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Review

An Overview of Smart Composites for the Aerospace Sector

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Abstract: The continuous evolution of aerospace technology has intensified the demand for innovative materials that enhance structural performance, fuel efficiency, and operational safety. This study conducts systematic bibliometric analysis using data from Scopus and the Web of Science, covering publications from the last decade. Smart composites have emerged as a transformative class of materials, integrating structural health monitoring (SHM), electromagnetic interference (EMI) shielding, and multifunctional capabilities such as self-sensing, self-healing, responsiveness to external stimuli, and adaptability to environmental conditions. Recent developments focus on nanotechnology, the additive manufacturing of smart materials, piezoelectric materials and sensors, as well as aerogels and ultralight structures. By analyzing the evolution of scientific contributions and identifying knowledge gaps, this review provides a valuable resource for guiding future advancements in smart composite materials for aerospace engineering.

Keywords: composites; aerospace; nanocomposites; SHM; bibliometric review

1. Introduction

The continuous advancement of aerospace technology has pushed the need for innovative materials that enhance structural performance, fuel efficiency, and operational safety. Materials play a crucial role as safety-critical components in aerospace structures, forming the wings, fuselage, empennage, landing gear, tail boom, and rotor blades of helicopters, aircraft, satellites, or unmanned aerial systems (UAS) [1,2]. Here, smart composites have emerged as a transformative class of materials capable of self-monitoring structural health, responding to external stimuli, and adapting to environmental conditions [3,4]. The multifunctionality of these materials is particularly relevant in aerospace applications, where weight reduction, durability, and real-time health monitoring are crucial factors [5,6].

There is an increasing interest in the development of adequate inspection techniques for Structural Health Monitoring (SHM) applications. Here, sensors are utilized to collect data, which is then processed and analyzed to build a control system that will be in place for the duration of an asset's life [7]. Several traditional SHM methods, including guided waves, acoustic emission, and ultrasonic, rely on intricate statistical and mathematical methods and do not provide complete real-time information regarding the condition of the structure. For this reason, it is necessary to explore other options. In this regard, smart composites present a promising solution for SHM. On the one hand, piezoelectric composites raise the ability of certain materials to generate an electric response to mechanical stress. These composites typically consist of piezoelectric ceramics (PZT, $BaTiO_3$, $PbTiO_3$, $KNbO_3$...) embedded in a polymer matrix, allowing them to function as both sensors and actuators [8,9]. On the other hand, piezoresistive composites incorporate conductive elements such as carbon or metal nanoparticles in polymer matrices, which enable real-time

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monitoring of structural integrity through changes in their electrical properties. The reason for interest is that, as has been well documented, their incorporation into these insulating systems enables the development of percolating electrical networks, fostering a widespread improvement in electrical conductivity [10–12]. More specifically, the electrical properties of these nanocomposites are primarily influenced by three key factors: the intrinsic resistivity of the nanoparticles, the contact resistance between adjacent particles, and the tunneling effect occurring between neighboring nanoparticles [13]. This means that their electrical resistivity changes when subjected to damage or mechanical strain.

Recent studies have also focused on the development of electromagnetic interference (EMI) shielding composites that enhance the resilience of aerospace electronics. With the increasing reliance on electronic systems in modern aircraft, protecting sensitive avionics from external electromagnetic disturbances is a growing priority [14,15]. Carbon-based nanomaterials, such as graphene and carbon nanotubes, have demonstrated exceptional EMI shielding capabilities while maintaining mechanical integrity, making them ideal candidates for next-generation aerospace applications [16,17].

In addition, smart composite-based adaptive and morphing structures are opening opportunities for revolutionary improvements in flight performance and aerodynamics. These structures can alter their shape in response to external stimuli, such as temperature changes or aerodynamic forces, optimizing flight efficiency under varying conditions. For example, self-healing materials enable autonomous or stimuli-triggered repair of structural damage that can mitigate the effects of microcracks and fatigue-induced damage, extending the lifespan of critical components and reducing maintenance costs [18,19]. Another example is shape memory composites that are characterized by retaining a programmed shape and returning to it when exposed to external stimuli such as heat or electrical currents [20]. Moreover, magnetoactive polymers work by responding to magnetic fields, enabling rapid and reversible shape changes, allowing aerospace engineers to develop morphing control surfaces without complex mechanical actuators [21]. Figure 1 shows the last focus of smart composites for the aerospace sector.

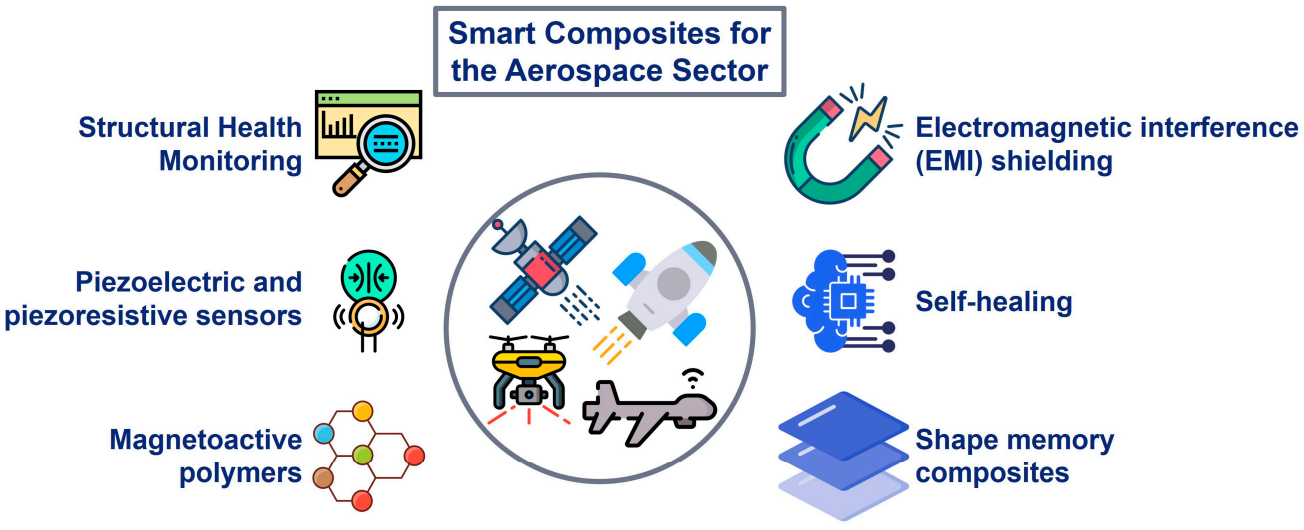


Figure 1. Revolutions brought about by smart composite-based adaptive in aircraft flight performance and aerodynamics.

A bibliometric approach is fundamental for understanding the evolution of research in smart composites for aerospace applications. In this study, a systematic bibliometric analysis was conducted using data from Scopus and the Web of Science, covering publications from the last decade. The results analyzed the growing research focus and identified emerging trends such as MXene-based composites, 4D-printed adaptive structures, and

nanomaterial integration for enhanced sensing and actuation. This review is a useful tool for directing future developments in the creation and use of smart composite materials in aeronautical engineering since it charts the growth of scientific contributions and pinpoints knowledge gaps.

2. Materials and Methods

The methodology employed in this bibliometric review was designed to be systematic and structured, comprising five distinct phases, as indicated in Figure 2.

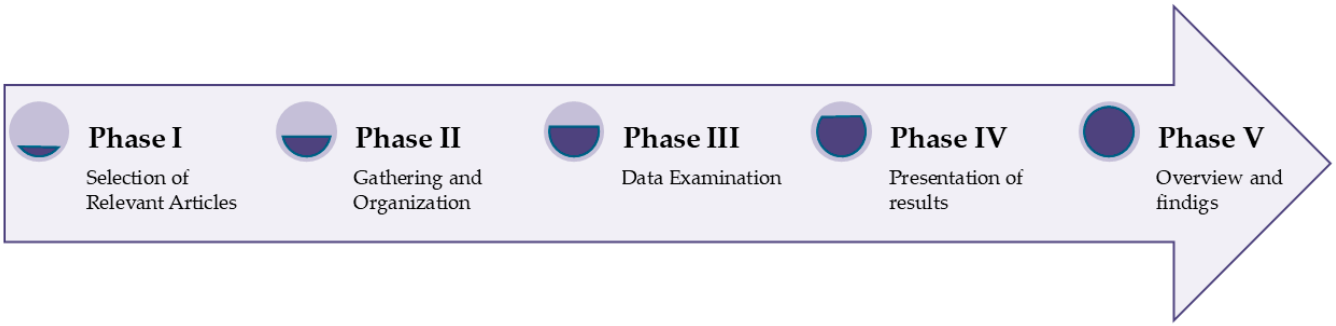


Figure 2. Methodology phases for this bibliometric review.

