ACCSCIENCE PUBLISHING

Asian Journal of Water, Environment and Pollution

REVIEW ARTICLE

Insights into development trends for photocatalytic degradation of PFAS: A bibliometric time-series perspective

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Abstract

Photocatalytic degradation has attracted increasing attention for the remediation of per- and polyfluoroalkyl substances (PFAS) because of its mild operating conditions, high treatment efficiency and relatively low energy demand. Based on literature indexed in the Web of Science from 1999 to 2025, this study used CiteSpace to analyze research output, collaboration networks, high impact journals and keyword evolution, and to identify the scientific contributions of countries, regions, institutions and leading researchers. The analysis shows the development pattern and major hotspots of photocatalytic degradation of PFAS. The field has gone from slow growth before 2010 to rapid expansion since 2020. Both China and the United States lead the global output in publications, with Chinese institutions at the collaboration core, although isolated nodes still limit full integration. Keyword analysis indicates research hotspots in catalyst design, reaction mechanisms and combined processes with other technologies. The field is shifting from studies on single target compounds to system-scale remediation of contaminant classes, and from mainly oxidative pathways to reductive and synergistic mechanisms. These trends emphasize process integration and practical application, while also pointing to frontier topics, knowledge gaps and directions for future research.

Keywords: Photocatalytic degradation; Per- and polyfluoroalkyl substances; Bibliometric analysis; CiteSpace; Defluorination mechanism; Water treatment

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Citation: Zhang H, Du Y, Liu Z, Wu B, Ge D. Insights into development trends for photocatalytic degradation of PFAS: A bibliometric time-series perspective. *Asian J Water Environ Pollut.* doi: 10.36922/AJWEP026210151

Received: May 18, 2026

Revised: May 25, 2026

Accepted: May 28, 2026

Published online: July 1, 2026

1. Introduction

Per- and polyfluoroalkyl substances (PFAS) represent a class of synthetic organofluorine chemicals characterized by the presence of at least one fully fluorinated methyl group ($-CF_3$) or methylene group ($-CF_2-$) within their molecular structure. Since the 1940s, PFAS, represented by perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), have been extensively applied in more than 60 industrial and consumer sectors

due to their excellent thermal stability, hydrophobicity, chemical inertness, and surfactant properties. The widespread and long-term use of PFAS has led to their significant release to environmental media.[1-5]

Because of the extremely high bond energy and stable electron arrangement of carbon–fluorine bonds, PFAS resist degradation in natural environments. As a consequence, they accumulate persistently in aquatic systems, soils, living organisms, and human tissues. Extensive research indicates that PFAS exhibit carcinogenic, teratogenic, and mutagenic effects. Their pronounced lipophilicity facilitates biomagnification within food chains, posing serious threats to both ecosystems and human health.[6,7] Therefore, the widespread presence of PFAS in environmental and biological samples has raised global awareness and concern. In response, regulatory frameworks in various countries and regions have been implemented or strengthened to encourage the development of highly efficient remediation technologies.[8]

The high recalcitrance of PFAS poses significant challenges for degradation technologies. In recent years, PFAS have emerged as a major research focus in environmental science, driving the development of various physical, chemical, and biological technologies for their effective removal and degradation.[9,10] However physical containment and separation techniques, such as adsorption,[11] membrane processes, and solidification/stabilization,[12] merely achieve pollutant transfer without molecular breakdown, and are susceptible to secondary environmental risks including desorption and leachate release.[13-15] In contrast, current mainstream degradation technologies such as advanced oxidation and reduction processes (AOPs and ARPs),[16-18] biodegradation,[19] and thermal decomposition are specifically designed to cleave the carbon–carbon or carbon–fluorine bonds within PFAS molecules.[20-23] These processes convert PFAS into less toxic or non-toxic intermediates, smaller molecular compounds, and ultimately yielding mineralized products such as CO_2, H_2O, and fluoride ions. Among these methods, photocatalytic degradation has attracted significant attention due to its unique electron transfer mechanism.[24] It enables efficient cleavage of C–F bonds under mild conditions such as room temperature and atmospheric pressure. Consequently, it has emerged as a key focus in PFAS degradation research.

Although a significant amount of research and review literature has been published regarding the application of photocatalytic technology in PFAS environmental remediation, elucidating its basic principles, typical materials, and specific application scenarios, most research remains at a macroscopic level, or focuses solely on the mechanism analysis of a degradation mechanism. As a result, there is a lack of horizontal comparison and systematic integration of different degradation pathways, leading to fragmentation and redundancy within the field of photocatalytic degradation PFAS. Therefore, there is a need for a comprehensive and quantitative analysis of the research trends in this area from a more holistic perspective. Bibliometric analysis, which applies mathematical and statistical methods, quantitatively evaluates the impact and significance of scholarly outcomes, and identifies research progress and focal points.[25-27] By analyzing the collaboration networks between authors, institutions, and countries, it reveals the structure and influence distribution within the academic community.[28] Furthermore, techniques such as co-citation analysis and keyword emergence are used to dynamically track shifts in research hotspots,[29-31] helping researchers understand frontier developments and potential breakthroughs, thereby better guiding future research.[32,33]

This study utilizes bibliometric methods to collect and analyze global literature on photocatalytic degradation of PFAS from the Web of Science Core Collection database between 1999 and 2025, selecting the most influential Science Citation Index Expanded (SCI-E) citation indicators for further investigation.[34-36] The primary aim is to explore the field's development trajectory, identify research hotspots, highlight frontier issues, and predict future trends. Using CiteSpace, the analysis covers publication trends, subject distributions, journal impact factors, research strength (including countries, institutions, and authors), co-occurring keywords,[37] and evolving research themes, offering a qualitative overview of the research dynamics.[38-41] This research provided valuable insights into the current status of photocatalytic PFAS degradation, identify knowledge gaps and technological breakthroughs, and promote the development of its theoretical and technical frameworks, supporting efforts to address the environmental and public health issues associated with PFAS pollution.

2. Data sources and analytical methods

2.1. Data sources

Data for this study were retrieved from the Web of Science (WOS) Core Collection database, which is widely used in bibliometric studies because of its standardized indexing system, high-quality citation records, and broad coverage of peer-reviewed academic publications.[42,43] To ensure data quality and consistency, this study used the SCI-E within WOS as the data source. The literature search was conducted on June 23, 2025, covering the period from 1999 to 2025. The search was performed using the Topic

Search (TS) field, which includes titles, abstracts, author keywords, and Keywords Plus. The complete search strategy was as follows: TS = ((PFAS OR perfluoroalkyl* OR polyfluoroalkyl* OR PFOA OR PFOS OR "per- and polyfluoroalkyl substance*" OR fluorosurfactant* OR "C–F bond*" OR "perfluorinated compound*") AND (photocatalyst* OR "UV treatment" OR "UV/sulfite" OR "photo-Fenton" OR "photocatalytic reduction" OR (light-driven AND defluorin*))). All retrieved records were exported in plain text format with full records and cited references, which are required for subsequent bibliometric and network analyses. The initial dataset was then screened to remove duplicate records and publications that were not directly related to photocatalytic degradation of PFAS. After this screening process, a total of 830 records were retained for further analysis.

