped into 8 clusters, with 1113 links and a total link strength of 2698. The central keyword was “buckling”, which showed strong links with “post-buckling”, “thermal buckling”, “finite element method”, “finite element analysis”, “vibration”, “delamination”, “laminates”, and “laminated composite”. This result indicates that

the field is mainly organized around numerical stability analysis, post-buckling response, thermal buckling, vibration-buckling interaction, and damage-related instability mechanisms.

The presence of terms such as “delamination”, “local buckling”, and “failure” shows that damage-induced instability is an important research direction in FRP composite structures. Recent studies have emphasized that delamination size, depth, and location can significantly affect stiffness reduction, buckling onset, post-buckling deformation modes, delamination propagation, and compressive failure mechanisms in composite laminates (Mekonnen et al., 2020; Muc, 2022; Xia et al., 2024). Similarly, the appearance of “thermal buckling” and “temperature-dependent” terms indicates increasing interest in the stability performance of FRP composites under thermal and thermo-mechanical conditions, especially for aerospace and high-performance structural applications (Chen and Chen, 1989; Süsler et al., 2025).

Overall, the keyword map shows that the literature has evolved from classical buckling analysis of laminated plates and shells toward more complex topics, including nonlinear finite element modeling, thermal effects, delamination growth, local-global buckling interaction, and optimization-based composite design.

Country co-authorship network

Country co-authorship analysis was performed to evaluate international collaboration patterns in the field (Figure 4). Co-authorship analysis is commonly used in bibliometric studies because it reflects scientific collaboration among countries, institutions, and researchers (Melin, 1996; Katz and Martin, 1997). In the present study, countries with at least five publications were included in the network.

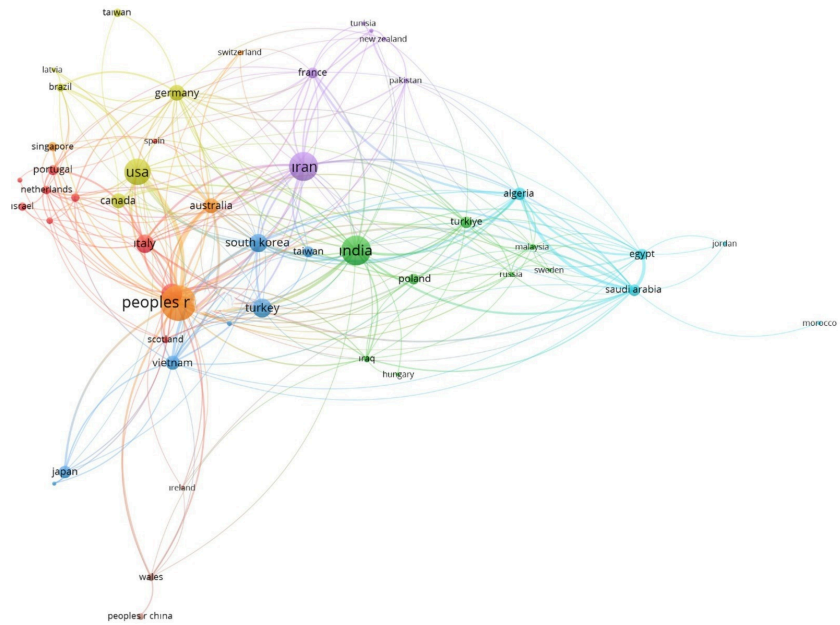

Figure 4. Country co-authorship network showing international collaboration patterns

The country collaboration network consisted of 49 countries grouped into 8 clusters, with 272 links and a total link strength of 739. The size of each node represents the number of publications associated with a country, while the links indicate co-authorship relationships between countries. Total link strength represents the overall intensity of collaboration between a country and other countries in the network (Katz and Martin, 1997).

China had the highest number of publications, followed by India, Iran, the USA, Türkiye, the UK, South Korea, Italy, Germany, and Australia. This distribution shows that research on the buckling behaviour of fiber-reinforced polymer composites is strongly represented

by countries with active research capacity in composite materials, structural mechanics, and advanced engineering applications. The relatively high total link strength values of countries such as China, Iran, the UK, the USA, India, and Australia also indicate that international collaboration plays an important role in the development of this research area. Previous bibliometric studies have shown that international co-authorship can increase scientific visibility and citation impact, especially in multidisciplinary engineering fields (Ortega, 2014; Abramo et al., 2009).