During phase I, relevant articles were selected by searching the most established academic databases, which are Scopus and Web of Science, by using the search string indicated in Figure 3. To ensure a comprehensive and focused search, various keywords were strategically combined using Boolean operators. Here, it is important to note that the data collection process was conducted in February 2025.

SEARCH STRING IN SCOPUS AND WEB OF SCIENCE
TITLE-ABSTRACT-KEYWORDS ("*composite*" AND "smart“)
AND
ALL ("aeronautic*" OR "aerospac*" OR "aviation" OR "aircraft" OR "drone" OR "airframe" OR "aerodynamic*" OR "spacecraft" OR "satellite" OR "UAV" OR "UAS" OR "Unmanned Aerial System“)

Figure 3. Search string used in Scopus and WOS for smart composite materials for the aerospace sector review. * Wording variations and enhanced search result expansion.

In phase II, bibliometric data were systematically extracted and organized following the PRISMA 2020 protocol [22], as shown in Figure 4. The PRISMA 2020 flow diagram offers a clear and well-structured representation of the study selection process, enhancing both the transparency and reproducibility of bibliometric reviews [23,24]. The protocol is structured in four main sections that reflect the study selection process: identification, screening, eligibility, and inclusion. Thus, this process began with the identification of 3809 records sourced from SCOPUS (n = 3108) and Web of Science (n = 701). After removing 392 duplicate records and 12 marked as ineligible by automated tools, 3405 records remained for screening. All records were screened, and no additional exclusions were made at this stage. Subsequently, these records were assessed for eligibility, resulting in the exclusion of 1450 entries that did not meet the criteria of being peer-reviewed articles published in English: conference papers (n = 484), review papers (n = 351), book chapters

(n = 177), conference reviews (n = 74), non-article documents (n = 145), and articles not in English (n = 219). As a result, the final data collection examined in this study involved 1955 documents published from 2015 to February 2025.

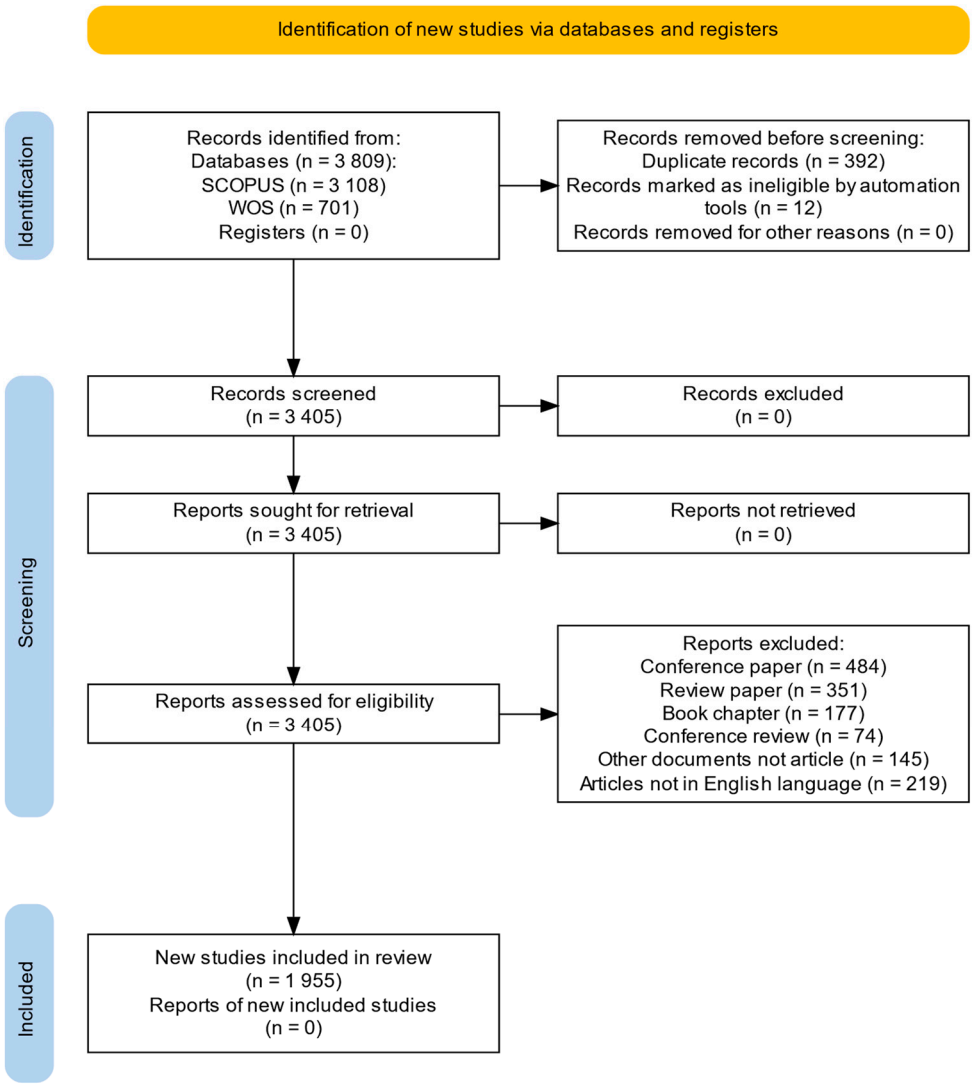


Figure 4. PRISMA 2020 protocol for smart composite materials for the aerospace sector review.

In phase III, bibliometric data such as document content, author, keywords, publication year, journal, and citations were extracted and organized by using Bibliometrix and Biblioshiny from R-4.4.2 software [25]. On the one hand, Bibliometrix facilitated data cleaning, structuring, and extraction of key indicators, including citation metrics, co-authorship networks, and keyword co-occurrence patterns. On the other hand, Biblioshiny enabled interactive visualization, generating network diagrams, thematic maps, and trend analyses to explore the evolution of the field.

In phase IV, the results were presented through graphical representations, such as network diagrams and bar charts, to clearly illustrate relationships among authors, institutions, and research themes. Finally, in phase V, the findings were synthesized into a cohesive narrative, providing an overview of the current state of research in smart composite materials for the aerospace sector, identifying knowledge gaps, and suggesting future research directions.

3. Results

The results of this study provide a deep bibliometric analysis of smart composite materials, examining key aspects such as document collection, annual published documents and citations, scientific journals, authors, affiliations, countries, and top-cited publications. This method enables an in-depth assessment of research trends, influential contributions, and the overall influence of scientific production on the subject. The study uses bibliometric indicators to identify patterns of information dissemination, collaborative networks, and the evolution of research throughout time.

3.1. Document Collection

A general overview of the bibliometric data is presented in Figure 5, where the number of documents, sources, authors, and collaboration metrics are stated. The dataset involves 1997 scientific articles from 643 scientific journals, with an annual growth rate of 5.14%, reflecting an increase in research output due to interest in this theme. The average document age is 4.23 years, and the average number of citations per document is 22.78, indicating significant research impact. Keywords Plus (ID) and Author's Keywords (DE) are central to bibliometric analysis, with 11,173 and 5608 occurrences, respectively, highlighting key research topics and trends. The dataset includes 552 unique authors, with only 37 authors contributing single-authored 43 documents, highlighting the collaborative nature of the field. The average number of co-authors per document is 4.98, and international co-authorship accounts for 5709 instances, demonstrating strong global collaboration.

DESCRIPTION	RESULTS
MAIN INFORMATION ABOUT DATA	
Timespan	2015:2025
Sources	643
Documents	1997
Annual Growth Rate %	5.14
Document Average Age	4.23
Average citations per doc	22.78
DOCUMENT CONTENTS	
Keywords Plus (ID)	11,173
Author's Keywords (DE)	5608
AUTHORS	
Authors	5152
Authors of single-authored docs	37
AUTHORS COLLABORATION	
Single-authored docs	43
Co-Authors per Doc	4.98
International co-authorships %	5709
DOCUMENT TYPES	
article	1974
article; book chapter	5
article; early access	15
article; proceedings paper	3

Figure 5. Summary of bibliometric data from 2015 to 2025.