2.2. Data processing

The analysis covered a period of 26 years, from 1999 to 2025. To facilitate temporal analysis, the retrieved publications were grouped into two periods: 1999–2020 and 2021–2025. The year 2021 was selected as the boundary because publication output increased rapidly after 2020, suggesting that photocatalytic PFAS degradation research entered a new stage of accelerated development. Thus, 1999–2020 represents the early and gradual development stage, while 2021–2025 represents the recent rapid-growth stage. CiteSpace (version 6.1 R6) was employed to conduct bibliometric and network analyses of the retrieved literature. Key analytical dimensions included country, institution, author, keyword, and cited reference (Figure 1). In the visualized networks, nodes represent analytical elements (*e.g.*, institutions or keywords), with their size corresponding to frequency or centrality. Links between nodes denote collaborative or semantic relationships, with thicker lines indicating stronger connections. Publication trends over time are indicated by colored rings. Figure S1 summarizes the software configuration.

2.3. Trend analysis

Keyword trend analysis can provide a reasonable prediction of future research priorities in the field. The substantial increase in the number of publications related to PFAS degradation studies from 2021 to 2025 signifies an escalation of research hotspots and also suggests potential directions for future research to focus on. Therefore, a trend analysis of the keywords has been carried out for this five-year period.

A comprehensive analysis was conducted on keywords of the publications from 2021 to 2025. The time period is divided into two parts, designated as past and current, respectively, based on the time span. The past period encompasses from January 2021 to March 2023, while the current period corresponds from April 2023 to June 2025. Should the keywords appear with greater frequency in current period than in the past, it can be deduced that the possibility of the keywords becoming a hotspot in the future is higher, and *vice versa*. The trend factor calculation method referring to previous study,[44] and the formulas are shown in **Equations 1** to **3**.

$$F_{Current} = 1000 \times \frac{\sum_{2023}^{2025} f_{yp}}{\sum_{2023}^{2025} N} \quad (1)$$

$$F_{Past} = 1000 \times \frac{\sum_{2021}^{2023} f_{yp}}{\sum_{2021}^{2023} N} \quad (2)$$

$$Trend\ factor = \log\left(\frac{F_{Current}}{F_{Past}}\right) \quad (3)$$

where f_{yp} is the frequency of the keyword, N is the total number of papers in the time period, and $F_{Current}$ and F_{Past} are defined as the number of times the keyword appeared in each 1000 papers in the past and present time periods after normalization, respectively.

3. Bibliometric results

3.1. Publication trends and subject distribution

Based on the 830 publications retrieved from the WOS, nine document types were identified, with research articles accounting for 82.77% (687 papers). This highlights the central role of articles in reflecting scientific output and development in this field. The annual and cumulative publication trends for photocatalytic degradation of PFAS from 1999 to 2025 show a clear increase over time (Figure 2). The first study in this field was published in 1999 in *Environmental Science & Technology*, using photocatalysis to degrade methyl perfluoroalkyl ethers on TiO_2 particles in air and opening the academic study of photocatalytic degradation of PFAS.[45] Between 1999 and 2011, the number of publications remained low, with fewer than 10 papers published annually, suggesting that research was still in its early exploratory phase. From 2012 to 2019, the annual number of papers rose from 13 to 52, almost a threefold increase. This strong growth is likely due to growing global concern about the wide detection of PFAS in the environment, especially after PFOS was added to the Stockholm Convention list of controlled substances in 2009, which raised international awareness and regulation of its environmental and health risks.[45-47]

Since 2020, research activity has expanded rapidly. From 2020 to 2024, the number of annual publications