Most productive countries

The most productive countries were identified according to the number of publications in the final Web of Science dataset. Country-level publication output is an important bibliometric indicator because it reflects the geographical distribution of scientific activity and research capacity in a specific field (Abramo et al., 2011; Velez-Estevez et al., 2022). The top 10 countries according to publication number are presented in Figure 5 and Table 1.

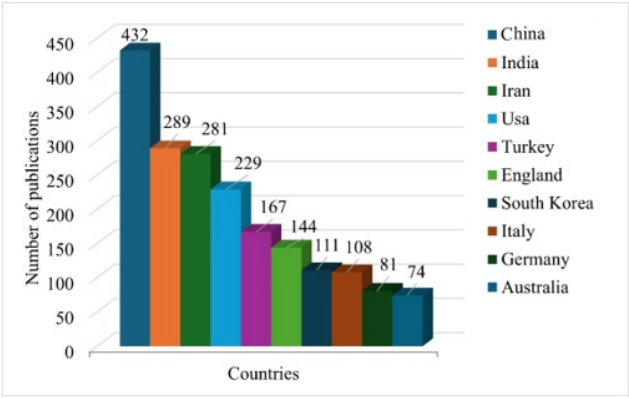

Figure 5. Top 10 most productive countries

Table 1. Top 10 most productive countries according to publication output

Country	Total link strength	Publications	
China	172	432	9414
India	81	289	6241
Iran	99	281	9677
USA	86	229	7703
Türkiye	56	167	4435
UK	88	144	4481
South Korea	67	111	3217
Italy	57	108	3934
Germany	54	81	2702
Australia	70	74	3175

China ranked first with 432 publications, followed by India with 289 publications and Iran with 281 publications. The USA, Türkiye, the UK, South Korea, Italy, Germany, and Australia also appeared among the top contributors. This distribution indicates that research on the buckling behaviour of fiber-reinforced polymer composites is strongly represented by countries with active research capacity in composite materials, structural mechanics, aerospace engineering, and civil engineering.

In addition to publication output, citation count and total link strength provide complementary information. For example, Iran and China showed high citation counts, while countries such as China, Iran, the UK, the USA, India, and Australia had relatively strong total link strength values. This suggests that both research productivity and international collaboration contribute to the visibility and development of the field. Previous bibliometric studies have also emphasized that international collaboration and country-level research performance are important indicators for evaluating the scientific influence of a research area (Abramo et al., 2011; Velez-Estevez et al., 2022; National Science Board, 2025).

Author co-authorship network

Author co-authorship analysis was performed to identify collaboration patterns among researchers in the field (Figure 6). Co-authorship analysis is commonly used as a bibliometric indicator of scientific collaboration because it reveals how researchers form collaborative groups and knowledge networks (Toney and Flagg, 2021; Dehdarirad and Nasini, 2017).In this study, authors with at least five publications were included in the network.

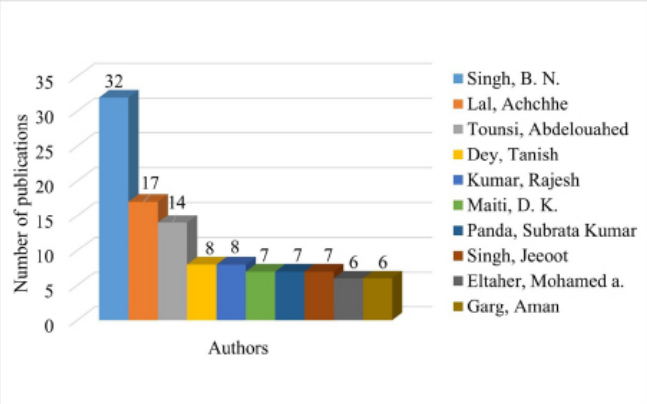

Figure 6. Top 10 most productive authors

The author collaboration network consisted of 18 authors grouped into 5 clusters, with 26 links and a total link strength of 62. The node size represents the number of publications by each author, while the links indicate co-authorship relationships. In VOSviewer, total link strength indicates the overall strength of co-authorship links of a researcher with other researchers in the network (Van Eck and Waltman, 2014). Top 10 most productive authors are shown in Table 2.