3.2. Annual Published Documents and Citations

Figure 6 shows the annual scientific production and citation evolution of smart composites for the aerospace industry. The number of published documents per year is represented by orange bars, while the mean total citations per article (MeanTCperArt) and the mean

total citations per year (MeanTCperYear) are depicted by the blue and green lines, respectively. The data reveal a progressive increase in the number of publications since 2015, peaking in 2024 with 332 documents. In 2025 we can appreciate just 25 documents, considering this is the publication until February 2025. This partial data should be viewed cautiously as it covers less than two months of research output, while previous years reflect full-year data. If the trend continues, the 2025 total could reach around 400 documents, highlighting the growing importance of this research field. This suggests a rising interest in the field over the past decade. Also, the mean total citations per year remain relatively stable, reflecting the consistent impact of the research in this domain. Nonetheless, the average number of citations per article has been declining since 2020, despite the rise in publications. This drop could be a sign that the field is saturated and that new articles are coming out more frequently than they can produce meaningful citations.

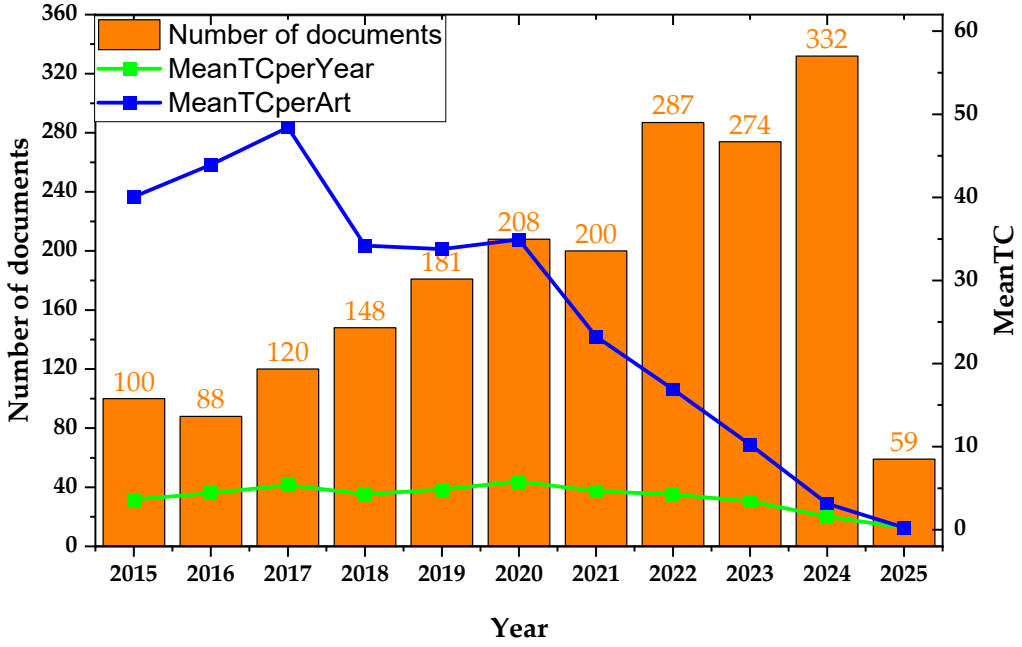


Figure 6. Annual scientific production and citation evolution.

3.3. Scientific Journals

Figure 7 reports the most relevant scientific journals contributing to this field by indicating the number of publications for each journal. The journal Composites Science and Technology leads with 76 publications, followed by Smart Materials and Structures and Composites Part B: Engineering, with 63 and 57 publications, respectively. These journals are recognized for their high impact in materials science and engineering, specifically in the subfield of composite materials. The other journals cover multidisciplinary disciplines such as materials science (Journal of Intelligent Material Systems and Structures, Composites Part A: Applied Science and Manufacturing, Materials, ACS Applied Materials and Interfaces), engineering (Mechanics of Advanced Materials and Structures), and applied physics (Sensors). Additionally, the concentration of articles in specialist journals promotes knowledge sharing throughout the scientific community, which supports the field's continuous progress.

Table 1 showcases the most influential scientific journals, ranked according to key bibliometric indicators. These include the h-index, which evaluates both the productivity and citation impact of a journal; the g-index, a variant of the h-index that places higher emphasis on highly cited articles; and the m-index, which adjusts the h-index by accounting for the number of years since the journal's first publication, offering a measure of annual

citation impact. Furthermore, the ranking considers total citations (TC), the number of publications (NP), and the starting publication year (PY_start).

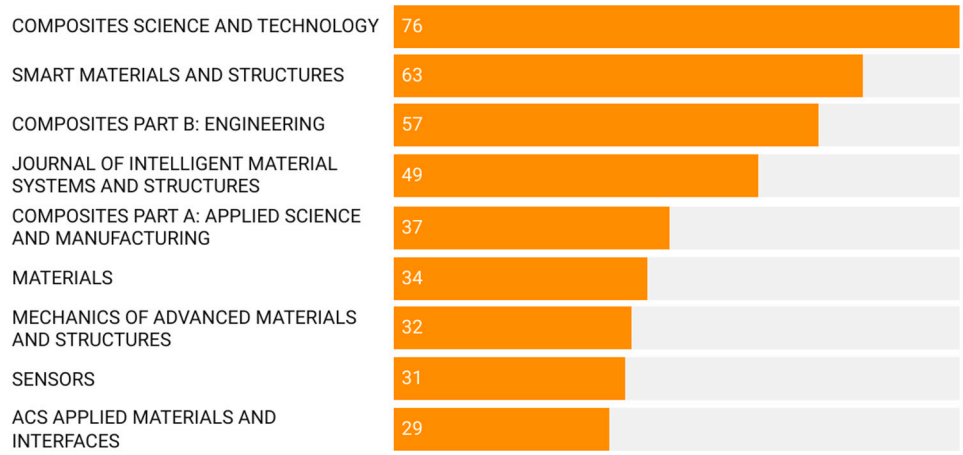


Figure 7. Most relevant scientific journals.

Table 1. Most impact scientific journals.

Scientific Journal	h_Index	g_Index	m_Index	TC	NP	PY_Start
Composites Science and Technology	31	49	2.81	2667	76	2015
Composites Part B: Engineering	29	45	2.63	2119	57	2015
Composite Structures	28	45	2.54	2573	99	2015
ACS Applied Materials and Interfaces	19	29	1.72	1998	29	2015
Composites Part B: Engineering	19	27	1.72	1303	27	2015
Smart Materials and Structures	19	29	1.72	1056	63	2015
Composites Part A: Applied Science and Manufacturing	18	34	1.64	1179	37	2015
Journal of Intelligent Material Systems and Structures	17	24	1.55	675	49	2015
Thin-Walled Structures	16	27	1.78	909	27	2017
Chemical Engineering Journal	12	19	1.50	951	19	2018

Among the journals listed in Table 1, Composites Science and Technology exhibits the highest impact, with an h-index of 31, a g-index of 49, and an m-index of 2.81, along with 2667 total citations. Composites Part B: Engineering and Composite Structures follow closely in terms of impact, with high citation counts and publication numbers. In this regard, the three journals are listed in the subcategory of Composites from Materials Science category. Alternatively, the presence of interdisciplinary journals such as ACS Applied Materials and Interfaces, Smart Materials and Structures, Journal of Intelligent Material Systems and Structures, and Chemical Engineering Journal suggests an increasing integration of advanced materials, instrumentation technologies, and chemical engineering approaches within the field.

Figure 8 shows the annual evolution of document production, presenting the cumulative number of publications from 2015 to 2025. The general trend indicates a uniform increase in publications per each journal, reflecting a progressively growing interest, as mentioned above. In this regard, Composite Structures exhibits the highest publication volume and, furthermore, the most significant growth in the past decade. The other scientific journals (Composites Science and Technology, Smart Materials and Structures, Composites Part B: Engineering, and Journal of Intelligent Material Systems and Structures) also show significant increases, indicating their continued relevance in the field. The observed increase in publications in a number of journals contributes to a rising amount of research that is advancing smart composite materials.

