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AI-Assisted Bibliometric Analysis of LWFA Research: Trends and Future Directions

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Abstract

This study employs a comprehensive bibliometric analysis to map the global scientific landscape of laser wakefield acceleration (LWFA) from 1990 to 2025. Using data extracted from the Web of Science (WoS) and analyzed with Bibliometrix, VOSviewer, and CiteSpace, the study identifies key publication trends, influential authors, leading countries, prominent journals, and thematic evolution within the field. The findings reveal exponential growth in LWFA-related research, driven by advances in high-power laser technology and controlled injection techniques. Network analyses demonstrate extensive international collaboration and a strong interdisciplinary structure linking plasma physics, optics, and accelerator science. Keyword co-occurrence and burst analyses highlight emerging topics such as ionization injection, dual-stage acceleration, betatron radiation, and machine learning-assisted optimization. These insights delineate both the historical progression and the dynamic frontiers of LWFA, providing a systematic understanding of its development and guiding future research toward the realization of compact, high-quality electron sources and next-generation plasma-based accelerators.

Keywords: laser-plasma accelerators; laser wakefield acceleration; artificial intelligence; bibliometric analysis; scientometric mapping

1. Introduction

Since the first operation of Lawrence's cyclotron, which produced a 1 MeV ion beam [1], accelerator science has undergone continuous development, leading to significant improvements in performance and efficiency. Modern large-scale facilities, such as the Large Hadron Collider (LHC), enable researchers to investigate fundamental particles, test the Standard Model, and explore physics beyond established theories. In parallel, accelerator technologies have transformed photon science through the development of synchrotron light sources and X-ray free-electron lasers (XFELs), which provide intense and ultrashort radiation pulses [2]. These sources have enabled time-resolved studies of dynamic processes in biology, chemistry, and condensed matter physics [3]. Despite these advances, the scalability of conventional accelerators is fundamentally limited by the maximum achievable electric field gradient in radio-frequency cavities, which is constrained by electrical breakdown [4]. As a result, accelerators designed to reach TeV energies often require kilometer-scale infrastructures, leading to high construction and operational costs. To overcome these limitations, Tajima and Dawson proposed in 1979 [5] the concept of plasma-based acceleration, in which ultrahigh electric fields are sustained in a plasma medium using intense laser pulses. In this scheme, the ponderomotive force of the laser displaces

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plasma electrons and excites relativistic plasma waves capable of accelerating charged particles with gradients orders of magnitude higher than those of conventional accelerators. The first experimental demonstrations of laser-driven plasma acceleration relied on externally injected electrons, which were accelerated by GV/m fields through beat-wave excitation or the early laser wakefield scheme [6–8]. Beam quality was initially poor because the electron bunches were much longer than the plasma wavelength, resulting in low capture efficiency. A breakthrough came in 1994 at the Rutherford Appleton Laboratory, where the relativistic wave-breaking limit was observed with accelerating fields of several hundred GV/m, producing energetic electron beams through the self-modulated laser wakefield (SM-LWF) regime [9–11]. These beams exhibited broad, quasi-thermal distributions characteristic of uncontrolled injection. Subsequent progress focused on improving beam quality. Experiments with compact, high-repetition-rate laser systems demonstrated the strong dependence of electron energy on plasma density, confirming the laser wakefield mechanism. In the early 2000s, controlled injection methods, such as the forced laser wakefield regime, enabled the production of quasi-monoenergetic beams with energies up to a few hundred MeV and significantly reduced divergence [2]. These advances marked the transition from proof-of-principle demonstrations to the precision control of injection dynamics, essential for generating beams suitable for applications. In the past two decades, the field has advanced rapidly with the advent of petawatt-class lasers, enabling multi-GeV electron beams from centimeter-scale plasmas [12–15]. Key innovations include bubble (or blowout) regime acceleration, where an intense laser pulse expels electrons completely, creating a nearly spherical ion cavity that traps and accelerates electrons to high energies with narrow energy spreads [16–20]. Controlled injection techniques such as colliding pulse injection [21,22], ionization-induced injection [23–25], density transition injection [26,27], and shock-front injection [28–30] have further improved beam stability and quality. Recent breakthroughs include the staging of multiple plasma accelerators, the demonstration of sub-10-femtosecond electron bunches, and the integration with advanced plasma optics for guiding laser pulses over long distances [31–33]. LWFA-driven beams have already been applied to generate bright betatron [34] and Compton-scattered X-rays [35], compact free-electron lasers [36], and ultrafast electron diffraction sources [37]. With ongoing development of high-repetition-rate laser systems and machine learning-based optimization, LWFA is increasingly seen as a pathway toward compact next-generation accelerators for both fundamental science and real-world applications such as medical radiotherapy and non-destructive imaging. In order to realize these applications, the central challenge remains the precise control of injection and acceleration dynamics, ensuring that electron bunches are much shorter than the plasma wavelength and occupy only a small region of phase space. Addressing these challenges continues to drive innovation in LWFA research, positioning plasma-based accelerators as one of the most promising candidates to complement or even replace conventional accelerator technology in the coming decades. This study employs bibliometric analysis as the primary approach to systematically investigate the scientific landscape of LWFA. By leveraging bibliometric tools, the research seeks to map the evolution of LWFA, identify emerging trends, and highlight potential future directions in the field. Bibliometric analysis serves as a robust methodological tool for uncovering research trends, intellectual structures, and emerging areas of interest within a particular scientific domain [38–42]. Widely applied in scientometrics and information science, it allows researchers to assess the evolution of knowledge production through quantitative examination of published literature. By employing mathematical, statistical, and visualization techniques, bibliometric studies not only provide a macro-level overview of scholarly output but also highlight the dynamics of collaboration, influence, and impact within the research community.

In this study, we focus on the global scientific literature on LWFA from 1990 to 2025. By integrating scientometric mapping and content analysis, the research aims to provide a holistic understanding of the developmental trajectory of LWFA. The advantages of bibliometric approaches lie in their ability to identify leading authors, influential journals, productive institutions, and active countries, as well as to trace patterns of international collaboration. Moreover, bibliometric methods facilitate the detection of "hot topics," citation impact, and thematic evolution, thereby offering valuable indicators for anticipating future research directions. The outcomes of this analysis are expected to assist both new and established researchers in navigating the LWFA field more effectively, recognizing knowledge gaps, and positioning their work strategically within the broader scientific landscape.