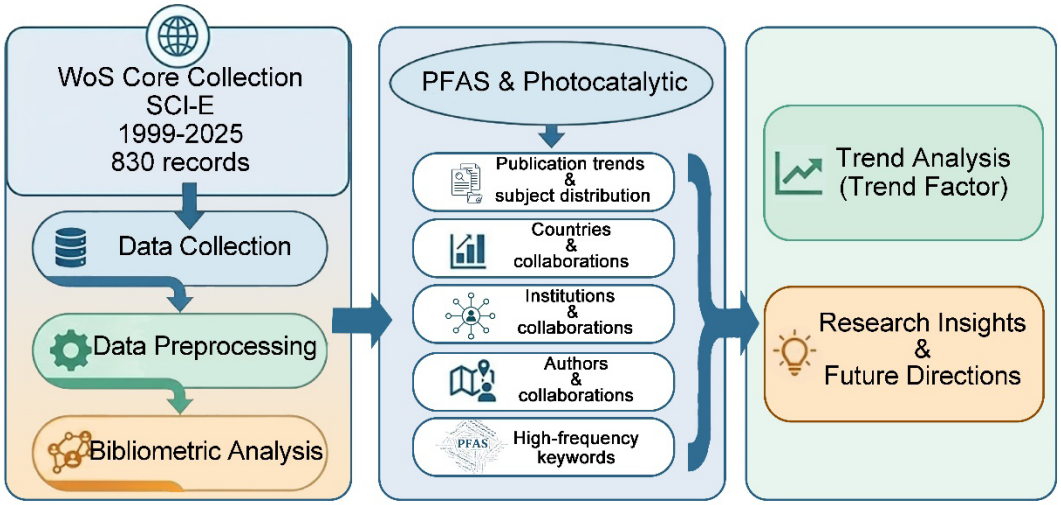

Figure 1. Flowchart of the research design and bibliometric analysis

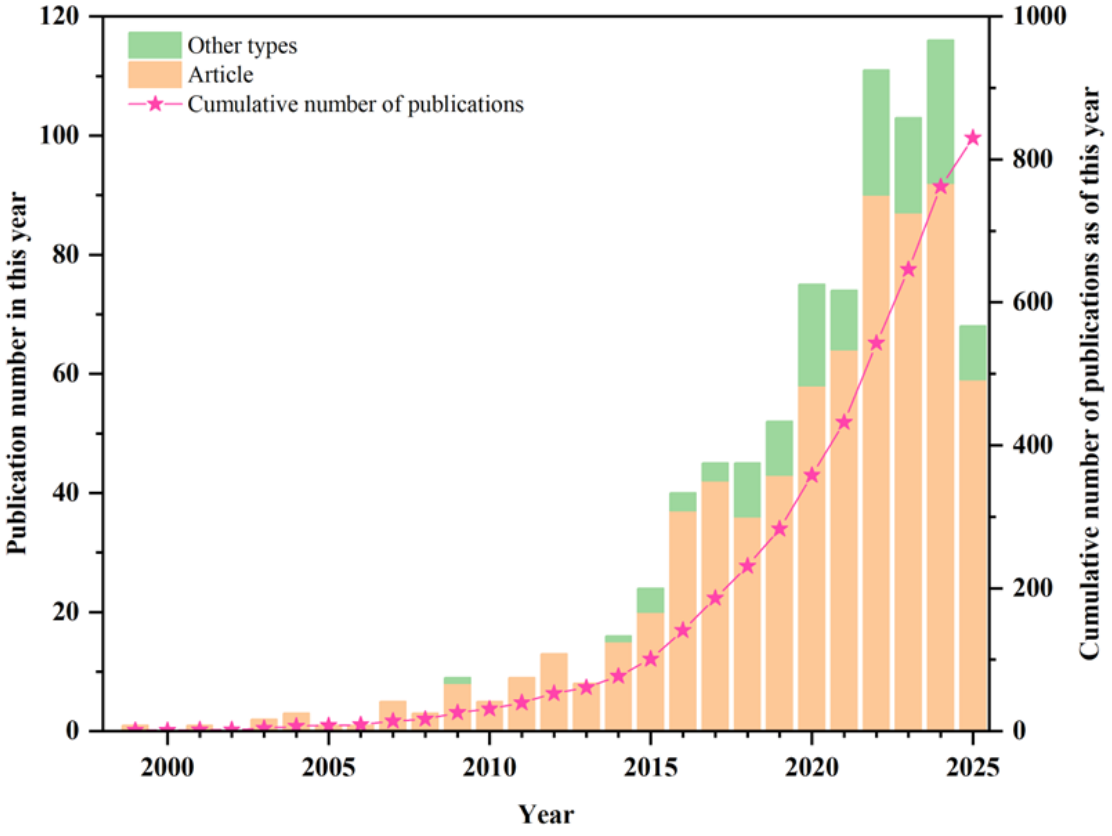

Figure 2. Distribution of publications of PFAS degradation technologies from SCI-E in 1999–2025

consistently exceeded 50, and by 2024 the output was more than double that of 2019, indicating a stage of accelerated growth. The lower count in 2025 is due to data being collected only through June, and further growth is anticipated. The sharp growth in publications indicates increasing academic attention in photocatalytic degradation of PFAS in recent years, and the sustained upward trend suggests that this field is poised for continued rapid development. A notable advance in photocatalytic C–F bond activation was reported in 2017 by Chen *et al.*,[48] who demonstrated selective single C(sp^3)–F bond cleavage in trifluoromethylarenes through visible-light catalysis combined with Lewis acid activation, providing mechanistic insights relevant to subsequent defluorination studies. Around 2019, multiple studies further revealed that, when coupled with certain advanced polymeric materials, photocatalysis enabled highly efficient PFAS degradation under low-energy conditions, reinforcing its potential as a promising remediation strategy.[49,50]

Analyses of journal and subject distributions help reveal the concentration of research outputs, academic influence, and disciplinary structure of the field. It also sheds light on the knowledge structure and interdisciplinary characteristics of the field, assisting researchers in identifying emerging trends, potential opportunities for cross-disciplinary collaboration, and selecting suitable journals for publication. As seen in Table 1, research on photocatalytic degradation of PFAS is primarily published in top international journals within the environmental and chemical engineering sectors. Journals such as *Chemical Engineering Journal*, *Journal of Hazardous Materials*, and *Environmental Science & Technology* each have over 30 articles published, with impact factors above 10, signaling a strong concentration of high-quality research. *Water Research* and *Angewandte Chemie-International Edition* also rank among the top ten, further emphasizing the global interest in this research.

The distribution of research by subject shows a strong focus on chemistry (35.48%), environmental engineering (24.01%), and environmental science and ecology (19.55%), which together contributing nearly 80 percent (Figure 3). This distribution highlights an interdisciplinary structure, where chemistry underpins material design and mechanism studies, environmental science explores the environmental behavior and ecological risks of PFAS, and environmental engineering facilitates the application of photocatalytic technologies in water treatment. The involvement of materials science and water resource research signals a growing trend toward new materials and sustainable management strategies. In conclusion, the concentration of publications in high-impact journals and the integration of multiple disciplines suggest that photocatalytic degradation of PFAS is a crucial area of research with significant theoretical and practical implications for pollution control and environmental remediation.

3.2. Countries and collaborations

PFAS remediation is recognized as a critical global environmental security issue, and the number of publications from each country serves as a key indicator of its research engagement. National contributions to PFAS degradation technologies are illustrated for two study periods, namely 1999–2020 and 2021–2025 (Figure 4a and 4b), and the top publishing countries are listed in Table S1 (in Supplementary File). In 1999–2020, the leading countries were China, the United States, Japan, Germany, Spain, Italy, the Netherlands, India, Argentina and Australia. In 2020–2025, most of these countries remained important contributors, and new major contributors included Canada, the United Kingdom, France, South Korea and Russia. China was found to top both intervals with 194 and 267 publications, accounting for 50.92% and 51.74% of the total, respectively. These countries are distributed across five continents, indicating the broad global engagement in PFAS degradation research. Emerging economies such as China and India have grown fast in this field together with developed nations, so PFAS treatment research has become diverse and more internationally coordinated.

The partnership between countries plays a critical role in the dissemination of research findings and academic exchange within the field of PFAS degradation technologies. In the international collaboration network, each node represents a country, and the connecting lines represent collaboration between them (Figure 4a and 4b). From 1999 to 2020, China and the United States clearly held dominant positions as major research hubs, maintaining close cooperation within the network. Over time, particularly after 2021, this structure began to shift. China not only continued to lead in the volume of publications but also significantly strengthened its central role in the international collaboration network, with notably increased cooperation with countries such as Germany, India, and Australia. This shift suggests that China has become a major contributor to global PFAS degradation technology research in terms of publication output and collaboration activity. Meanwhile, the previous dual-center model, dominated by China and the United States, has gradually evolved into a more diversified, multipolar structure, reflecting the accelerating trend of more open and balanced global research cooperation. This trend suggests that global PFAS research collaboration not only fosters technological innovation but also promotes closer

Table 1. Top 10 most productive journals in photocatalytic degradation of PFAS research (1999–2025)

Journal	TP	TP (%)	Rank	IF (2023)
Chemical Engineering Journal	47	5.7	Q1	13.4
Journal of Hazardous Materials	34	4.1	Q1	12.2
Environmental Science & Technology	33	4.0	Q1	10.9
Organic Letters	26	3.1	Q1	4.9
Chemosphere	24	2.9	Q1	8.1
Water Research	21	2.5	Q1	11.5
Journal of Organic Chemistry	21	2.5	Q1	3.4
Angewandte Chemie-International Edition	21	2.5	Q1	16.1
Separation and Purification Technology	20	2.4	Q1	8.2
Science of the Total Environment	20	2.4	Q1	8.2

Abbreviations: IF: Impact factor; TP: Total publications.