Table 2. Top 10 most productive authors

Author	Total link strength	Publications	Citations	
Singh, B. N.	24	32	1252	Nonlinear buckling/post-buckling of laminated composite plates; thermal and stochastic stability analysis
Lal, Achchhe	16	17	274	Thermal buckling, post-buckling, and random system-property effects in laminated composites
Tounsi, Abdelouahed	8	14	1054	Higher-order shear deformation theories, laminated/advanced composite plates, and thermal buckling
Dey, Tanish	3	8	125	Finite element-based buckling and post-buckling analysis of laminated/sandwich composite structures
Kumar, Rajesh	8	8	149	Nonlinear stability, thermal buckling, and vibration-related behaviour of laminated composite plates
Maiti, D. K.	3	7	428	Numerical modelling, optimization, and buckling/post-buckling of composite structural elements
Panda, Subrata Kumar	3	7	242	Nonlinear vibration, thermo-mechanical buckling, and post-buckling of composite panels and shells
Singh, Jeeoot	5	7	119	Buckling and stability analysis of laminated composite plates under mechanical and thermal loading
Eltaher, Mohamed A.	1	6	162	Buckling and thermal stability of advanced composite, functionally graded, and micro/nano-scale structures
Garg, Aman	11	6	146	Computational prediction, optimization, and data-driven analysis of composite structural behaviour

To provide a qualitative interpretation of the most productive authors, the dominant sub-topics associated with their publications in the dataset were also considered. As shown in Table 2, the leading authors are not concentrated on a single narrow topic; instead, they contribute to different but mechanically related subfields of FRP composite stability. For example, Singh, B. N. and Lal, Achchhe are mainly associated with nonlinear buckling/post-buckling, thermal buckling, and stochastic stability analysis of

laminated composite plates. Tounsi, Abdelouahed is more closely related to refined and higher-order shear deformation theories for laminated, advanced composite, and thermally loaded plate structures. Other productive authors, such as Panda, Maiti, and Kumar, are associated with finite element modelling, vibration-buckling interaction, thermo-mechanical stability, and optimization-based analysis of composite structural elements. Therefore, the author-level results suggest that the intellectual development of the field has been shaped by several specialized research directions, including thermal buckling, nonlinear post-buckling, delamination-sensitive stability, vibration-buckling interaction, and computational/optimization-based composite design.

The results indicate that author-level collaboration in this field is relatively concentrated around a limited number of research groups. Singh, B. N. had the highest number of publications, followed by Lal, Achchhe and Tounsi, Abdelouahed. However, publication output, citation impact, and collaboration strength do not always show the same ranking. This suggests that the field contains both highly productive authors and smaller collaborative groups with different levels of citation visibility and network connectivity.

The central position of highly cited and productive authors such as Singh, B. N. can be interpreted not only as a result of publication output but also as a consequence of their methodological contribution to the field. In particular, studies associated with Singh and co-authors addressed important theoretical and numerical gaps in the buckling and post-buckling analysis of laminated composite plates by incorporating higher-order shear deformation theory, von Kármán geometric nonlinearity, stochastic material/geometric uncertainties, elastic foundation effects, and thermal loading conditions (Singh et al., 2001; Singh et al., 2009; Lal et al., 2009; Dash and Singh, 2012). These contributions are closely aligned with the dominant themes identified in the keyword co-occurrence network, including “buckling”, “post-buckling”, “finite element method”, “thermal buckling”, and “laminated composites”. Therefore, the centrality of these authors appears to reflect their role in extending the field from deterministic critical buckling load prediction toward more realistic nonlinear, stochastic, and thermo-mechanical stability analyses of FRP composite structures.