2. Materials and Methods

In this study, bibliometric data were retrieved on 30 September 2025, from Clarivate Analytics' Web of Science (WoS) database, one of the most comprehensive and authoritative sources of scholarly records. WoS enables researchers to track diverse focus areas across nearly 1.9 billion cited references contained in more than 171 million indexed publications [43–45]. To capture the global research landscape on LWFA, the initial dataset was extracted using the following search query: topic search (TS) = ("laser wakefield acceleration" OR "LWFA" OR "laser-plasma accelerator"). Here, "TS" identifies the keywords within titles, abstracts, author keywords, and keywords plus. To ensure a comprehensive overview of research activities, no restrictions were placed on document type; thus, journal articles, conference papers, reviews, and proceedings were all included in the dataset. This initial search yielded 3199 publications. To refine the dataset and focus specifically on LWFA, we restricted our analysis to relevant WoS categories, including but not limited to: Physics, Applied Physics, Laser Physics, Plasma Physics, Optics, Multidisciplinary Physics, Instruments & Instrumentation, Engineering Electrical Electronics, and Materials Science Multidisciplinary. After excluding duplicates and documents unrelated to LWFA, a final dataset of 3177 records was obtained. These records were exported in plain text format to serve as input to bibliometric analysis tools. Bibliometric analysis combines quantitative techniques and statistical measures to provide insights into the structure and evolution of scientific fields [46]. In this study, we conducted performance analyses (e.g., publication output, citation counts, h-index), science mapping (e.g., co-authorship, co-occurrence), and network visualization to identify research dynamics and collaboration patterns. For this purpose, we employed the Bibliometrix R-tool (version 3.2.1) [47], a comprehensive package for advanced bibliometric and scientometric analyses. The use of Bibliometrix allowed us to enrich our study with co-word analysis, author collaborations, bibliographic coupling, and citation networks. In addition to conventional bibliometric indicators, this study adopts an AI-assisted analytical framework through the use of advanced computational algorithms embedded in Bibliometrix, VOSviewer, and CiteSpace. These platforms employ automated text-mining procedures, keyword normalization and filtering, co-word clustering, community detection, and network optimization techniques to identify latent thematic structures and emerging research trends. No explicit language restrictions were imposed during the initial database query. However, because the Web of Science database predominantly indexes English-language publications in the field of plasma and accelerator physics, the final dataset consists almost entirely of English-language records. Non-English records, when present, were retained provided that sufficient bibliographic information was available for analysis. All document types retrieved from the database, including journal articles, conference proceedings, review papers, and technical reports, were included without applying differential weighting. Each record was treated as one unit in the bibliometric analysis in order to avoid introducing subjective bias and to preserve the original structure of the scientific output. Citation-based indicators were used separately to assess impact and influence. During subject category filtering, records belonging to clearly relevant Web of Science categories (e.g., Plasma Physics, Applied Physics, Optics, Accelerator Science) were retained automatically. For publications classified under borderline or multidisciplinary categories, a manual screening procedure was applied based on titles, abstracts, and keywords to ensure direct relevance to laser wakefield acceleration. Records that did not primarily address LWFA-related physics, technology, or applications were excluded. This multi-step filtering strategy was designed to balance dataset completeness with thematic specificity, thereby enhancing the reproducibility and reliability of the analysis. Also, citation burst detection and temporal trend analyses are performed using algorithmic pattern-recognition methods, enabling the extraction of dynamic research fronts from large-scale bibliographic data. Although no user-trained machine learning model is implemented, these data-driven and AI-inspired techniques significantly enhance the efficiency, objectivity, and depth of the scientometric analysis. To further analyze content structures and detect thematic clusters, we used CiteSpace (version 6.3.R1) [48] and VOSviewer (version 1.6.20) [49]. CiteSpace provided temporal and structural mapping of the LWFA knowledge domain, allowing us to identify collaboration networks, author co-citations, and temporal bursts of keywords [50]. Meanwhile, VOSviewer enabled the visualization of bibliometric networks involving authors, institutions, countries, and thematic keywords through co-authorship, co-occurrence, and co-citation analyses. A schematic workflow of the methodology is presented in Figure 1. Furthermore, to capture the temporal evolution of research trends in LWFA, we performed a keyword temporal trend analysis following the approach of Zhu et al. [51]. Specifically, the dataset covering the period 2000–2025 was divided into two intervals: 2000–2019 (emergence and early development) and 2020–2025 (rapid growth and consolidation). Keywords showing significant increases in frequency during the recent period were identified as “emerging” or “hot” topics, while those with declining frequency were categorized as diminishing themes. The trend keyword indicator was calculated using the following equations [51]:

$$F_{yrs} = \frac{\sum_{yr=i}^{j} f_{yrs}}{\sum_{yr=i}^{j} N_{yrs}} (\text{if } i \neq j) = \frac{f_i}{N_i} (\text{if } i = j) \tag{1}$$

$$F_{past} = 1000 \times \frac{\sum_{2000}^{2019} f_{yrs}}{\sum_{2000}^{2019} N_{yrs}} \text{ and } F_{current} = 1000 \times \frac{\sum_{2020}^{2025} f_{yrs}}{\sum_{2020}^{2025} N_{yrs}} \tag{2}$$

$$\text{trend factor} = \log\left(\frac{F_{current}}{F_{past}}\right) \tag{3}$$

where F_{yrs} represents the normalized cumulative keyword frequency, f_{yrs} is the keyword frequency, and N_{yrs} indicates the number of papers. In addition, F_{past} and $F_{current}$ stand for the past or current normalized cumulative keyword frequencies per 1000 papers in the past or current period, respectively.

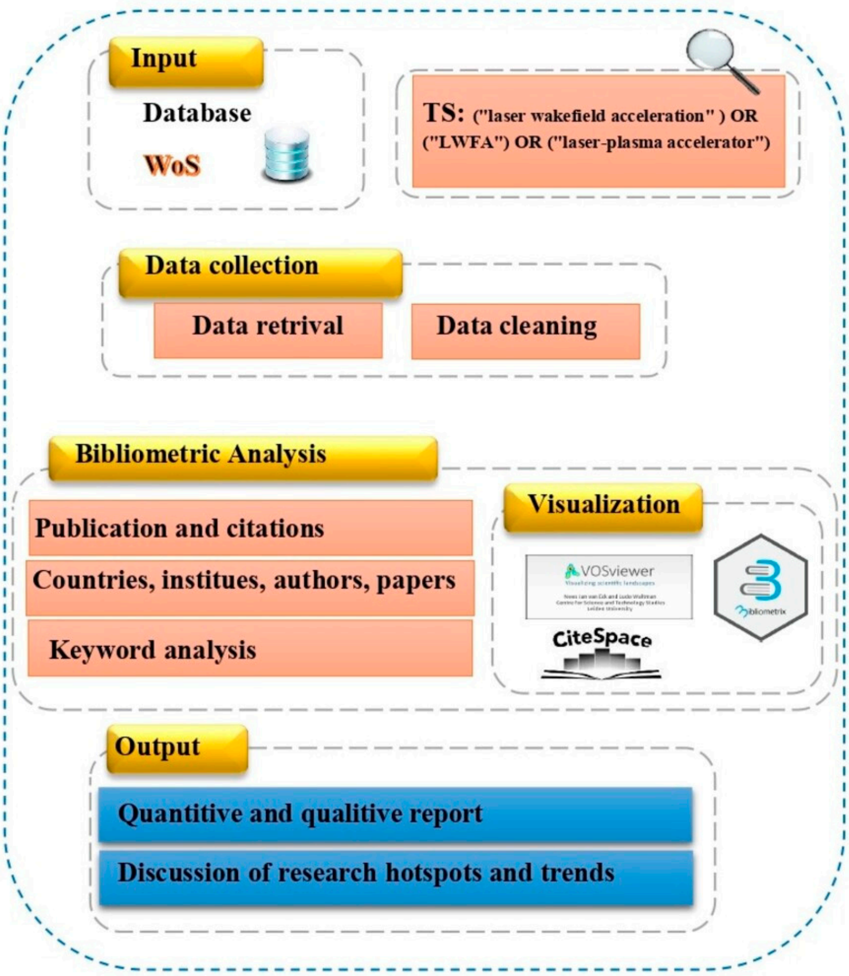

Figure 1. A scheme of document collection and bibliometric analysis.