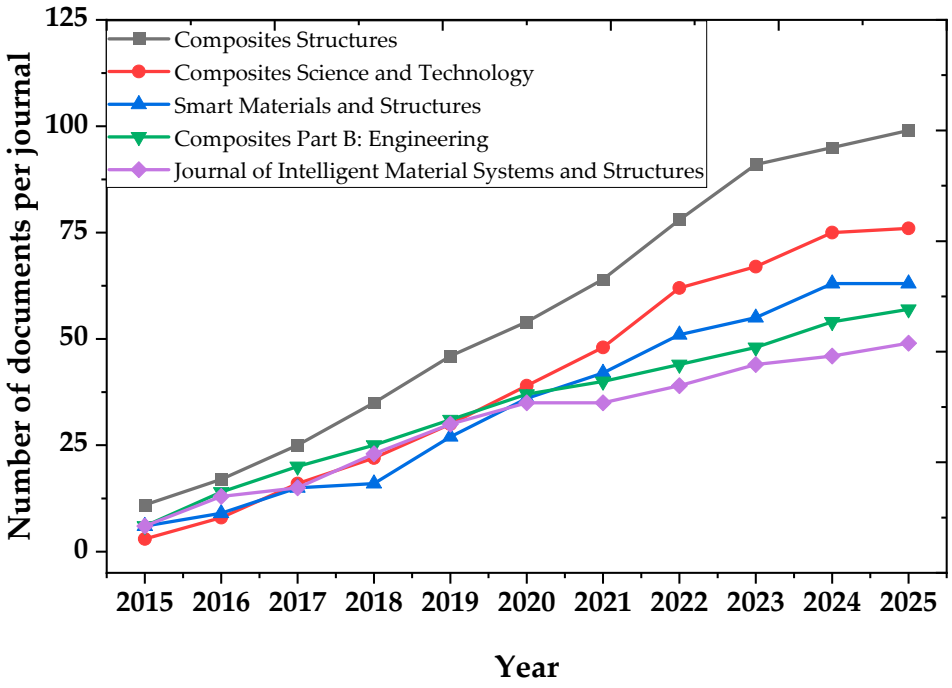


Figure 8. Scientific journal production over time.

3.4. Authors

The bibliometric data related to authors are presented in Figure 9 and Table 2. On the one hand, Figure 9 identifies the top 10 most relevant authors based on the number of published papers and their fractional contribution to the total. In this regard, Y. Liu stands out as the leading author, with 91 published articles and a fractionalized count of 15.44%. Other highly productive researchers include Y. Wang (88 articles, 15.13% fractionalized) and Y. Li (50 articles, 8.19% fractionalized). On the other hand, the scientific impact of these authors is evaluated in Table 2 by using the h-index, g-index, m-index, TC, and NP. Here, Y. Liu not only leads in terms of article count but also exhibits the highest index (h-index: 27, g-index: 73, m-index: 2.455), reinforcing his strong citation impact. Similarly, Y. Wang (h-index: 25, g-index: 41, m-index: 2.273) follows closely, demonstrating considerable influence in the field. The existence of more authors with an h-index over 16 indicates a solid research base. Finally, the diverse range of TC and NP among the top authors indicates varying degrees of research influence, with some authors contributing fewer but highly cited works.

Table 2. Authors local impact by h-index.

Author	h_Index	g_Index	m_Index	TC	NP	PY_Start
Y. Liu	27	73	2.455	5343	77	2015
Y. Wang	25	41	2.273	1875	76	2015
X. Wang	19	30	1.727	952	43	2015
S. Ahn	18	20	1.636	1290	20	2015
Y. Chen	18	31	1.636	1019	31	2015
J. Leng	18	36	1.636	1406	36	2015
L. Guadagno	16	19	1.455	928	19	2015
W. Wang	16	24	1.455	912	24	2015
J. Yang	16	29	1.600	973	29	2016
L. Zhang	16	25	1.600	856	25	2016

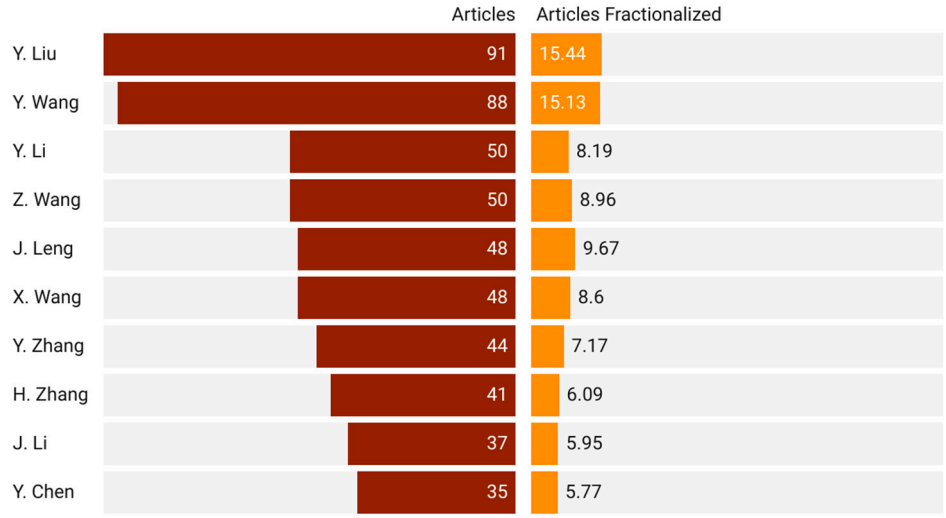


Figure 9. Most relevant authors.

3.5. Affiliations and Countries

Figure 10 shows the most influential affiliations contributing to the proposed research. In general, even though China dominates East Asian research, the existence of South Korean and Italian institutions shows that there is interest from around the world. The Harbin Institute of Technology (84 publications) tops the list, confirming its position as a significant center for aeronautical research. China's strong presence in this sector is further shown by the noteworthy contributions of Nanjing University of Aeronautics and Astronautics (63 publications) and Northwestern Polytechnical University (49 publications). Several other Chinese institutions, including Beihang University (42 publications), Zhejiang University (42 publications), and the Chinese Academy of Sciences (32 publications), further highlight China's leadership in smart composite materials. Outside of China, Seoul National University (48 publications) represents a key research center in South Korea, reflecting the country's growing interest in aerospace innovation. Additionally, the University of Salerno (27 publications) stands out as the most relevant European institution, indicating the participation of Italy in this field. Although Figure 9 demonstrates that many of the most prominent authors in the subject are Chinese, Figure 10 emphasizes that institutions from other nations, including the USA and India, are also significant contributors to smart composite research. It also suggests that although there are many individual high-output researchers in China, research in other areas might be more collaborative or institutionally dispersed.

Figure 11 presents the global distribution of scientific production, where darker blue shades indicate higher publication levels, while lighter shades represent lower output. As commented in the previous section with top affiliations, China leads overwhelmingly with 892 publications, reinforcing its dominant role in this research area. India (274 publications) and the United States (245 publications) follow as significant contributors, highlighting their strong scientific engagement despite the absence of specific institutions in the top rankings. Among European countries, Italy (151 publications) shows the highest data, followed by the United Kingdom (124 publications), France (75 publications), and Germany (67 publications), indicating a relevant but comparatively lower contribution. In Asia, Iran (122 publications) and South Korea (118 publications) demonstrate a growing presence in this field.

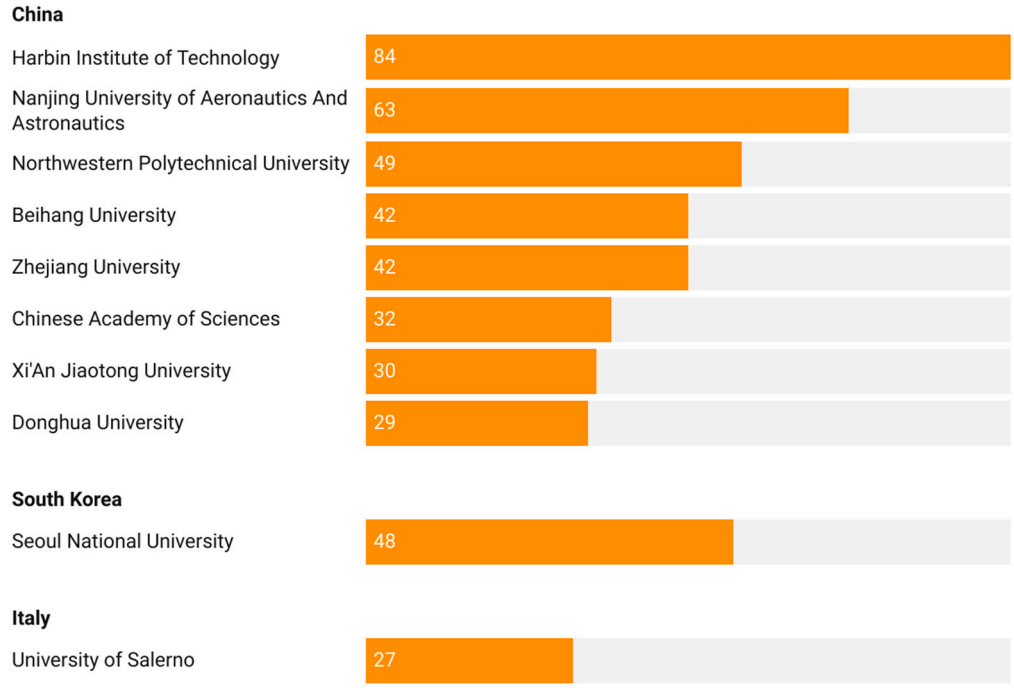


Figure 10. Most relevant affiliations.