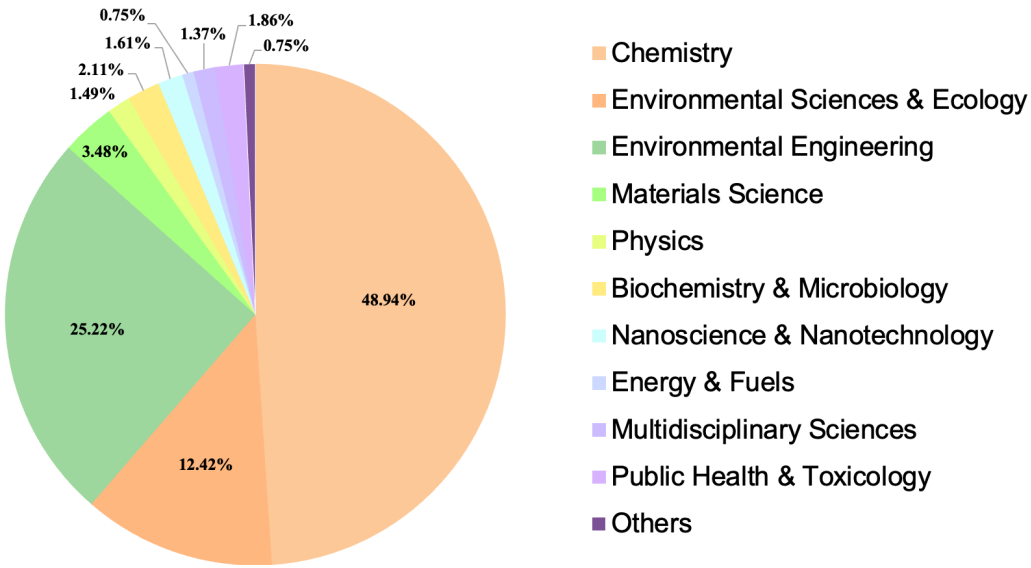

Figure 3. Top 10 Web of Science subject categories associated with photocatalytic degradation of PFAS from 1999 to 2025

cooperation and knowledge sharing among countries in the field of environmental remediation, thereby advancing the globalization of this research area.

3.3. Institutions and collaborations

Research institutions play a key role in academic research and knowledge innovation, and their outputs and collaboration networks strongly influence knowledge production and dissemination. Consequently, institution level analysis provides a critical perspective for understanding the academic ecosystem.[51] The institutional distribution and collaboration network in PFAS degradation research is displayed as a network graph, showing how institutions are linked and which one occupy central positions (Figure 4c and 4d). A quantitative summary of the ten most productive institutions in different periods is provided (Table S2). It shows the level of concentration in research output and the differences among institutions. Overall, these figures reveal the key in forces behind knowledge production in this field and help the analysis of collaboration patterns and research trends.

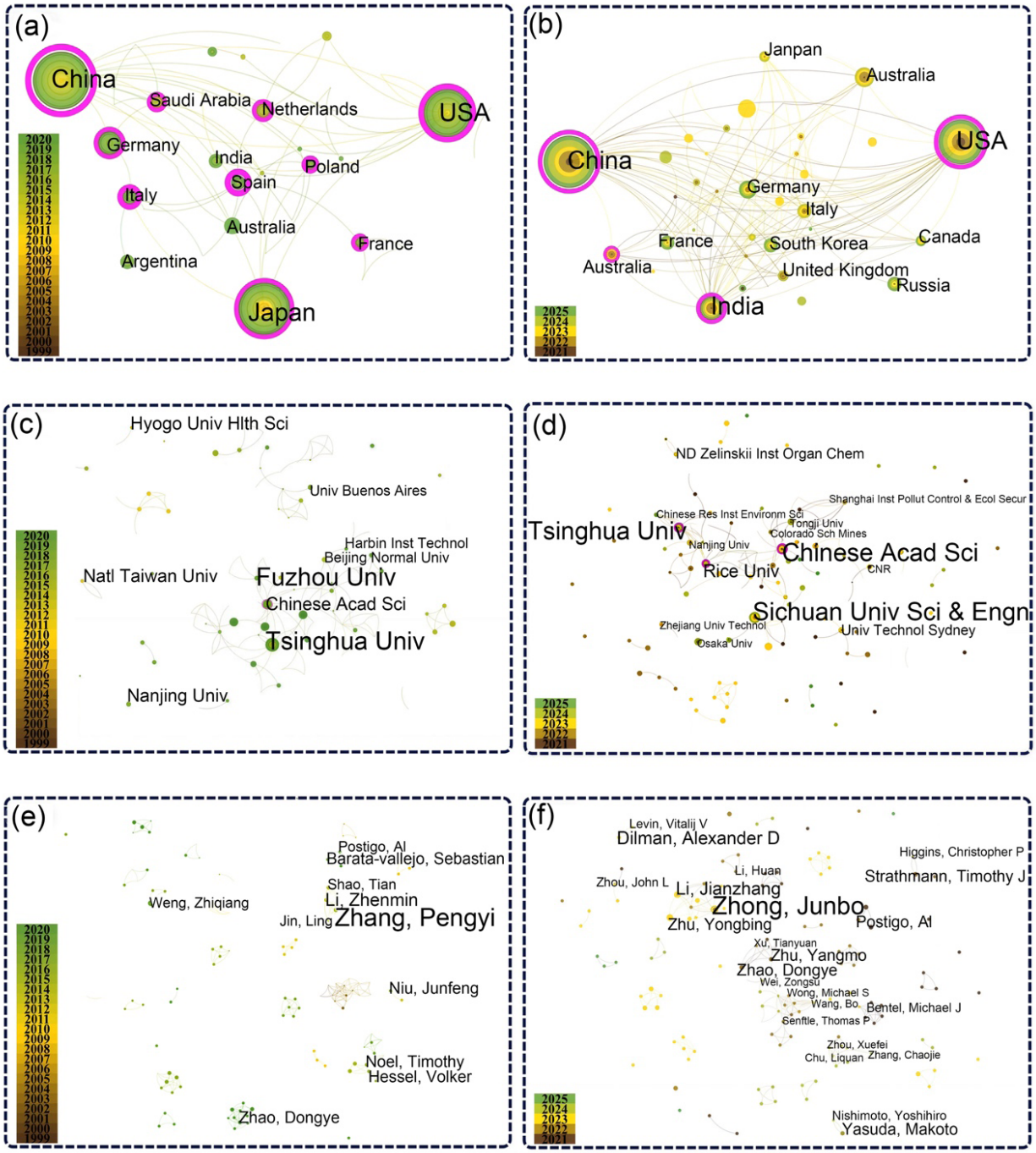

Figure 4. Visualization of contributions and collaboration networks in photocatalytic PFAS degradation. (a, b) Country networks; (c, d) institution networks; (e, f) author networks for 1999–2020 and 2021–2025. In each network, nodes represent countries, institutions, or authors, while links represent collaborative relationships. The node size is proportional to the number of publications. The link thickness indicates the strength of collaboration. The node colors and colored rings indicate the temporal distribution of publications across different time slices, rather than citation bursts. Nodes with more colors or rings indicate contributions distributed across a broader time span.