3. Results and Discussions

3.1. Spatiotemporal Publications and Citations Trends

Figure 2 illustrates the distribution of publications and their citations on LWFA over the years. It clearly shows the progressive growth of research output and its scientific impact over more than three decades. In the early 1990s, both the number of publications and the number of citations remained very low, reflecting the nascent stage of LWFA research. A noticeable increase begins around the late 1990s and early 2000s, coinciding with advancements in high-power laser technology and experimental breakthroughs in plasma-based accelerators. From 2005 onwards, the number of publications oscillated, surpassing 100 per year by the end of the 2000s. This period also corresponds to a rapid increase in citations, suggesting that LWFA had started to attract significant attention in the broader scientific community. Between 2010 and 2020, the field experienced a sustained surge in both productivity and impact. Annual publications consistently fluctuate between 110 and more than 200 papers, while citations reach several thousand per year. This indicates not only the maturity of LWFA research but also its integration into diverse applications, including compact accelerators, medical physics, and radiation sources. Citation peaks around 2016 and 2018 indicate that highly influential works were published during those years. In the most recent years (2021–2024), publications remain high, with more than 120 papers annually, while citations and publications reached their maximum in 2018, exceeding 200 and 5500, respectively. The slight decrease in 2025 is likely due to the ongoing year and incomplete data collection at the time of research (30 September 2025). Overall, the trend highlights the growing importance of LWFA as a cornerstone of advanced accelerator research, with both sustained scientific output and increasing recognition across the physics community.

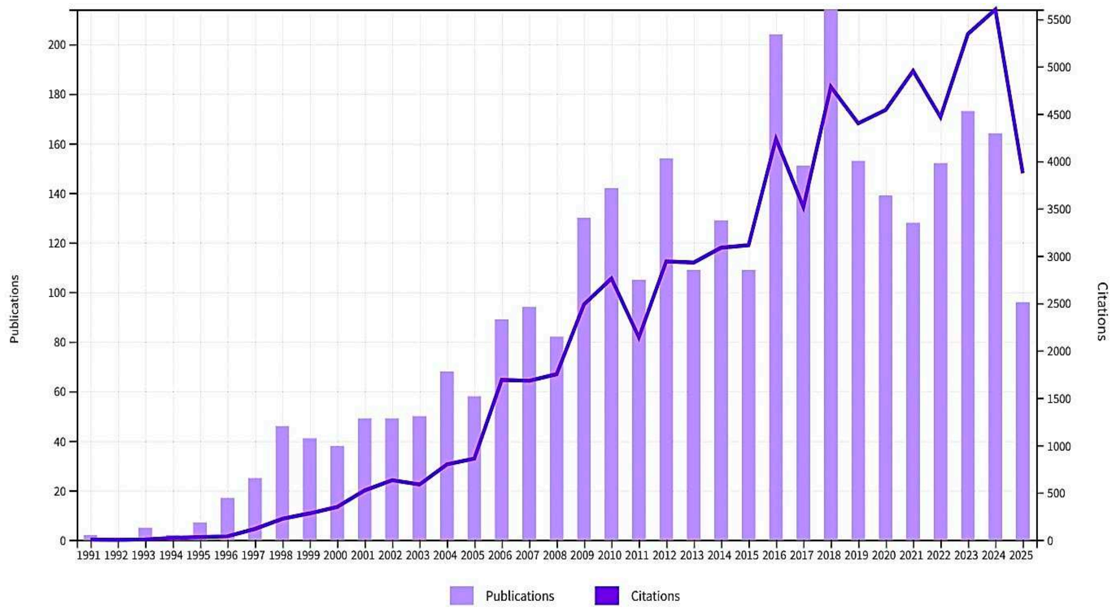

Figure 2. Annual distribution of publications and citations in LWFA.

Table 1 presents the top 15 most productive countries in LWFA research, showing both productivity and impact through total publications (TP), total citations (TC), and average number of citations (ANC). The US clearly dominates the field, contributing 824 publications (26.2%) and accumulating over 27,567 citations, with an average citation per paper of 33.46. This indicates not only the highest research volume but also consistently high-quality output with strong international influence. China ranks second with 466 publications (14.8%), but despite its strong productivity, the country's average citation rate (12.20) is relatively low, suggesting that while China is rapidly expanding in LWFA, the global impact of its publications is still catching up with that of leading Western countries. Germany and France rank third and fourth in terms of output, with 258 and 239 publications, respectively, but their average citations (36.17 and 42.22) are significantly higher, placing them among the most impactful contributors. Similarly, the UK (192 publications, 39.11 citations per paper) demonstrates a strong influence, despite fewer publications compared to China and Japan. This underlines that European countries have maintained a reputation for producing highly cited, influential works in LWFA research. Japan contributes 205 papers (6.5%) but has a modest average citation count (16.02), reflecting solid but less impactful research compared to European leaders. Among emerging contributors, India (141 papers) and Iran (77 papers) show notable growth, though their citation averages (9.51 and 6.88) remain low, indicating that while their research communities are active, visibility and global recognition are still developing. Interestingly, smaller European nations such as Portugal, Sweden, and the Netherlands, each with only 28 publications, achieve disproportionately high average citations (19.00, 26.18, and 10.46, respectively). This suggests that their contributions, while fewer in number, are strategically significant and attract strong attention in the LWFA community. Overall, the table demonstrates a clear geographical diversity in LWFA research, with the USA leading in both quantity and influence, China emerging as a major contributor with rapid growth but lower impact, and several European countries excelling in research quality and citation performance. This pattern indicates a highly collaborative, globally distributed research field where both established and emerging players contribute to advancing LWFA.

Table 1. Top 15 most productive countries.