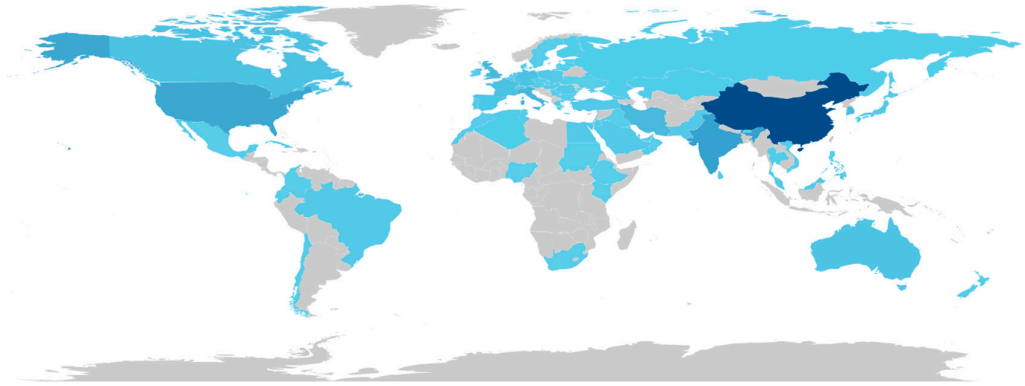


Figure 11. Countries' scientific production.

Moreover, as seen in Figure 10, eight of the top ten research centers are in China, demonstrating the dominance of Chinese institutions in the field of smart composites. This focus is consistent with China's dominant position in research production (Figure 11). Nonetheless, South Korean and Italian institutes, as well as more general contributions from the USA and India, show that pertinent research is also being carried out globally. Rather than a lack of significant contributions from other locations, the apparent discrepancy can be caused by variations in research funding, institutional specialties, and collaborative networks.

Table 3 presents the most cited countries based on TC and average article citations. As expected regarding the previous sections, China ranks first with 17,761 citations and an average of 28.10 citations per article, followed by the USA (3313; 23.80) and India (2974; 14.20). Other notable countries include Korea (2316; 23.90), Italy (2209; 22.10), Iran (2111; 20.90), and Canada (1421; 26.80). Despite having fewer publications, Canada has a high average citation rate, suggesting a considerable influence per article, while China's dominance in overall citations implies a robust research output in the topic.

Table 3. Most cited countries.

Country	TC	Average Article Citations
China	17,761	28.10
USA	3313	23.80
India	2974	14.20
Korea	2316	23.90
Italy	2209	22.10
Iran	2111	20.90
Canada	1421	26.80

3.6. Publications Analysis

Table 4 lists the top-cited publications according to total and annual citations. The most cited work is by J. Liu et al. (1468 citations, 163.11 TC per year, normalized TC of 30.32) [26], followed by Z. Xun Khoo et al. [27] and Z. Ma et al. [28]. These publications continue to be relevant in the area, as evidenced by their high annual citation rates. Other high-impact publications, such as those by G. Zhan Lum et al. [29] and H. Wei et al. [30], exhibit moderate total citation counts but maintain a steady annual impact, indicating constant academic interest in their results.

Table 4. Top-cited publications by total and annual citations.

Reference	Authors	TC	TC per Year	Normalized TC
[26]	J. Liu et al.	1468	163.11	30.32
[27]	Z. Xun Khoo et al.	762	69.27	19.02
[28]	Z. Ma et al.	647	107.83	18.52
[29]	G. Zhan Lum et al.	499	49.9	11.36
[30]	H. Wei et al.	415	46.11	8.57
[31]	Q. Mu et al.	361	40.11	7.46
[32]	Y. Wan et al.	337	42.13	9.85
[33]	Z. Fan el al.	333	55.50	9.53
[34]	A. Jain et al.	324	29.45	8.09
[35]	F. Guo et al.	280	35	8.19

4. Discussion

This section provides an analysis of the results with a focus on key developments through top publications, keyword trends, and thematic mapping. The findings reveal the most influential research areas, from well-established fundamentals to emerging innovations.

4.1. Trends in Top Publications

The most impactful publications indicated in Table 4 show four main trends that have guided research in recent years. These lines of development stand out for their focus on (i) electromagnetic interference (EMI) shielding, (ii) additive manufacturing of smart materials, (iii) piezoelectric materials and smart sensors, and (iv) aerogels and ultralight materials.

The first trend responds to the growing demand for EMI shielding, driven by the expanding use of electronic devices in areas such as aviation, defense, and intelligent systems. In this context, various advanced material solutions have demonstrated their potential to enhance protection against electromagnetic interference. Here, carbon-based nanoparticles such as graphene, carbon nanotubes, and MXene have gained a great deal of attention. On the one hand, MXenes have emerged as promising alternatives to graphene for EMI applications due to their high electrical conductivity. A recent development has led to the creation of a flexible, hydrophobic, and lightweight MXene foam with a

shielding effectiveness of approximately 70 dB, surpassing the 53 dB of its non-foamed equivalents [26]. Another innovative approach involves the fabrication of MXene paper nanocomposites combined with silver nanowires, enabling the development of ultraflexible materials with an electrical conductivity of up to 3725.6 $S \cdot cm^{-1}$ and an EMI effectiveness close to 80 dB [28]. On the other hand, hybrid nanocomposites such as hybrid silver-carbon foams have proven to be another effective solution with an EMI effectiveness of 70.1 dB and an extremely low density of 0.00382 g/cm^3, promoting flexibility, corrosion resistance, and high electron transport efficiency, making it ideal for aerospace applications and portable electronic devices [32]. Moreover, combining graphene with MXene has led to the creation of a hybrid foam with an EMI effectiveness of 50.7 dB and a shielding effectiveness per density ratio (SSE) of 6217 cm^3/g [33].

The second trend is related to the additive manufacturing (3D and 4D printing) of smart materials. From one perspective, 3D printing using digital light processing has enabled the production of conductive nanocomposites, allowing the creation of hollow capacitive sensors, flexible circuits, and shape-memory materials for advanced electronics and sensing without compromising mechanical properties [31]. From another perspective, 4D printing enables new possibilities in soft robotics, flexible electronics, and minimally invasive medicine, with architectures that can transform between different configurations (e.g., 3D–1D–3D or 3D–2D–3D) using thermal or magnetic stimuli, expanding adaptive and dynamic system applications [30]. Moreover, a universal method has been proposed to program soft, magnetoactive materials, enabling the creation of bioinspired robots like a jellyfish and an artificial cilium that replicate biological beating patterns, with applications in biomedical engineering and microfluidics [29].

The third trend is the development of piezoelectric materials, which have been widely used in sensors and actuators. These materials have evolved into flexible polymer composites reinforced with ceramic nanoparticles to enhance performance. Flexible piezoelectric composites have seen significant advancements. Materials based on PVDF-PZT have been developed to combine the flexibility of polymers with the high piezoelectric response of ceramics, enabling greater sensitivity in advanced sensors. These improvements are particularly useful in structural health [34].

The fourth and latest trend detected is the use of aerogels and ultralight materials. Carbon aerogels and other porous structures have shown great potential in aerospace applications due to their low density and multifunctional properties. One of the most notable developments is the creation of highly elastic carbon aerogels. A newly designed aerogel exhibits reversible elongation of 200% and fatigue resistance exceeding 10^6 cycles. These characteristics make it ideal for use in advanced strain sensors capable of identifying complex shape changes in aerospace applications [35].

4.2. Keywords Trends

The analysis of keywords reveals key areas of focus in the research on smart composites in the aerospace sector. For this purpose, Figure 12 presents the most frequently occurring keywords in the literature. The prominence of “piezoelectricity” (271 occurrences) highlights the central role of energy harvesting and self-sensing capabilities in the development of intelligent composite materials [36,37]. This finding aligns with the growing interest in piezoelectric materials for SHM and adaptive aerospace applications. Piezoelectricity is closely linked to “nanocomposites” (207 occurrences), which play a key role in this field due to their exceptional properties. Polymeric piezoelectric nanocomposites have good mechanical flexibility, lower manufacturing cost, suitable output voltage, and fast processing compared to ceramic-based composites [38]. Moreover, the term “laminated composites” (176 occurrences) ranks among the most cited terms, reflecting the continued

exploration of advanced materials with enhanced mechanical, thermal, and functional properties. These materials can be engineered with tailored properties for enhanced strength, stiffness, and damage tolerance, making them ideal for the complex demands of aerospace structures [39,40].