Between 1999 and 2020, Tsinghua University and the Chinese Academy of Sciences (CAS) led PFAS degradation research with 24 and 22 publications, respectively. Importantly, CAS exhibited a betweenness centrality of 0.10, indicating that it functions not only as a high-output institution but also as a pivotal bridge connecting multiple countries and research organizations. Other high-output Chinese institutions, such as Fuzhou University and Harbin Institute of Technology, also occupied key positions in the collaboration network, demonstrating a clear clustering effect in China's research landscape. Six of the top ten institutions were from China, highlighting the country's concentrated advantage in knowledge production and international collaboration. This concentration not only promotes sustained high-quality output but also establishes stable core nodes that facilitate knowledge dissemination and innovation.

From 1999 to 2025, the collaboration network evolved from a dispersed to a more centralized structure. During 1999–2020 (Figure 4c), the network was relatively fragmented, some institutions isolated or forming regional clusters. CAS and Tsinghua University, because of their high output and central positions, acted as core hubs, leading domestic research collaboration, whereas other high-output institutions such as Fuzhou University and Eindhoven University of Technology were located at the network periphery with lower centrality, indicating limitations in integration and international influence. In the recent period (2021–2025, Figure 4d), network concentration increased, node distribution became more compact, and edge connectivity strengthened, indicating enhanced cross-institution and international collaboration. CAS and Tsinghua University retain central roles, but collaborations extended to a broader range of international institutions, such as the University of Buenos Aires and Eindhoven University of Technology, indicating the gradual formation of a global research collaboration network in this field.

Overall, the field has formed a network structure in which central institutions connect other organizations and support knowledge transfer and technology advancement. The sustained activity of these core nodes ensures research stability, while the expansion of international collaborations creates opportunities for future breakthroughs. Increasing the density of collaborations and encouraging broader multi-national participation will further accelerate the globalization of the field and enhance its overall research impact.

3.4. Authors and collaborations

Author collaboration network analysis enables the recognition of leading scholars and illustrates their contributions to cooperation patterns, academic communication, and scholarly impact.[52] It also highlights gaps in collaboration, offering valuable insights for improving cooperative practices, enhancing global engagement, and fostering the discipline's evolution toward openness and integration.[53,54]

The most productive authors in the PFAS degradation technology field from 1999 to 2025 is provided (Table S3), showing changes in core authors and their lasting influence. Between 1999 and 2020, Zhang Pengyi was the top author with 13 publications. From 2021 to 2025, Zhong Junbo became the top author with 14 publications, showing the emergence of leading researchers. Although both Zhang and Zhong focus on photocatalytic PFAS degradation, their research perspectives differ.[55-58] Zhang focuses on the photochemical reaction mechanisms, such as iron-based pathways and the factors that influence these reactions. Zhong works on how to develop and change catalysts so that their structure and interfaces can lead to higher degradation efficiency. This difference reflects the field's multidimensional growth and indicates evolving research priorities. Mechanistic studies remain critical, while catalyst design and performance enhancement have gained prominence, driving the advancement of the field. Moreover, during 1999 to 2020, early researchers such as Barata-Vallejo, Hessel Volker, and Noel Timothy primarily investigated the mechanism of visible light photocatalytic perfluoroalkylation, laying foundation for optimizing photocatalytic degradation systems and improving efficiency.[59-62] Since 2021, the ongoing contributions of Zhong Junbo and Li Jianzhang have advanced the field to a new stage, characterized by an emphasis on catalyst modification and enhanced degradation performance.

Focusing on the work of these leading scholars helps to find the key theories and main discoveries in this field and shows how they guide research in the long term. A time analysis of the author collaboration networks shows a clear change in collaboration patterns. Between 1999 and 2020 (Figure 4e), the network exhibited a core and edge structure, with collaborations concentrated around several stable teams such as Zhang Pengyi from China and Barata Vallejo Sebastian from Spain. These nodes had many publications but belonged to clearly separated groups. In 2021 to 2025 (Figure 4f), network density increased and a more centralized cluster emerged around Zhong Junbo and Li Jianzhang, reflecting the aggregation and driving role of new leadership groups. Postigo Al and Zhao Dongye had high connectivity and high betweenness centrality in both periods and served as bridges that linked different groups and supported knowledge transfer. In recent years, several isolated new nodes have also appeared, meaning that more

new teams are joining the field. This trend supports greater research diversity but also indicate that collaboration is still not fully integrated. Notably, links between some European and American scholars, for example Timothy J. Strathmann, and the core teams remain weak, and certain small isolated groups such as those around John L. Zhou and Michael J. Bentel point to collaboration blind spots that may limit cross regional technology diffusion. Overall, strengthening cross disciplinary and cross regional connections is essential to improve the efficiency of academic exchange and the scholarly impact of the field, and to promote global sharing of knowledge and technology.

3.5. High-frequency keywords analysis

As key semantic carriers in academic literature, keywords with their frequency distributions and co-occurrence patterns systematically reveal the developmental trajectory and internal connections of a research field, thereby enabling researchers to rapidly identify its dominant themes.[63] In this study, keyword frequency statistics and clustering were conducted using VOS (visualization of similarities) viewer (Figure 5), enabling the identification of thematic structures and underlying linkages. The resulting network delineates the overarching framework of photocatalytic PFAS degradation research and highlights influential, interconnected research hotspots.

The connection network revealed four prominent clusters. The red cluster, focuses on perfluoroalkylation, PFOA, and defluorination, connects to terms such as reaction mechanism, C–F bond cleavage, and selective degradation. It reflects research on degradation pathways and bond breaking at the molecular level, with a focus on selective defluorination and high mineralization efficiency. The blue cluster, centered on photocatalysis, is associated with TiO_2, band gap, electron transfer, and radical generation, underscoring the role of semiconductor-based materials (particularly modified TiO_2) in achieving efficient PFAS degradation via band-gap engineering, charge-carrier separation, and targeted radical generation. The green cluster is organized around water, removal, wastewater, and adsorption and shows how photocatalysis is applied in water treatment, including pollutant removal, process optimization and the use of adsorption and membrane separation. The yellow cluster, around perfluorocarboxylic acids, persulfate, hydroxyl radical and sulfate radical, describes the generation of reactive species and compares the performance of oxidative degradation under different reaction conditions. Overall, these clusters cover four major lines of research: catalytic performance optimization, defluorination pathway elucidation, reactive species regulation, and process integration. Their links to each other show how basic knowledge of reaction mechanisms and applied engineering work together help PFAS degradation research move from laboratory studies toward practical applications.

Temporal analysis of keyword frequency and centrality (Table S4, Figure 6) further uncovers shifts in research priorities. Between 1999 and 2020, the most frequent keywords were water (70), degradation (56), PFOA (55), perfluorocarboxylic acid (53), and photoredox catalysis (53), with early studies focusing on photocatalytic degradation mechanisms of single compounds in aqueous systems, especially PFOA and other perfluorocarboxylic acids. Centrality analysis revealed that perfluorinated compound (0.13) served as a bridging term across research themes. By contrast, in 2021–2025, the top keywords shifted to PFOA (93), water (78), degradation (75), perfluoroalkyl substance (72), decomposition (61), and photocatalytic degradation (54), indicating a transition toward generalized PFAS systems and systematic defluorination strategies. While centrality indices declined (*e.g.*, PFOA from 0.06 to 0.02), broader PFAS related terms took over as key hubs, showing that research interests have become more diverse and more wide ranging. In general, the results show a structural change from degradation pathways for individual compounds to defluorination strategies at the system level, and it has become the main trend in photocatalytic PFAS research.