Rank	Country	TP		TC	ANC
		No.	%		
1	USA	824	26.2	27,567	33.46
2	China	466	14.8	5686	12.20
3	Germany	258	8.2	9331	36.17
4	France	239	7.6	10,090	42.22
5	Japan	205	6.5	3284	16.02
6	UK	192	6.1	7509	39.11
7	India	141	4.5	1341	9.51
8	Italy	138	4.4	1642	11.90
9	Russia	127	4.0	1875	14.76
10	Korea	106	3.4	1620	15.28
11	Iran	77	2.5	530	6.88
12	Czech Republic	56	1.8	335	5.98
13	Netherlands	28	0.8	293	10.46
14	Portugal	28	0.8	532	19.00
15	Sweden	28	0.8	733	26.18

3.2. Influential Authors and Co-Authorship Network

The analysis of co-authorships is one of the most important scientometric analyses, facilitating the assessment of collaboration trends and the identification of influential authors [52]. Research on LWFA has been contributed by 6581 authors. There are 183 authors of single-authored documents. The number of documents per author is 0.483, while the number of co-authors per document is 7.98. Figure 3 illustrates a co-author network for authors with more than 20 documents and 100 citations. The size of labels and circles varies based on the number of documents. Moreover, the color of an author depends on the cluster he belongs to. The line illustrates the co-authorship link between researchers. Each link has a weight that represents the number of publications two researchers have co-authored. The co-authorship network reveals clear clustering of research communities in the field of LWFA, highlighting several strong collaborative groups. The larger nodes correspond to highly productive authors, often acting as central hubs that bridge multiple clusters and promote cross-institutional cooperation. The density of links indicates that collaboration is a key feature of LWFA research, with many authors contributing jointly to publications rather than working in isolation. Interestingly, the network shows a few dominant clusters in which international collaborations are concentrated, reflecting the global and interdisciplinary nature of LWFA studies. The relatively high number of co-authors per paper (close to eight) reinforces the collaborative character of this field, likely due to the experimental complexity and resource-intensive nature of laser-plasma acceleration research. The visual separation of clusters also indicates specialization, where different groups focus on distinct approaches to achieving LWFA, including theoretical modeling, advanced simulation strategies, and diverse experimental methods. At the same time, inter-cluster connections demonstrate knowledge exchange and scientific synergy, which are essential for driving innovation in LWFA. In fact, the figure not only illustrates the structural backbone of author collaborations but also underscores how collective efforts and network centrality shape the progress of this rapidly advancing research area.

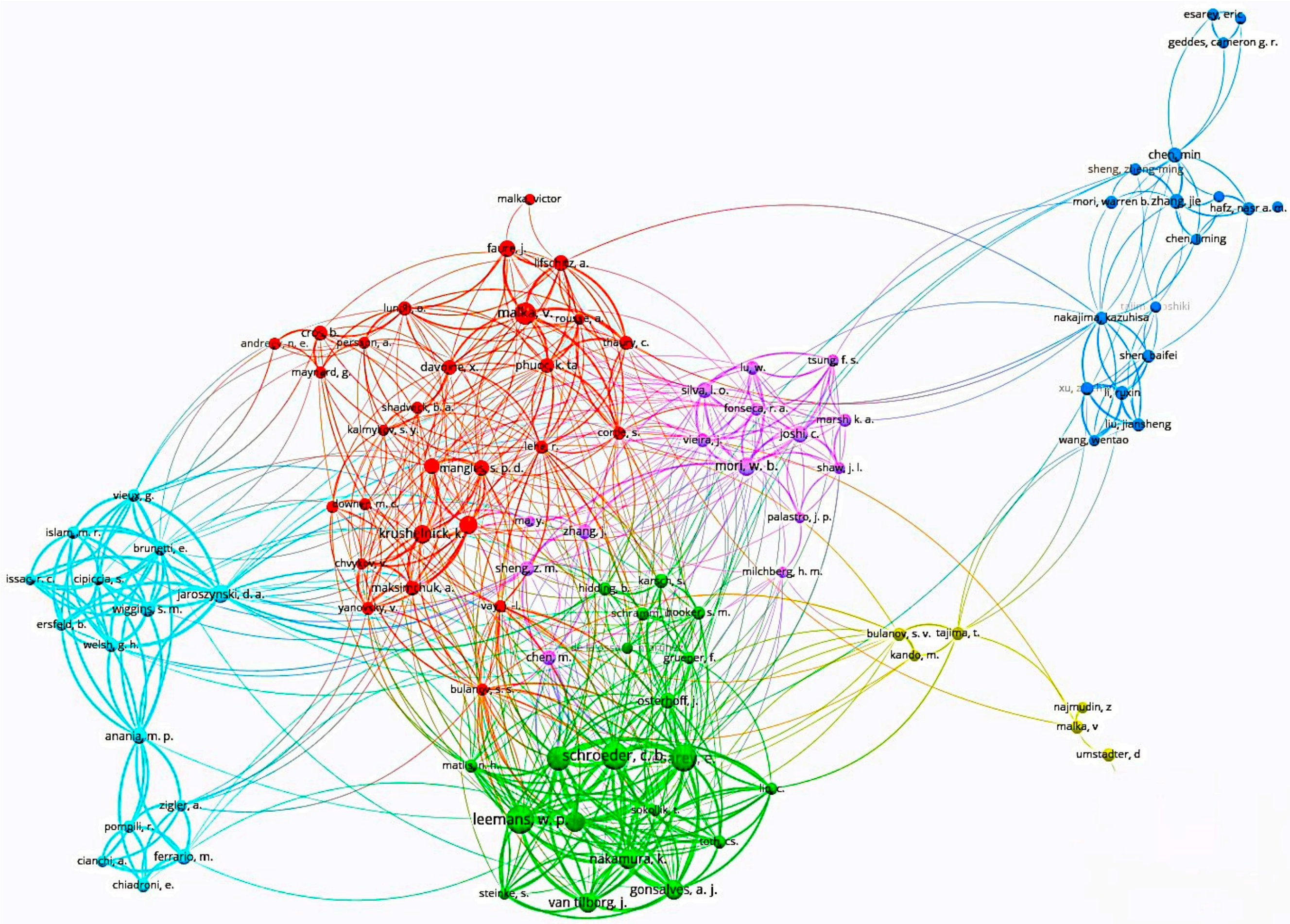

Figure 3. A co-authorship network.

3.3. Prominent Journals

The analysis of journals provides scholars with relevant information about a particular area of research. According to Table 2, the top 10 journals produce the most articles among 446 sources (journals, books, etc.). The distribution of LWFA publications across journals reveals both the multidisciplinary nature of the field and the concentration of impactful work in a few specialized outlets. Physics of Plasmas stands out as the most productive journal, publishing 306 papers (9.6% of 3177 articles), underscoring its central role as a dedicated platform for plasma-related research. However, Physical Review Letters (141 articles, 4.4%) achieves the highest scientific impact, with an impressive total citation (11,203) and the largest H-index (62), reflecting its position as the leading venue for disseminating groundbreaking results. Plasma Physics and Controlled Fusion (149 papers, 4.6%) also contributes significantly, balancing productivity and visibility, while Physical Review Accelerators and Beams and Physical Review E serve as important outlets for more specialized theoretical and experimental advances. Among multidisciplinary journals, Scientific Reports and New Journal of Physics provide alternative platforms that broaden the visibility of LWFA research beyond the core plasma physics community, with their relatively high impact factors (3.9 and 2.8, respectively). Laser and Particle Beams and Nuclear Instruments & Methods A: Accelerators, Spectrometers, Detectors and Associated Equipment highlight the strong engineering and instrumentation aspects of LWFA, reflecting the close ties between laser technology development and experimental progress. Although Applied Physics Letters has the lowest share of publications (1.1%), its comparatively high impact factor (3.6) indicates that papers published there can achieve wide influence. Also, the table suggests that while highly specialized plasma physics journals dominate publication volume, high-impact general physics journals such as Physical Review Letters play a critical role in amplifying the visibility of pioneering LWFA research. This dual structure demonstrates that the field not only thrives within its core community but also achieves recognition in broader scientific forums, thereby accelerating the dissemination and adoption of LWFA findings across multiple disciplines.