Institutional co-authorship network

Institutional co-authorship analysis was conducted to identify the leading organizations and collaboration patterns in the field (Figure 7). Institutional collaboration networks are useful for understanding how research capacity is distributed among universities, research centers, and technical institutions (Newman, 2001; Leydesdorff and Persson, 2010). In this study, organizations with at least five publications were included in the network.

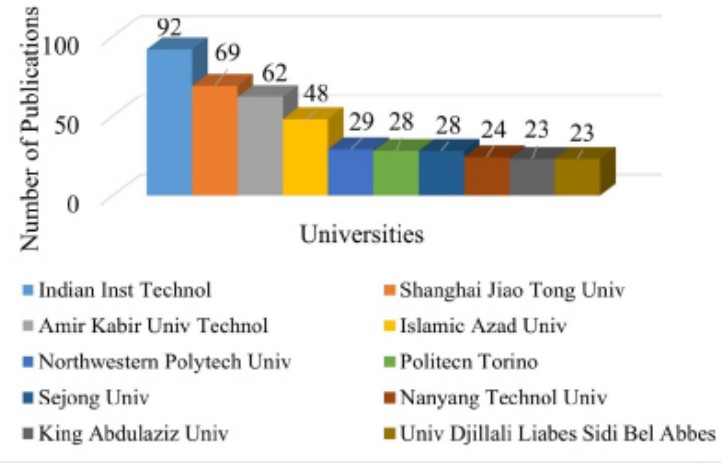

Figure 7. Top 10 most productive universities

The institutional collaboration network consisted of 54 organizations grouped into 10 clusters, with 79 links and a total link strength of 164. The node size represents the publication output of each institution, while the links indicate co-authorship relationships between organizations. Institutions with higher total link strength values have stronger collaborative positions in the network. Top 10 most productive universities are shown in Table 3.

Table 3. Top 10 most productive universities

Universities	Total link strength	Documents	Citations
Indian Inst Technol	10	92	2814
Shanghai Jiao Tong Univ	19	69	2366
Amir Kabir Univ Technol	16	62	3130
Islamic Azad Univ	20	48	2588
Northwestern Polytech Univ	5	29	430
Politecn Torino	3	28	1849
Sejong Univ	8	28	1003
Nanyang Technol Univ	1	24	730
King Abdulaziz Univ	26	23	1658
Univ Djillali Liabes Sidi Bel Abbes	12	23	1176

The results show that the Indian Institute of Technology, Shanghai Jiao Tong University, Amirkabir University of Technology, Islamic Azad University, and Northwestern Polytechnical University were among the most productive institutions. However, the highest publication output did not always correspond to the highest collaboration strength. For example, King Abdulaziz University and Islamic Azad University showed relatively high total link strength values, indicating stronger institutional collaboration. This suggests that the field has developed through both highly productive individual institutions and multi-institutional collaborative networks.

General discussion and research implications

The bibliometric results show that research on the buckling behaviour of fiber-reinforced polymer composites has developed into a multidisciplinary field. The keyword network indicates that the main research focus is concentrated around buckling, post-buckling, finite element analysis, thermal buckling, vibration, delamination, and laminated composites. These themes are consistent with recent studies emphasizing the importance of nonlinear stability, damage-sensitive buckling, and computational modeling in composite structures (Chen et al., 2023; Sorour et al., 2024; Zhang et al., 2024).

The findings also show that the field is strongly influenced by numerical and analytical approaches. This is expected because FRP composite buckling is affected by anisotropy, lay-up sequence, boundary conditions, imperfections, delamination, temperature, and local-global instability interactions. Recent studies on variable-stiffness composite laminates and curvilinear fiber-reinforced structures also show that optimization-based design is becoming increasingly important for improving buckling resistance (Zhao et al., 2019).

The collaboration analyses indicate that the literature is shaped by both internationally connected country networks and specialized author/institution groups. China, India, Iran, the USA, Türkiye, the UK, South Korea, Italy, Germany, and Australia were among the most productive countries. However, the author and institutional networks were more fragmented, suggesting that the field contains several active research groups rather than a single dominant collaboration network.