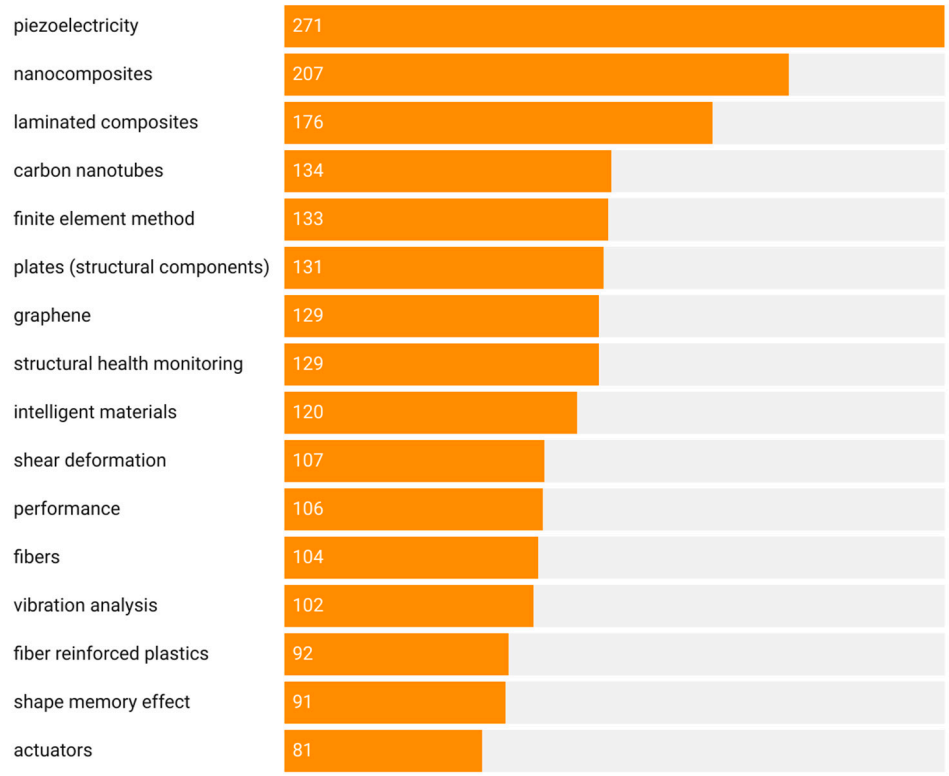


Figure 12. Most frequent keywords.

A significant research focus is observed on carbon-based nanomaterials, including "carbon nanotubes" (134 occurrences) and "graphene" (129 occurrences). These materials are widely studied for their exceptional mechanical strength, electrical conductivity, and potential applications in multifunctional aerospace composites. The addition of conductive nanoparticles to a flexible polymer matrix has emerged as a possible alternative to conventional strain gauges, which have limitations in detecting small strain levels and adapting to different surfaces in the aeronautical sector [41].

The "finite element method" (133 occurrences) appears frequently, emphasizing its critical significance in the simulation and predictive study of smart composite behavior under varied operational situations [42,43]. Similarly, "structural health monitoring" (129 occurrences) and "intelligent materials" (120 occurrences) indicate a strong research focus on real-time damage detection and adaptive material responses in aerospace applications [44,45]. Lastly, the presence of "shape memory effect" (91 occurrences) and "actuators" (81 occurrences) proposes a rising interest in self-healing and morphing capabilities for next-generation aerospace structures.

Once the most frequent keywords are analyzed, it is necessary to explore the relationship between them. Thus, Figure 13 shows the keyword co-occurrence network, where we can clearly differentiate three clusters: blue, red, and green.

The largest and most central cluster (green) is dominated by the term piezoelectricity, emphasizing its fundamental role, as it is in consonance with the most frequent keywords: This cluster is closely linked to laminated composites, finite element method, and structural components, suggesting a strong emphasis on the integration of piezoelectric materials into laminated composite systems and their computational modeling. The other terms

are related to piezoelectric equations and vibration words, which are the basis for the previous words.

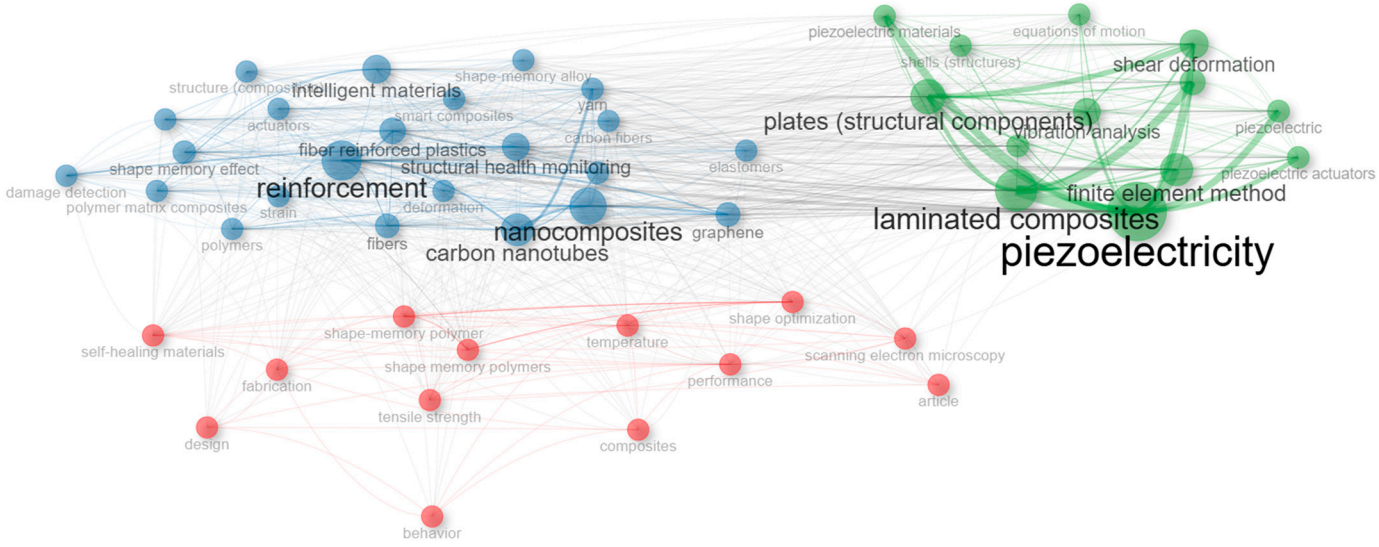


Figure 13. Keywords co-occurrence network.

Another prominent cluster (blue) revolves around nanocomposites, carbon nanotubes, and reinforcement, indicating the significant research efforts dedicated to enhancing mechanical and functional properties through nanomaterial integration. The association with structural health monitoring (SHM) and intelligent materials suggests that these advanced composites are being explored for self-sensing and damage detection applications. In this regard, self-sensing nanocomposites incorporate conductive fillers like graphene platelets or carbon nanotubes into polymer matrices, enabling damage detection through changes in electrical properties [46,47] and they can detect various types of damage, including impact and delamination [48,49]. Self-sensing nanocomposites in smart carbon fiber-reinforced polymer composites hold promise for structural health monitoring and early damage detection in aerospace applications.

Finally, the red cluster consists of less frequently co-occurring keywords, such as shape memory polymers and scanning electron microscopy, which indicate emerging research areas focused on material characterization and adaptive capabilities. It is important to note that shape memory polymers offer the ability to change shape in response to stimuli like temperature or light. They are being explored for use in morphing aircraft structures, deployable space components, and self-healing materials for aerospace [50,51].

4.3. Thematic Map

Figure 14 presents the thematic map, categorizing research topics based on their development degree (density) and relevance (centrality): (i) motor themes, (ii) basic themes, (iii) niche themes, and (iv) emerging or declining themes.

The upper-right quadrant (motor themes) contains the most developed and central topics, including smart materials, polymer-matrix composites, piezoelectric materials, and finite element methods. This position emphasizes how important they are to aeronautical applications, especially when designing multifunctional and adaptable structures. Their extensive use in airplanes, spacecraft, and other cutting-edge aerospace systems, where performance, weight reduction, and energy efficiency are critical, demonstrates their relevance.

The lower-right quadrant (basic themes) includes structural health monitoring, self-healing, and carbon nanotubes, indicating well-established but continuously evolving areas

that form the foundation of smart composite research. They are less likely to produce quick breakthroughs due to their basic character, but they do contribute to the safety and dependability of aerospace structures by serving as the essential foundation for more sophisticated aerospace technologies.