Table 2. Prominent journals.

Rank	Journal	TP		TC	H Index	IF	Initial Year
		No.	%				
1	Physical Review Letters	141	4.4	11,203	62	9.0	1993
2	Physics of Plasmas	306	9.6	7502	44	2.2	1996
3	Physical Review Accelerators and Beams	79	2.4	3269	32	1.8	2000
4	Physical Review E	66	2.1	2110	27	2.4	1997
5	Plasma Physics and Controlled Fusion	149	4.6	2904	26	2.3	1996
6	Scientific Reports	67	2.1	1558	23	3.9	2013
7	New Journal of Physics	58	1.8	1502	21	2.8	2006
8	Laser and Particle Beams	67	2.1	1371	20	1.9	1995
9	Nuclear Instruments & Methods in Physics Research Section A	179	5.6	1779	20	1.16	1996
10	Applied Physics Letters	34	1.1	1024	19	3.6	1999

3.4. Prominent Articles

The analysis of papers assists scholars in identifying the most cited and influential papers in a specific field [53]. Citations often indicate the attention and interest paid to important publications. Table 3 lists the top 10 highly cited papers. In addition to reporting total citations (TC) and citations per year, this study employs the normalized total citation (NTC) indicator to enable temporally balanced comparison across publication years. Because older publications have had more time to accumulate citations, direct comparison of raw citation counts may bias the analysis in favor of earlier works. To address this limitation, the normalized total citation (NTC) is defined as the ratio between the total citation count of a given article and the average citation count of all LWFA-related publications published in the same year. Mathematically, for article i published in year y, NTC is expressed as:

$$NTC_i = \frac{TC_i}{\overline{TC_y}} \tag{4}$$

where TC_i is the total citation count of article i, and $\overline{TC_y}$ denotes the mean citation count of all documents in the dataset published in year y. This normalization reflects how many times an article performs relative to the average citation level of its publication cohort. An NTC value greater than 1 indicates above-average impact within its year, while larger values indicate stronger relative influence. The set of papers listed in Table 3 confirms two complementary narratives in the bibliometrics of LWFA: historically foundational works that accumulate the largest absolute citation totals, and relatively younger or context-outperforming papers that emerge as especially influential once citation counts are normalized. In absolute terms, Esarey (2009, Rev. Mod. Phys.) [54] is the most cited paper (TC = 2080) and also leads in citations per year (122.4), reflecting its role as the field's comprehensive review and long-lived reference. However, when the normalized total citation (NTC) index is applied, the ranking changes substantially: Daido (2012, Rep. Prog. Phys.) [55] and Lu (2007, Phys. Rev. Spec Top-Ac) [56] rise to the top (NTC = 32.31 and 30.16, respectively), and Leemans (2006, Nat. Phys.) [57] also scores highly on the normalized metric (NTC = 22.84). These NTC values indicate that, relative to the normalization baseline used in the dataset, Daido and Lu substantially outperform expectations for their publication cohorts despite having lower raw totals than Esarey (2009) [54]. The three near-simultaneous experimental breakthroughs published in Nature in 2004 (Faure, Geddes, Mangles) remain prominent both in raw counts (TC ≈ 1800–1944) and in normalized impact (NTC ≈ 17.6–18.8), which confirms their status as watershed experimental demonstrations that changed the trajectory of LWFA research. By contrast, Esarey's classic theoretical and review contributions (for example Esarey 1996 [58] and Esarey 2009 [54]) show a divergence between absolute and normalized indicators: the 2009 review has the highest raw influence but a relatively modest NTC (2.023), suggesting that the normalization procedure in this dataset moderates the advantage of broad, highly cited review articles (that it emphasizes relative performance within more narrowly defined publication cohorts). Taken together, the joint use of TC, TC per year, and NTC provides a more nuanced portrait than any single metric. Raw TC and TC/year identify historically central and sustained influence, whereas NTC reveals papers that have performed exceptionally well relative to contemporaneous expectations (for example, Daido 2012 [55] and Lu 2007 [56]). This dual perspective is particularly useful for distinguishing papers that are canonical because they accumulated citations over many years from those that are comparatively overperforming in their time or subfield and therefore may better indicate emerging or concentrated impact. Practically, the bibliometric interpretation should, therefore, report both raw and normalized indicators: cite-counts to document historical reach, and NTC to highlight above-expected performance within the publication context. A brief methodological caveat: two entries in the table (Esarey 1996 [58] and Pukhov 2002 [59]) display citation totals with decimal formatting (TC = 12.65 and TC = 10.82), which is likely a formatting or import error (they plausibly represent 1265 and 1082 citations).

Table 3. Prominent papers.

Author & Journal	DOI	TC	TC per Year	NTC
Esarey E, 2009, Rev Mod Phys [54],	10.1103/RevModPhys.81.1229	2080	122.4	2.023
Faure J, 2004, Nature [60]	10.1038/nature02963	1944	88.4	18.84
Geddes CGR, 2004, Nature [61]	10.1038/nature02900	1863	84.7	18.05
Mangles SPD, 2004, Nature [62]	10.1038/nature02939	1817	82.6	17.61
Leemans WP, 2006, Nat Phys [57]	10.1038/nphys418	1599	80.0	22.84
Esarey E, 1996, IEEE T Plasma Sci [58]	10.1109/27.509991	12.65	42.2	7.62
Pukhov A, 2002, Appl Phys B [63]	10.1007/s003400200795	10.82	45.1	21.79
Daido H, 2012, Rep Prog Phys [55]	10.1088/0034-4885/75/5/056401	879	62.8	32.31
Lu W, 2007, Phys Rev Spec Top-Ac [56]	10.1103/PhysRevSTAB.10.061301	831	43.7	30.16
Faure J, 2006, Nature [64]	10.1038/nature05393	767	38.4	10.95