The bibliometric indicators obtained in this study also provide quantitative support for the increasing importance of computational and data-oriented approaches. In the keyword co-occurrence analysis, the network consisted of 106 keywords, 1113 links, and a total link strength of 2698, indicating a highly interconnected conceptual structure. Within this network, computationally oriented terms such as "finite element method", "finite element analysis", "optimization", "post-buckling", "thermal buckling", "vibration", and "delamination" appeared among the strongly connected themes. This suggests that the field is increasingly structured around complex, multi-parameter stability problems rather than only classical critical buckling load calculations. Since FRP composite buckling is influenced simultaneously by lay-up sequence, anisotropy, boundary conditions, geometric imperfections, delamination, thermal effects, and nonlinear post-buckling response, recent studies have begun to highlight machine learning, intelligent optimization, and data-driven prediction as complementary tools for handling such multi-variable design spaces (Chen et al., 2023; Sorour et al., 2024). Therefore, the expected growth of data-driven methods should be interpreted as an emerging extension of the existing computational and optimization-oriented research structure, rather than as a fully dominant keyword cluster at the present stage.

Overall, future research is expected to move toward more integrated approaches combining experiments, nonlinear finite element modeling, damage mechanics, optimization, and data-driven methods. Recent studies have already highlighted the potential of machine learning and intelligent design strategies for predicting and optimizing the mechanical behaviour of laminated FRP composites. Therefore, future work on FRP composite buckling should focus not only on critical buckling loads but also on post-buckling safety, damage tolerance, environmental effects, manufacturing imperfections, and design optimization.

Although the keyword co-occurrence analysis separated the literature into eight clusters, these clusters should not be interpreted as completely independent research areas. Instead, they represent mechanically interconnected aspects of the buckling behaviour of FRP composite structures. For example, the relationship between vibration and buckling is important because the stiffness reduction caused by compressive loading, delamination, thermal softening, or geometric imperfections can alter the natural frequencies and dynamic stability of laminated composite members. Similarly, post-buckling behaviour is closely related to damage evolution, since local buckling may promote matrix cracking, delamination growth, and progressive stiffness degradation. Thermal buckling also interacts with laminated composite design because temperature-dependent material properties, residual thermal stresses, and anisotropic thermal expansion can change both the critical buckling load and the subsequent post-buckling path. In this context, finite element analysis functions as a connecting methodological cluster, linking classical buckling theory with vibration analysis, delamination modelling, thermal stability, nonlinear post-buckling response, and optimization-based laminate design. Therefore, the eight keyword clusters collectively indicate that the field has evolved from isolated critical-load prediction toward an integrated stability framework in which mechanical, thermal, dynamic, damage-related, and computational factors are considered together.

CONCLUSION

This study presented a bibliometric analysis of research trends and the knowledge structure of buckling behaviour in fiber-reinforced polymer composites. A total of 2215 English language articles and review articles indexed in the Web of Science Core Collection between 1975 and 2026 were analysed. The dataset received 61,986 citations, with an average of 27.98 citations per item and an h-index of 98, indicating that the topic has gained considerable scientific attention.

The keyword co-occurrence analysis showed that the field is mainly structured around buckling, post-buckling, thermal buckling, finite element analysis, vibration, delamination, laminated composites, and FRP structural applications. These results indicate that research has evolved from classical stability analysis toward more complex problems involving nonlinear modelling, damage-induced instability, thermal effects,

local-global buckling interaction, and optimization.

The country co-authorship network revealed that China, India, Iran, the USA, Türkiye, the UK, South Korea, Italy, Germany, and Australia were among the most productive countries. The author and institutional analyses showed that the field is shaped by specialized research groups and leading institutions rather than a single dominant collaboration network. The institutional network also confirmed the active role of universities and technical research centers in advancing FRP buckling studies.

Overall, the findings demonstrate that buckling behaviour in FRP composites is a multidisciplinary and continuously developing research field. Future studies are expected to focus more on integrated experimental-numerical approaches, damage tolerance, post-buckling safety, thermal and environmental effects, manufacturing imperfections, optimization-based design, and data-driven prediction methods. The results of this bibliometric study provide a useful overview for researchers seeking to understand the evolution, major contributors, and emerging directions of FRP composite buckling research.

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