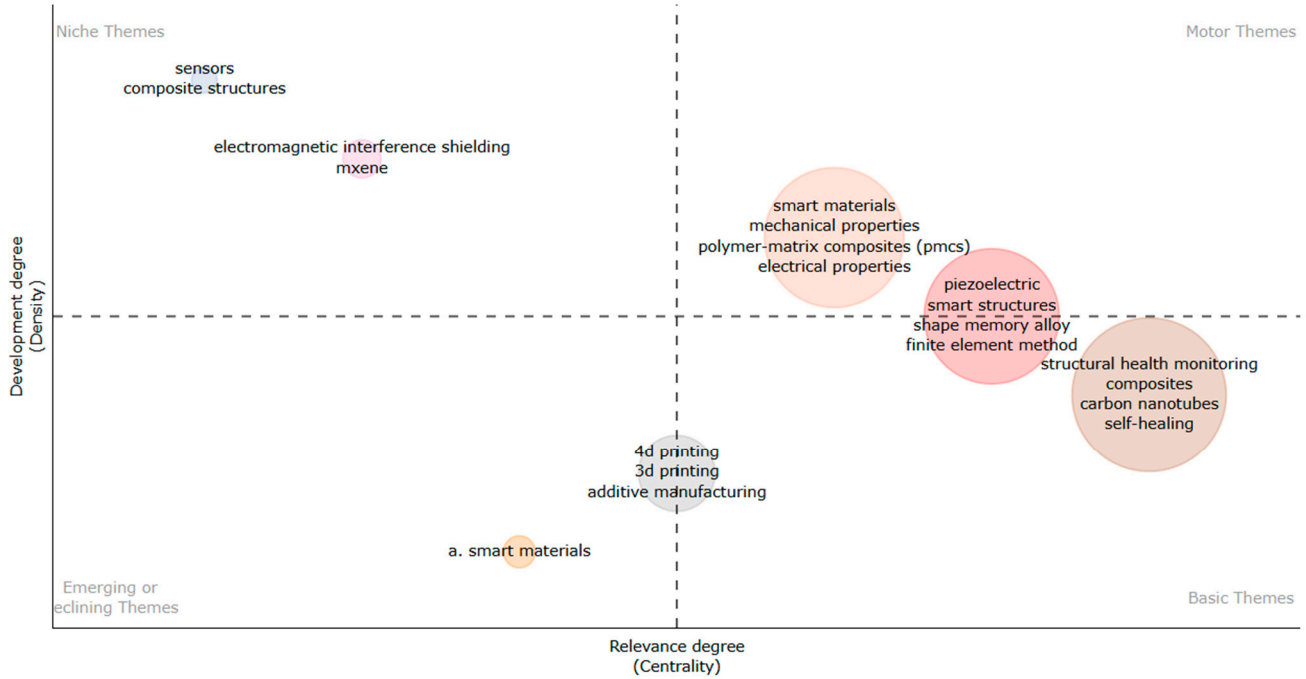


Figure 14. Thematic map of the topic.

The upper-left quadrant (niche themes) features EMI shielding and MXene, suggesting specialized research directions with growing interest but limited impact on the broader field. These topics have the potential to address issues including enhancing electromagnetic compatibility and developing innovative, high-performance materials. Their specialized market indicates that they are still in the early phases of development, but as new uses and production techniques are developed, they can grow considerably.

Finally, the lower-left quadrant (emerging or declining themes) includes 3D/4D printing and additive manufacturing, which, despite their current peripheral role, may gain prominence as fabrication technologies for next-generation aerospace composites. The production of aerospace composites may undergo a revolution as fabrication technologies develop and become more affordable. These technologies offer previously unheard-of levels of customization, material efficiency, and rapid prototyping capabilities, which may eventually result in the creation of next-generation aerospace structures.

The future of smart composites in the aerospace industry is geared towards developing even more efficient, sustainable, and adaptive solutions. The integration of emerging technologies such as 4D printing, advanced self-healing materials, and ultra-high sensitivity embedded sensors will enable more accurate real-time monitoring and unprecedented structural optimization. In addition, the combination of innovative nanomaterials, such as MXenes, carbon nanotubes, or graphene foams, promises significant improvements in electromagnetic interference shielding and energy efficiency of airborne systems. In parallel, exploring more sustainable manufacturing methods and implementing circular economy strategies will be key to reducing the environmental impact of these materials. As demand for lighter, safer, and more efficient aircraft grows, collaboration between academia, industry, and regulators will be essential to drive the adoption of these advances and cement the role of smart composites in the aviation of the future.

4.4. Topic Analysis

Based on the results obtained above, the development of a topical analysis is proposed below. Topical analysis in bibliometric reviews is a technique used to identify and group topics or areas of research within a set of scientific publications [52].

The six themes defined from the above analysis are (i) advanced materials; (ii) composite structures; (iii) functional properties; (iv) analysis and computational methods; (v) structural components; and (vi) monitoring and performance. Table 5 shows each of the defined topics, as well as the keywords and records identified.

Table 5. Research topics.

Denomination	Research Topic	Keywords	Results n (%)
t1	Advanced materials	Nanocomposites, carbon nanotubes, graphene, fibers and fiber reinforced plastics	580 (29.7%)
t2	Composite structures	Laminated composites, composite structures, laminating and reinforcement	179 (9.2%)
t3	Functional properties	Piezoelectricity, shape memory effect and intelligent materials	51 (2.6%)
t4	Analysis and computational methods	Finite element method, shear deformation and vibration analysis	108 (5.5%)
t5	Structural components	Plates (structural components) and actuators	159 (8.1%)
t6	Monitoring and performance	Structural health monitoring and performance	340 (17.4%)

This grouping provides a logical and comprehensive organization of the terms, reflecting the main areas of interest of the dataset: Advanced materials (t1) and composite structures (t2) focus on the fundamental composition and construction of the materials; functional properties (t3) highlight the unique characteristics that make these materials valuable for specific applications; analysis and computational methods (t4) represent the tools used to study and design these materials and structures; structural components (t5) are narrowed down to specific elements used in engineering applications, while monitoring and performance (t6) address the practical aspects of applying and evaluating these materials in real-world scenarios.

The results reflect the distribution of research attention on six key topics related to advanced materials and composite structures. Advanced materials (t1) stands out as the dominant theme, representing 29.7% of the total. This suggests that advanced materials are the main focus of interest in this field, probably due to their wide applicability in sectors such as energy, construction, and aerospace. This prominence may be driven by the development of innovative technologies such as nanocomposites, carbon nanotubes, and graphene, which offer unique properties and great potential to solve technological challenges.

On the other hand, monitoring and performance (t6) is in second place with 17.4%, reflecting a growing concern for assessing and ensuring the performance of materials and structures in real applications. This interest could be related to the need to monitor structural integrity in real time, especially in critical industries such as automotive, aeronautics, and civil infrastructure. Furthermore, this approach is aligned with global trends towards sustainability and material life cycle optimization.

In contrast, topics such as functional properties (t3) (2.6%) and analysis and computational methods (t4) (5.5%) have a lower representation, which could indicate that they are more specialized or complementary areas within the general field. However, their relevance should not be underestimated, as these areas are fundamental for developing specific properties (such as piezoelectricity or shape memory) and for modeling the behavior of materials using advanced computational tools. Taken together, these results show

a balanced picture where some topics are major drivers of the field, while others act as technical or emerging pillars to underpin broader advances.

Following the topic analysis, the evolution of topics over time is studied. This approach allows us to identify key patterns, such as the emergence of emerging themes, the decline of specific areas, and changes in research priorities within the field. To carry out this analysis, the relative frequency of records, organized by topic and year, has been examined. This has allowed the construction of time series that reflect how the relevance of each topic has changed over time (Figure 15).