3.5. Keyword Analysis

3.5.1. Author Keywords Occurrence

An appropriate keyword is a critical factor in determining the mechanism and effectiveness of the document search [65]. Figure 4 illustrates the network and overlay visualization of author keywords co-occurrence network, analyzed using VOSviewer software. The size of the label and the circle of an item are determined by occurrence. In addition, the closer two keywords are located to each other, the stronger their relatedness. The keyword analysis provides valuable insight into the research structure and evolving directions in LWFA. In the cluster visualization (Figure 4A), the co-occurrence network clearly separates into distinct groups of keywords, each representing a thematic focus of the field. Larger nodes, such as laser wakefield acceleration, ionization injection, electron acceleration, and laser-plasma accelerator, highlight their dominant role, serving as foundational concepts that connect across multiple clusters. The spatial proximity of terms such as undulator, free-electron laser, synchrotron radiation, and X-ray indicates strong interconnections, suggesting that recent studies are increasingly linking injection schemes to secondary radiation sources. Furthermore, peripheral clusters involving machine learning or applications illustrate emerging interdisciplinary directions. The timeline view (Figure 4B) demonstrates the chronological development of keyword prominence. Early research focused on fundamental physics, with keywords such as plasma waves, laser–plasma interaction, and relativistic electrons, reflecting the groundwork of LWFA theory and the initial experimental demonstrations. Over time, new terms such as electron energy gain, beam dynamics, direct laser acceleration, plasma wakefield acceleration (PWFA), and magnetic field emerged, showing the transition from conceptual development to practical optimization and application-driven research. Notably, the increasing appearance of keywords associated with ionization injection and particle-in-cell simulation underscores the maturation of computational methods and advanced injection techniques as central drivers of current progress. Together, these analyses reveal that LWFA research is no longer confined to proof-of-principle studies but is expanding toward applied and cross-disciplinary domains. The clustering highlights the thematic breadth of the field, while the timeline visualization captures its dynamic evolution, showing both the persistence of core physics topics and the rise of innovative directions that shape its future trajectory.

(A)

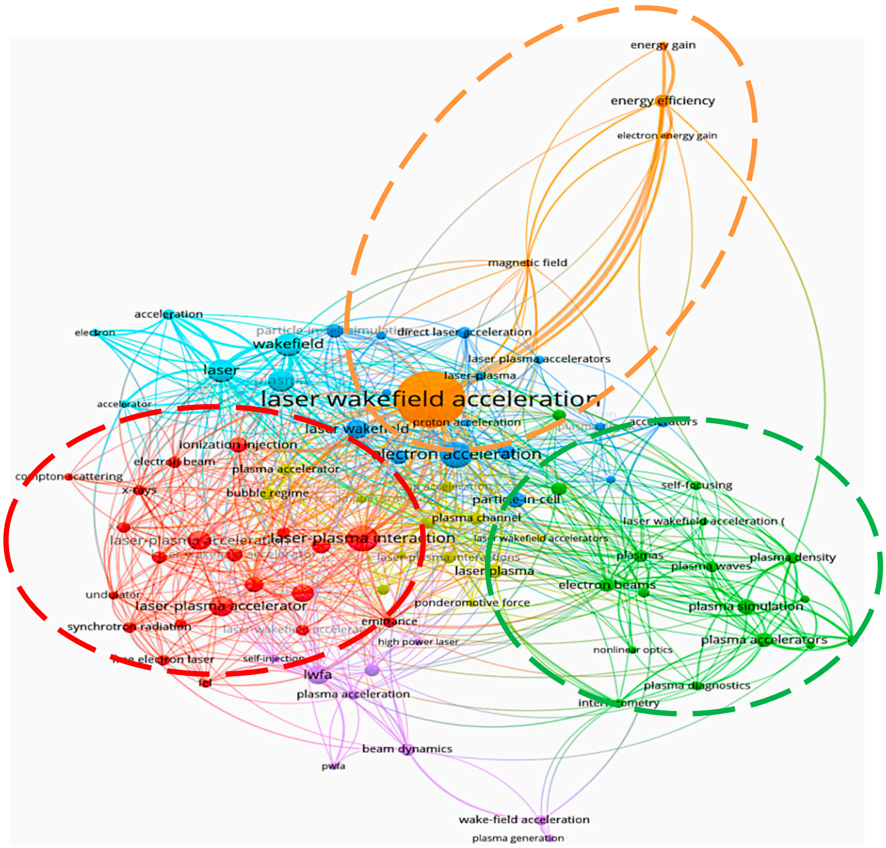

Figure 4. *Cont.*

(B)

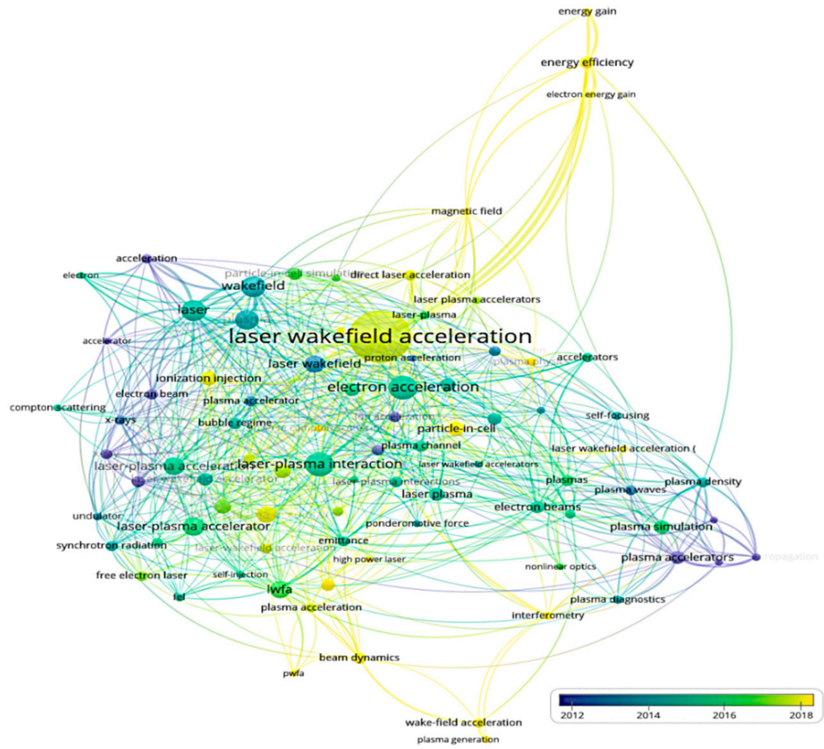

Figure 4. (**A**) Clusters and (**B**) timeline of the author keywords.

3.5.2. Frequency and Trend Analysis of Keywords

Figure 5 maps the temporal dynamics of the 1000 most frequent keywords in LWFA-related publications over (2000–2025), using the trend factor defined in Equations (1)–(3). Keywords plotted in the upper-left quadrant and rendered in green denote terms whose use has accelerated in the most recent interval (2020–2025) relative to earlier years; their position above and to the left of the diagonal therefore signals both a high recent growth rate and greater regency. Conversely, keywords located on or below the diagonal, especially those on the right side, reflect topics whose relative prominence has declined or matured since the early period of the dataset. In fact, the spatial clustering and color coding in Figure 5 make two points clear for the LWFA field: (1) a noticeable cohort of emergent topics is driving current research momentum (these appear as compact green clusters in the upper-left), indicating the field is actively evolving rather than stagnating; (2) a set of long-established themes persists (points near the diagonal or lower-right), reflecting foundational concepts that remain frequently cited but show limited recent growth. Taken together, these patterns indicate a healthy disciplinary balance between consolidation of core knowledge and rapid growth in newer subareas. It also should be noted that methodological caveats that can temper interpretation are that the trend factor is sensitive to the temporal window (so bursts that begin after the end of our window will be missed), synonymous keywords or differing phraseologies can split signals (e.g., "ionization injection" vs. "ionization-induced injection"), and very general terms (e.g., "laser", "electron") can dominate counts without indicating conceptual novelty.