4. Research trends and future outlook

The temporal evolution of keywords illustrates the transformation of research themes and helps identify emerging areas of interest. However, these bibliometric signals should be interpreted as indicators of research attention rather than direct predictors of forthcoming technological breakthroughs. The top 50 keywords over time are shown in a bubble plot, with bubble size standing for frequency and the trend index controlling both position and color (Figure 7). Extra quantitative information is provided in Table 2. In 2020–2025, compared with 2014–2019, there are more large red bubbles and fewer cool colored bubbles, suggesting that the structure of the research field has changed in an important way.

4.1. Shift in research focus: From single compounds to systemic remediation

In the early stages of PFAS photocatalytic degradation research, the focus was primarily on the degradation of individual PFAS compounds, particularly PFOA and PFOS. Keywords such as “perfluorocarboxylic acid” and “photoredox catalysis” concentrated in the lower right quadrant, highlighting strong interest in photochemical

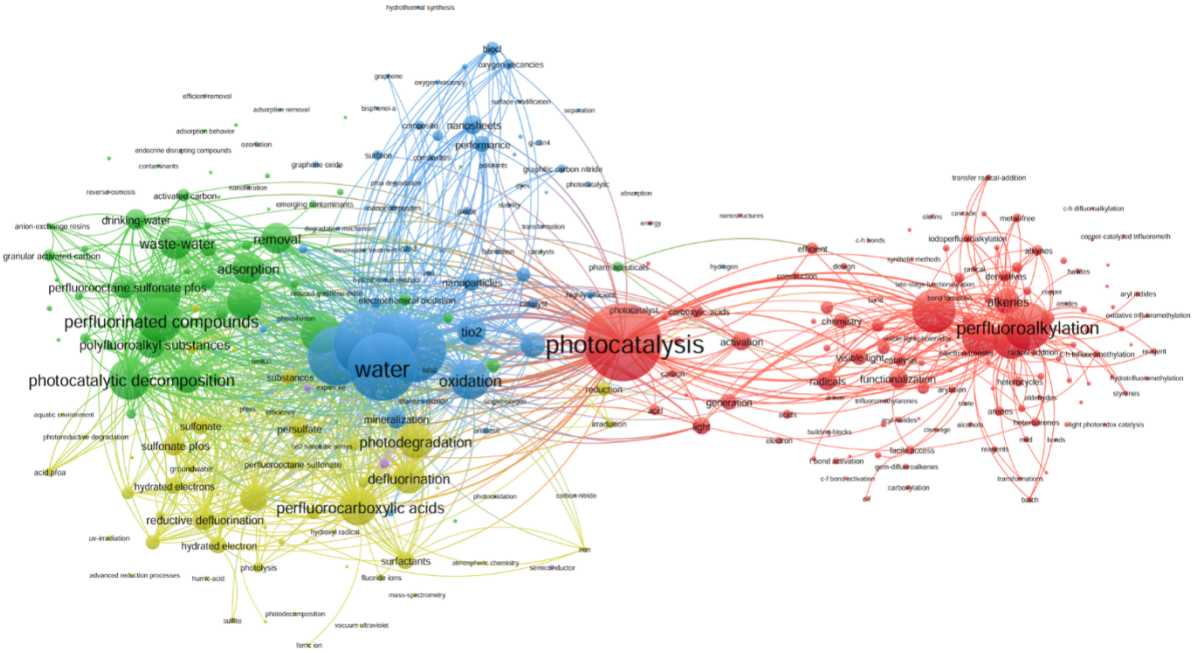

Figure 5. Visualization figure of all keywords from 1999 to 2025

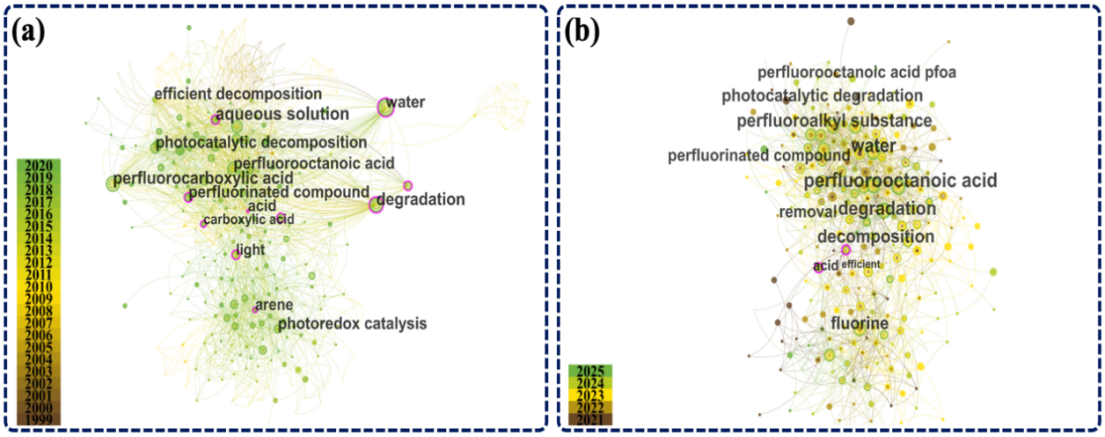

Figure 6. Keywords contribution visualization figure: (a) 1999–2020, and (b) 2021–2025. Pink circles indicate factors with high centrality, and displaying only the labels of the top 10 nodes in terms of frequency ranking.

oxidation and single-molecule pathways. With the increasing global concern over PFAS contamination, the research focus has gradually shifted toward broader PFAS class-based management (Figure 8). Keywords like "perfluoroalkyl substance" and "polyfluoroalkyl substance" have moved rapidly to the upper left quadrant, signaling the transition from controlling single target compounds to developing general degradation strategies for PFAS classes. These results suggest that comprehensive treatment strategies for diverse PFAS substances may receive increasing attention in future research.