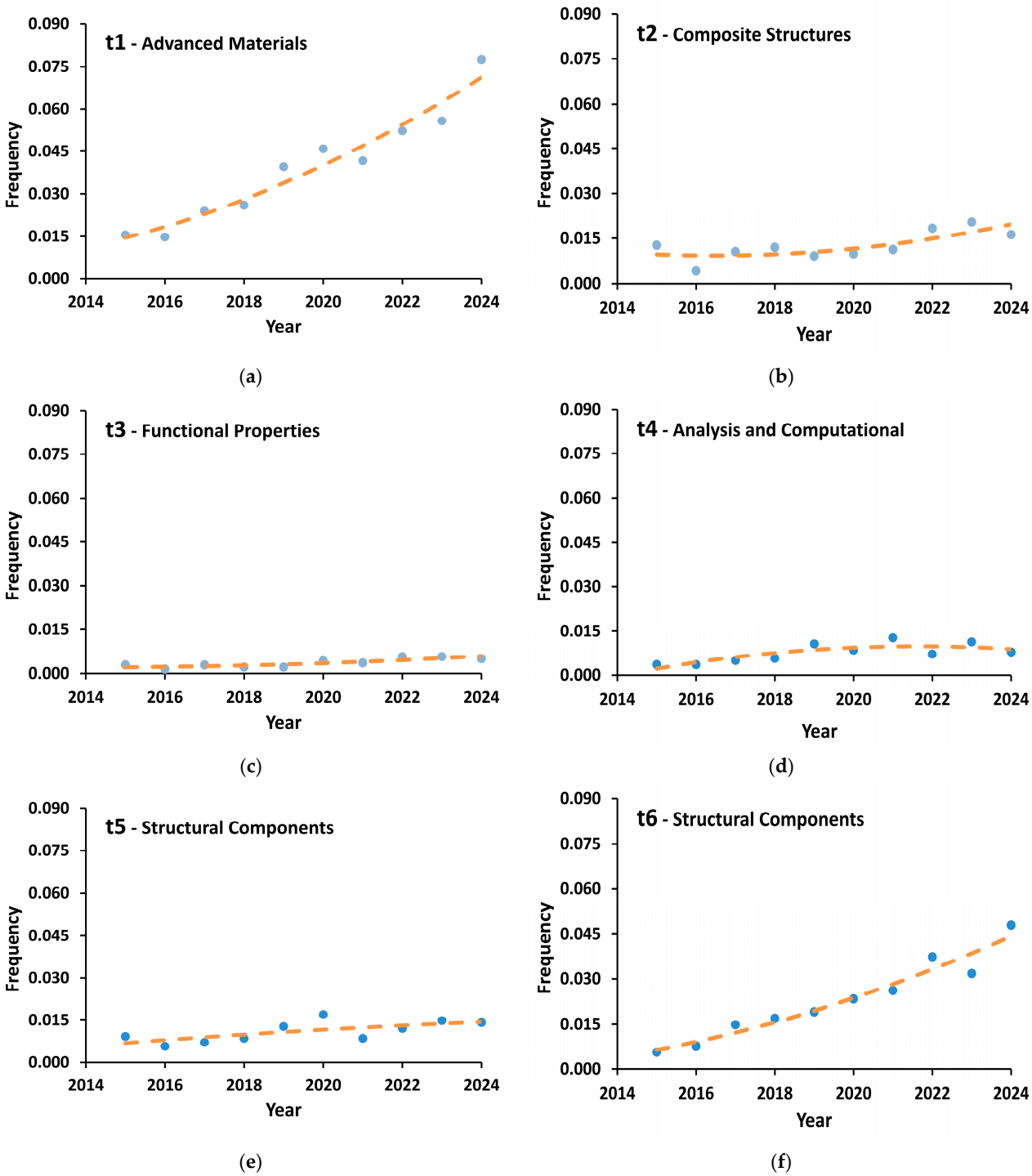


Figure 15. Temporal evolution frequency of topics: (**a**) t1—advanced materials; (**b**) t2—composite structures; (**c**) t3—functional properties; (**d**) t4—analysis and computational methods; (**e**) t5—structural components; and (**f**) t6—monitoring and performance.

Overall, advanced materials (t1) consistently lead in absolute occurrence throughout the period, reaching a significant peak in 2024 with 110 mentions (77.6% in relative proportion). This reflects a growing interest in advanced materials, probably driven by their relevance in key sectors such as aerospace, construction, and energy, as highlighted in the reports on innovation in composite materials. On the other hand, topics such as monitoring and performance (t6) also show steady growth, especially between 2018 and 2024, suggesting an increased focus on assessing the structural performance and sustainability of materials.

In contrast, some topics such as functional properties (t3) and structural components (t5) show a smaller relative share and more moderate fluctuations over time. For example, functional properties (t3) fluctuate between 0.14% and 0.56%, while structural components (t5) peak in 2020 with 1.69%. This could indicate that these topics are more specific or specialized within the field of composites, aligning with specific applications such as actuator design or the incorporation of piezoelectric properties. However, their relevance should not be underestimated, as these areas could be fundamental for specific technological advances.

4.5. Aerospace Applications of Smart Composites

The identified research hotspots in smart composites align with critical aerospace application scenarios, addressing key challenges in modern aircraft, spacecraft, and UAS. For instance, the development of EMI shielding materials, particularly those based on MXene and carbon-based nanomaterials, is essential for protecting avionics in next-generation aircraft and satellites from electromagnetic interference, ensuring the reliability of communication, navigation, and control systems [53–55]. In applications involving defense and space, where interference from outside sources may compromise mission success, these materials are very important.

Additive manufacturing (3D/4D printing) is transforming aerospace engineering by enabling the fabrication of adaptive airframe structures and deployable space components. These smart composites facilitate the development of morphing wings that optimize aerodynamics in real time, lightweight structural panels with embedded functionalities, and deployable elements for space missions, such as foldable satellite antennas and self-unfolding solar panels [56,57]. By reducing weight and enhancing structural efficiency, these innovations contribute to improved fuel economy and lower emissions in commercial aviation.

Piezoelectric and self-sensing composites play a crucial role in SHM systems, allowing real-time assessment of aircraft integrity by detecting stress, strain, and microcracks before they become critical failures. Predictive maintenance can drastically reduce downtime, lower operating costs, and improve safety in next-generation airlines and military aircraft, making this technology especially pertinent to these aircraft [58,59]. These materials are also being included in wind turbines and helicopter rotor blades, where long-term performance depends on constant vibration and stress distribution monitoring [60,61].

Furthermore, ultralight aerogels and self-healing materials are driving advancements in aerospace thermal protection systems, cryogenic fuel tanks, and impact-resistant structures. These materials are especially useful in reusable spacecraft, where higher insulation and resistance are required due to exposure to high temperatures and mechanical forces [62,63]. The ability of self-healing composites, which draw inspiration from biological healing processes to self-heal fatigue-induced microcracks, could minimize the need for costly maintenance and increase the lifespan of vital parts like high-performance turbine blades, landing gear structures, and fuselage panels.

Finally, future research should focus on overcoming key challenges in smart composites for aerospace applications. Scalability remains a critical issue, as many laboratory-scale

innovations have yet to be successfully implemented in large-scale production, as most commented in this paper. Cost-effectiveness is another concern, as advanced materials such as MXene-based composites and aerogels require optimization for large-mass manufacturing. Durability in extreme aerospace environments, including high radiation exposure to space and mechanical stress in high-speed aircraft, must be further investigated to enhance long-term performance. Additionally, integrating AI-driven predictive maintenance models with self-sensing composites could revolutionize real-time aircraft monitoring, reducing failure risks and maintenance costs. Future research should investigate innovative material processing methods, hybrid composite designs with improved multifunctionality, and the integration of sustainable materials to meet the increasing need for environmentally friendly aerospace solutions.

5. Conclusions

This bibliometric review examines the evolution and key trends in smart composites for aerospace applications. The increasing demand for lightweight, multifunctional, and adaptive materials has led to the advancement of nanocomposite integration, shape-memory polymers, self-healing capabilities, and real-time structural health monitoring.

Here, it is observed the increasing impact of carbon-based nanomaterials, such as graphene and carbon nanotubes, in enhancing mechanical, electrical, and sensing properties. The emergence of MXene-based composites and hybrid structures is paving the way for superior electromagnetic interference shielding and next-generation adaptive aerospace structures. The development of 3D and 4D printing technologies further highlights the shift toward customizable, responsive, and reconfigurable composite materials. Moreover, the analysis of top publications identifies four dominant research areas: (i) electromagnetic interference shielding, (ii) additive manufacturing of smart materials, (iii) piezoelectric materials and smart sensors, and (iv) aerogels and ultralight materials. These trends illustrate a shift toward multifunctional composites that improve aerospace performance and reliability.

The topic analysis classifies research into six themes, with advanced materials and monitoring and performance showing the most growth, reflecting a focus on new composites and real-time assessment. In contrast, functional properties and computational methods remain specialized but essential areas.

Bibliometric findings reveal a substantial increase in research output, with China, the United States, and India leading contributions. The analysis of co-authorship networks and keyword co-occurrence maps has revealed key research clusters, with dominant themes including structural health monitoring, piezoelectric materials, and additive manufacturing. Despite rapid advancements, difficulties remain in scalability, cost-efficiency, and durability in real-world applications.

Future research should prioritize scalable production, sustainability, and AI-driven predictive maintenance. Collaboration between academia, industry, and regulatory bodies will be crucial in ensuring the adoption and reliability of smart composites in aerospace systems.

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Abbreviations

The following abbreviations are used in this manuscript:

SHM	Structural health monitoring
EMI	Electromagnetic interference
TC	Total citations
NP	Number of publications
UAS	Unmanned aerial system

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