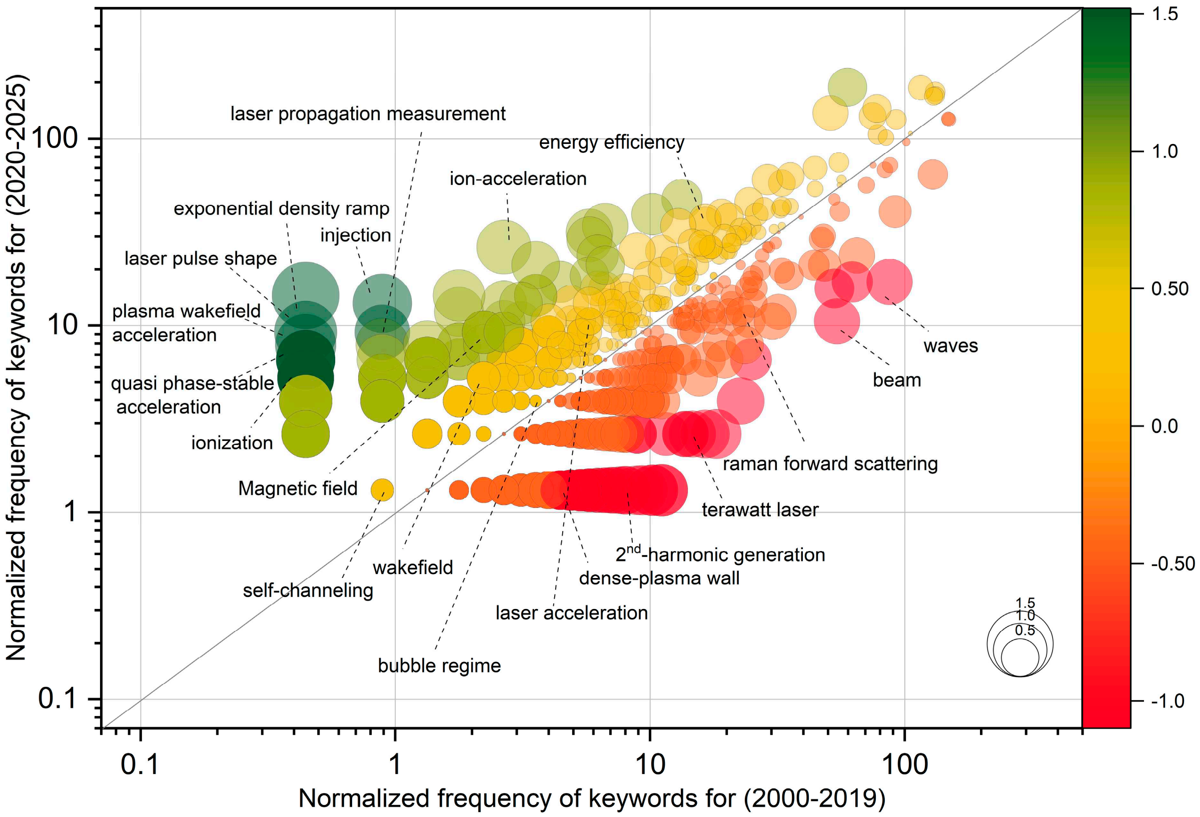

Figure 5. Distribution of the temporal trend of the popular keywords during (2000–2025).

3.5.3. Detecting Hot Terms Using Citation Burst

To identify hot keywords in this research area, we used the Citation Burst Index [54] in CiteSpace. Citation burst refers to the detection of a burst event over multiple years, as well as over one year. A citation burst reveals keywords with high frequency during specific periods, indicating research trends and hotspots [66]. In this section, burst detection refers to keywords that have attracted considerable attention from other scholars. Figure 6 displays the keywords with the strongest recent citation bursts (i.e., 2015–2025) after removing similar and unrelated ones. The red line indicates the time span with the strongest citation burst. In fact, the keyword burst analysis presented in Figure 6 provides a clear visualization of how research priorities in LWFA have evolved over the past decade. The red segments indicate periods when certain terms attracted sudden and significant attention, reflecting emerging hotspots within the community. Early bursts are associated with foundational topics such as plasma waves and laser-driven acceleration, which established the conceptual framework of the field. In contrast, more recent bursts correspond to advanced themes including ionization injection, betatron radiation, and ultrashort pulse lasers, highlighting the community's transition toward refined injection mechanisms, secondary radiation sources, and compact accelerator applications. The sequential appearance of these bursts underscores how LWFA has moved from proof-of-principle demonstrations to the exploration of high-quality beams and secondary sources, mapping a trajectory of scientific maturity. The temporal distribution of bursts in Figure 6 also reveals an important distinction between sustained and transient research fronts. Long-lasting bursts, such as those related to plasma density and laser pulse duration, indicate enduring research challenges that continue to underpin experimental and theoretical progress. Conversely, short but intense bursts, for example, those linked to novel injection schemes or dual-stage acceleration, point to fast-rising topics that generate immediate attention but may later merge into broader research themes. This pattern reflects both the steady progression of fundamental parameters critical to LWFA optimization and the periodic emergence of innovative ideas that briefly dominate the literature before stabilizing. Such insights help identify not only the main directions pursued by the community but also the points of transition where new paradigms have been introduced. Closer inspection of the bursts allows one to associate them with landmark achievements in the field. For instance, the onset of bursts related to ionization injection corresponds with the publication of pivotal experimental demonstrations in the early 2016s, which enabled stable production of high-charge electron beams. These correlations emphasize that burst detection is not merely a bibliometric artefact, but a reflection of genuine scientific progress driven by technological breakthroughs and influential publications. By linking bursts to specific milestones, the analysis transforms raw data into a coherent narrative of LWFA's scientific development. Keywords such as multi-pulse drivers, dual-stage acceleration, and machine learning signify a shift toward strategies that enhance beam quality, extend acceleration length, and integrate computational optimization. The relatively short but intense nature of these bursts suggests that these topics are still in a rapid growth phase, likely to shape the next generation of LWFA experiments and applications. Monitoring the continuation or decline of these bursts in subsequent years will be essential for forecasting the stability of these trends and identifying which directions will crystallize into long-term research programs.