4.2. Mechanistic innovation: From oxidation-dominated to reduction and coupled mechanisms

In earlier research, photocatalytic degradation of PFAS predominantly relied on oxidation species like hydroxyl radicals. Studies focused on developing oxidation pathways for efficient PFAS degradation (Figure 8). As knowledge

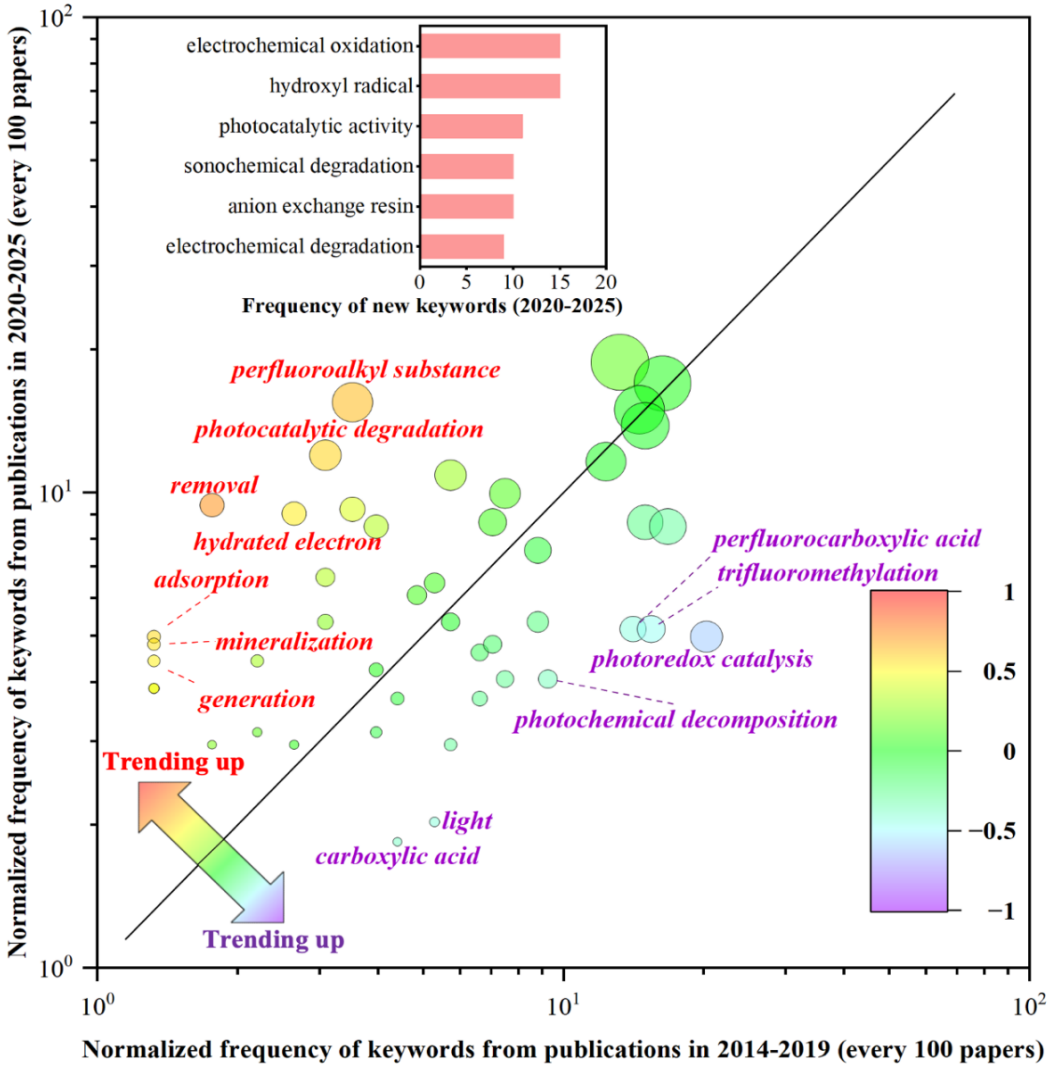

Figure 7. Bubble plot of future research trends based on keywords for publications from 2014 to 2025

about hydrated electrons advanced, research began to focus on reduction-driven defluorination, highlighting the role of hydrated electrons (0.53) and reductive defluorination (0.33) as crucial strategies for breaking high-energy C–F bonds. Meanwhile, traditional oxidation processes (*e.g.*, advanced oxidation processes, −0.10) and photodegradation (−0.27) have become less prominent, indicating a shift away from conventional oxidation routes. Moreover, the rise of keywords like "oxygen vacancy" (0.47) and "activation" (0.83) underscores the growing importance of defect engineering to enhance electron transfer and catalytic activity in these coupled systems.

4.3. Materials innovation: The rise of two-dimensional nanostructures and composite photocatalysts

Emerging two-dimensional nanostructures have become a highly active area of research. The keyword "nanosheet" (0.84) has the highest trend factor, suggesting increasing research attention to two-dimensional nanostructures. Their large surface area and tunable defect sites may provide potential advantages for photocatalytic applications, although further experimental validation and engineering assessment are still needed. In contrast, traditional semiconductors have seen declining attention,

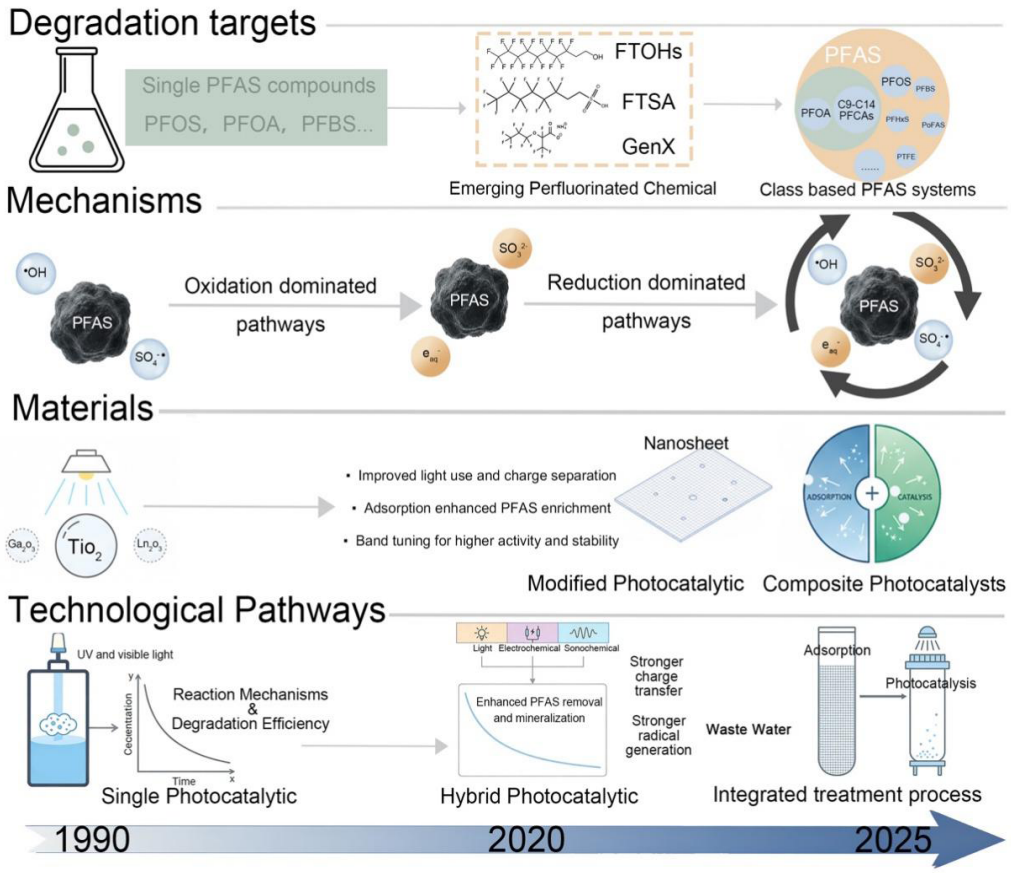

Figure 8. Research trends in photocatalytic treatment of PFAS across targets, mechanisms, materials and technologies

as indicated by the negative trends for TiO_2 (−0.03) and visible light (−0.22). Research is increasingly focusing on functional composite materials (0.22) and multi-field synergistic systems, which are gaining momentum in PFAS photocatalytic degradation.