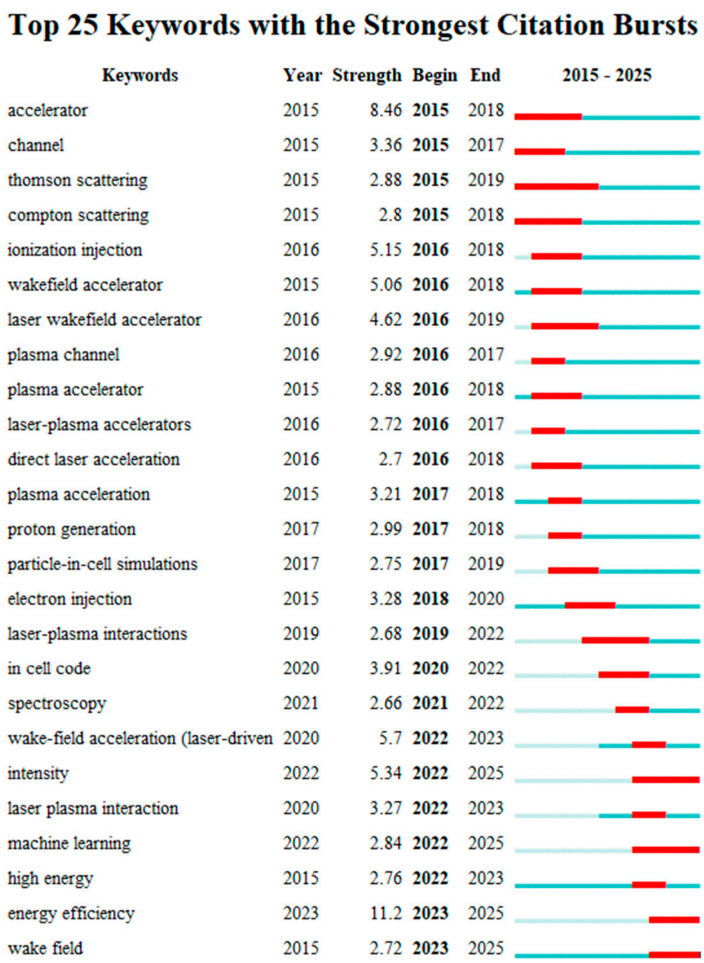

Figure 6. Top recent keywords with the strongest citation bursts during 2015–2025.

The temporal evolution of keywords and thematic clusters revealed in Figures 4–6 closely reflects the major technological milestones in the development of laser wakefield acceleration. In the early and mid-2000s, the increasing prominence of terms such as "bubble regime," "blowout," and "self-injection" corresponded to the experimental demonstration of highly nonlinear wakefields and the realization of quasi-monoenergetic electron beams. This period marks the transition from self-modulated and beat-wave acceleration toward stable single-bubble operation, which became the foundation for high-quality beam generation. Subsequently, the growing appearance of keywords related to “multi-stage acceleration,” “dual-stage,” “staging,” and “plasma guiding” reflects efforts to overcome dephasing and depletion limits through cascade and staged acceleration schemes. These developments enabled sustained energy gain over extended distances and facilitated the production of multi-GeV electron beams using compact plasma structures. In more recent years, the emergence of terms such as “machine learning,” “artificial intelligence,” “optimization,” and “adaptive control” indicates a paradigm shift toward data-driven approaches for stabilizing laser–plasma interactions. These methods aim to mitigate shot-to-shot fluctuations, optimize injection conditions, and improve beam reproducibility in increasingly complex experimental configurations. The keyword burst analysis further demonstrates that bursts associated with ionization injection, ultrashort pulse lasers, and betatron radiation coincide with landmark experimental achievements that expanded the functionality of LWFA systems toward secondary radiation sources and compact light facilities. This evolution illustrates the progressive integration of LWFA with applied photonics and radiation science. Despite these advances, the bibliometric trends also reveal persistent research bottlenecks that continue to shape the field. High-frequency keywords related to “energy spread,” “emittance,” “stability,” and “laser contrast” indicate ongoing challenges in controlling beam quality and reproducibility. Furthermore, the limited growth of terms associated with high-repetition-rate operation and long-term reliability reflects technological constraints imposed by laser system durability, thermal management, and target replenishment. Another major bottleneck concerns the efficient coupling of laser energy into plasma waves under realistic experimental conditions, particularly in complex geometries involving tailored density profiles and advanced plasma optics. In addition, scaling LWFA toward practical applications remains hindered by synchronization issues in multi-stage configurations and by the sensitivity of injection mechanisms to environmental fluctuations. Overall, the integration of keyword evolution with technological milestones and persistent challenges provides a comprehensive perspective on the maturation of LWFA research. The field has progressed from proof-of-principle demonstrations to sophisticated, application-oriented systems, while current efforts increasingly focus on achieving stability, scalability, and reliability. These trends suggest that future breakthroughs will likely arise from the synergistic combination of advanced laser technologies, precision plasma engineering, and AI-assisted optimization strategies.

4. Conclusions

This bibliometric analysis provides a comprehensive overview of the evolution, productivity, and intellectual structure of global LWFA research from 1990 to 2025. The results reveal an accelerating pace of development characterized by sustained growth in publication output, strong international collaboration networks, and increasing interdisciplinary integration between plasma physics, laser science, and accelerator technology. Highly cited publications and leading research nations reflect both historical leadership and the expanding participation of emerging research centers worldwide. Thematic and temporal analyses demonstrate a clear transition from early theoretical and proof-of-principle studies toward application-oriented research emphasizing beam quality, stability, and scalability. The growing prominence of keywords related to multi-stage acceleration, advanced injection schemes, and data-driven optimization highlights the field’s shift toward complex, integrated accelerator architectures. Based on the identified research trends, several specific challenges and future directions emerge. Beam matching and phase-space preservation in multi-stage and cascade acceleration systems remain critical bottlenecks, as imperfect coupling between stages leads to emittance growth and energy spread degradation. Addressing these issues will require coordinated advances in plasma tailoring, beam diagnostics, and transport optics. Also, the increasing appearance of machine learning and artificial intelligence-related keywords reflects a growing interest in real-time parameter optimization and adaptive experimental control. Future research is expected to focus on the development of robust AI-assisted feedback systems capable of operating under realistic experimental conditions, enabling improved stability, reproducibility, and operational efficiency. Additionally, the successful translation of LWFA toward practical applications depends on the synergistic development of high-repetition-rate laser systems, advanced plasma lenses, and long-distance guiding structures. Improving laser durability, thermal management, and target replenishment, while simultaneously enhancing plasma-based focusing and transport, will be essential for achieving high-average-power and user-oriented accelerator platforms. In addition, further progress will require continued efforts to reduce shot-to-shot fluctuations, control injection dynamics, and enhance laser–plasma coupling efficiency in complex geometries. The integration of precision plasma engineering with advanced diagnostics and computational modeling will play a key role in overcoming these limitations. Generally, the combined bibliometric and thematic evidence indicates that LWFA research is entering a phase of technological consolidation, in which stability, scalability, and reliability are becoming as important as peak performance. The convergence of high-power laser technology, plasma-based optics, and AI-assisted optimization is likely to define the next generation of compact accelerator systems. As these challenges are addressed, LWFA is poised to play a central role in future light sources, ultrafast science, medical applications, and next-generation accelerator infrastructures.

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Abbreviations

The following abbreviations are employed in this manuscript:

LWFA	Laser Wakefield Acceleration
WoS	Web of Science
AI	Artificial Intelligence
LHC	Large Hadron Collider
XFELs	X-ray Free-Electron Lasers
SM-LWF	Self-Modulated Laser Wakefield
TS	Topic Search
TP	Total Publications

ANC	Average Number of Citations
PWFA	Plasma Wakefield Acceleration

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