4.4. Technological pathways: Expansion beyond single photocatalysis to hybrid systems and process integration

Early research was predominantly centered on single photocatalytic systems, employing UV or visible light to activate photocatalysts for PFAS degradation. While significant progress has been made, this approach still faces limitations in efficiency and scalability. The increasing interest in hybrid technologies, such as electrochemical oxidation, electrochemical degradation, and sonochemical degradation, signals a shift toward combining multiple techniques to improve PFAS removal and mineralization. Research is no longer confined to single photocatalytic systems but is expanding to explore photo-electrochemical and photo-sonochemical hybrid systems. Furthermore, keywords like "adsorption" and "anion exchange resin" highlight the coupling of photocatalysis with traditional separation techniques, emphasizing the importance of the "concentration followed by degradation" strategy for addressing PFAS at trace levels.

4.5. Practical applications: Moving from laboratory studies to engineering implementation

The trend factors indicate a clear shift from laboratory-based mechanism studies to engineering-scale applications. The sharp increase in keywords like "removal" (0.73), "adsorption" (0.58), and "mineralization" (0.56) shows that research is progressing beyond improving degradation rates in laboratory settings to focusing on overall mineralization efficiency and environmental safety. The positive trends for "drinking water" (0.24) and "wastewater" (0.09) confirm the increasing emphasis on real environmental matrices. Future research will not only focus on laboratory-scale developments but also accelerate the scaling up of these

Table 2. Top 50 keywords in terms of total frequency of occurrence and their trend factors in 2014–2025

Keyword	Trend factor	Keyword	Trend factor
Nanosheet	8.40×10^{-1}	Chemistry	4.80×10^{-2}
Activation	8.26×10^{-1}	Nanoparticle	2.95×10^{-2}
Removal	7.28×10^{-1}	Water	1.76×10^{-2}
Defluorination	6.83×10^{-1}	Degradation	1.20×10^{-2}
Perfluoroalkyl Substance	6.43×10^{-1}	Substance	0.00×10^{0}
Photocatalytic Degradation	5.90×10^{-1}	Perfluorinated Compound	-2.58×10^{-2}
Adsorption	5.76×10^{-1}	TiO_2	-2.95×10^{-2}
Mineralization	5.60×10^{-1}	Decomposition	-3.44×10^{-2}
Hydrated Electron	5.34×10^{-1}	Irradiation	-6.62×10^{-2}
Generation	5.25×10^{-1}	Radical reaction	-7.69×10^{-2}
Performance	4.67×10^{-1}	Advanced Oxidation Processes	-1.02×10^{-1}
Oxygen Vacancy	4.67×10^{-1}	Aqueous Solution	-1.56×10^{-1}
Oxidation	4.18×10^{-1}	Alkene	-1.67×10^{-1}
Reductive Defluorination	3.33×10^{-1}	Visible Light	-2.17×10^{-1}
Polyfluoroalkyl Substance	3.31×10^{-1}	Photocatalytic Decomposition	-2.37×10^{-1}
Reduction	3.03×10^{-1}	Functionalization	-2.53×10^{-1}
Perfluorooctanoic Acid	2.79×10^{-1}	Photodegradation	-2.66×10^{-1}
Drinking Water	2.39×10^{-1}	Sulfonate	-2.88×10^{-1}
Composite	2.24×10^{-1}	Perfluoroalkylation	-2.95×10^{-1}
Perfluorooctanoic Acid	1.54×10^{-1}	Photochemical Decomposition	-3.58×10^{-1}
Activated Carbon	1.54×10^{-1}	Carboxylic Acid	-3.78×10^{-1}
Fluorine	1.24×10^{-1}	Light	-4.16×10^{-1}
Perfluorooctane Sulfonate	9.92×10^{-2}	Perfluorocarboxylic Acid	-4.36×10^{-1}
Wastewater	9.00×10^{-2}	Trifluoromethylation	-4.75×10^{-1}
Mechanism	8.69×10^{-2}	Photoredox Catalysis	-6.09×10^{-1}

technologies for real-world applications. The combination of photocatalysis with conventional separation and enrichment techniques, such as activated carbon (0.15) and anion exchange resin, provides a strong technical foundation for tackling PFAS contamination in real water systems and supports the scalability of PFAS remediation solutions.

In summary, the field of photocatalytic PFAS degradation is advancing toward multidimensional, interdisciplinary development. Research has expanded from single-molecule mechanisms to class-based remediation strategies, and from oxidation-dominated pathways to reduction and synergistic mechanisms. Materials research is increasingly focused on two-dimensional nanostructures and functional composites, while technological development emphasizes hybrid systems and integrated enrichment-degradation strategies. These directions suggest that future research must integrate deeper mechanistic insights with practical validation in real-world water systems, ultimately establishing scalable solutions for PFAS remediation.

5. Conclusion

Through a bibliometric analysis of 830 publications on the photocatalytic degradation of PFAS, this study sheds light on the field's rapid development, especially since 2020. This sharp increase in publications mirrors the growing international concern over PFAS pollution. Moving forward, research will shift from studying individual PFAS compounds to exploring more comprehensive degradation strategies that address a wider range of PFAS substances. The analysis of keywords suggests a growing trend toward diverse degradation pathways, transitioning away from single, photocatalytic routes. A key research area will be the development of photocatalysts based on

two-dimensional nanomaterials, known for their high surface areas and tunable defects, positioning them as a focal point in future studies. Furthermore, the future of PFAS research will also see an increasing focus on integrating photocatalysis with other technologies such as photo-electrochemical, sonochemical, and adsorption methods, aimed at improving both PFAS removal and mineralization. With advancements in materials science, the development of functional composite materials and multi-field synergistic systems will be another major focus. These breakthroughs will not only advance theoretical knowledge in photocatalytic PFAS degradation but will also provide practical solutions for environmental remediation. As a result, future studies will likely center on applying these technologies in real-world water treatment systems, ensuring the broader application of PFAS remediation solutions.

Acknowledgments

None.

Funding

This work was financially supported by National Natural Science Foundation of China [Grant number 52270137, 52570173] and Shanghai Oriental Talent Program [Grant number QNCX2024034].

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be viewed as a potential conflict of interest.

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Availability of data

Data are available from the corresponding author upon reasonable request.

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