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A bibliometric analysis of global landscape and emerging frontiers of nanogels from 2000 to 2024

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Abstract
Nanogels are hydrogels embedded with nanoparticles. They have been increasingly applied in drug delivery, biomedical engineering and environmental remediation. At present, no bibliometric study has provided a comprehensive analysis of nanogels. This study aims to summarize the current development and future trends of nanogels publications through bibliometric analysis. Publications on nanogels from January 1, 2000, to August 1, 2024, were retrieved from the Science Citation Index Expanded of the Web of Science Core Collection for further bibliometric analysis. We used VOSviewer and Bibliometrix to conduct the co-authorship analysis of countries/regions, institutions and authors, summarized the most productive contributors, and keywords co-occurrence analysis to identify research hotspots and future trends on nanogels. A total of 9,569 publications were included in this study. This study revealed an overall growth trend of nanogels, peaking in 2022 ($n=948$). China was the most contributive country ($n=3785$). The most productive institution was the Chinese Academy of Sciences ($n=335$). Kazunari Akiyoshi ($n=112$) was the most prolific author. A total of 230 keywords were grouped into five clusters: nanogels and drug delivery; crosslinking chemistry of nanogels; nanogels in water treatment and biodegradation; nanogels and scaffolds; and temperature and pH-responsive nanogels. Emerging research directions included the application of novel nanogels in drug delivery and biomedical fields. This study reveals the research trends, collaboration patterns, research hotspots, and emerging frontiers in nanogels research. These findings can provide researchers with a comprehensive understanding of nanogels research and offer guidance for future research directions.

Keywords Bibliometric analysis, Nanogels, Materials, VOSviewer, Bibliometrix

1 Introduction

Nanogels, as nanoscale hydrogel, seamlessly integrate the unique properties of hydrogels and nanomaterials. Their structure is defined by a three-dimensional polymeric network formed through chemical and/or physical crosslinking, endowing them with a high specific surface area, adjustable pore structure, and remarkable biocompatibility [1, 2]. Nanogels offer many advantages in drug delivery systems. They have advantages of high encapsulation capacity, high biocompatibility, tunable size, ease of synthesis, minimal toxicity and stability in biological environments, which make them an ideal platform for therapeutic applications [3, 4]. Because of their responsiveness to external stimuli, such as pH and temperature, they can be used to control precisely the release of drug and improve both efficacy and targeting capabilities [5, 6]. Moreover, noncovalent encapsulation of protein- based drugs into nanogels overcomes the stability and shelf- life limitations of these drugs [7]. Apart from drug delivery, nanogels have shown great potential in other biomedical area, such as diagnostic imaging, cellular engineering and tissue repair [8, 9]. Nanogels are used to remove pollutants, such as heavy metals and organic contaminants, from water in environmental science. As adsorbents and catalysts, nanogels play a role in environmental protection initiatives [10]. Thus, nanogels have significant applications across a variety of fields, including chemistry, materials science, and biomedicine, which makes the analysis of their research hotspots and trends highly meaningful.

Bibliometric analysis is an emerging field within information science [11]. It has been used in many fields such as medicine, materials, biology, engineering, and so on. Its foundational theories are power law distribution, graph theory-based citation network analysis, matrix model, and time-series model [12–15]. Power law distribution is used to analyze author productivity, citation counts, and keyword frequency. Graph theory-based citation network analysis is used to present the citation relationship and knowledge structure of publications. Matrix models are used to support the analysis of co-citation, and collaboration networks. Time series model is used to analyze the dynamic change of topic evolution and research hotspots. Based on these theories, bibliometrics can give statistical and summarized analysis of quantitative information in a given field, revealing performances, co-authorship patterns and research hotspots [16–18].

In recent years, nanogels research have developed rapidly. Nanogels represent a novel class of hydrogels that are distinct from smart hydrogels. The essential differences between nanogels and smart hydrogels are in size (ranging from 20 to 200 nm) and the requirement for stimulus responsiveness [19]. Although there are some reviews on nanogels, they focus on different aspects [20–22]. There is no comprehensive bibliometric analysis specifically targeting publications on nanogels. We utilized VOSvoiwer to conduct the co-authorship analysis of countries/regions, authors and institutions, co-occurrence of keyword, and the temporal evolution of keywords. We hope to provide a clearer depiction of past research hotspots and forecasting future publication trends on nanogels, so that future researchers can get one-stop overview and identify research gap.

2 Materials and methods

2.1 Data sources and search strategies

We utilized the Web of Science Core Collection (WoSCC) as the database for this study. The Web of Science is an online platform that includes bibliographic information and information analysis resources, which can be used to assess and analyze research performance [23]. On August 1, 2024, a comprehensive search on nanogels was conducted within the Science Citation Index Expanded (SCI-E) of the WoSCC database. The time range for the data source was from January 1, 2000, to August 1, 2024. The search strategies were TS= (“Nanogel$” or “Nanocomposite Gel$” or “Nanocomposite Hydrogel$” or

"Nano-gel$" or "Nano-Hydrogel$"). A total of 11,351 publications were retrieved. After refining the document type to article, 9,635 publications remained. After further refining the language to English, 9,569 publications remained. These 9,569 publications were ultimately included in this study. We exported the complete records of the bibliographic items retrieved from WoSCC in plain text file format, including all custom options. The data were downloaded on the same day to prevent potential data bias due to database updates. Finally, we imported the data into VOSviewer and Bibliometrix for bibliometric analysis. We adopted full counting methods in VOSviewer. The detailed selection process is shown in the flowchart (Fig. 1).

2.2 Bibliometric analysis

In bibliometric analysis, metrics for performance analysis play important roles. The annual or group publication output and citation counts are the most prominent metrics. Publication output reflects productivity, while citation count reflects impact. In addition, average normalization citations represent the average number of citations per publication, normalized relative to the average citation level of publications in the same year and field [24]. We employed VOSviewer [25] and Bibliometrix [26] software

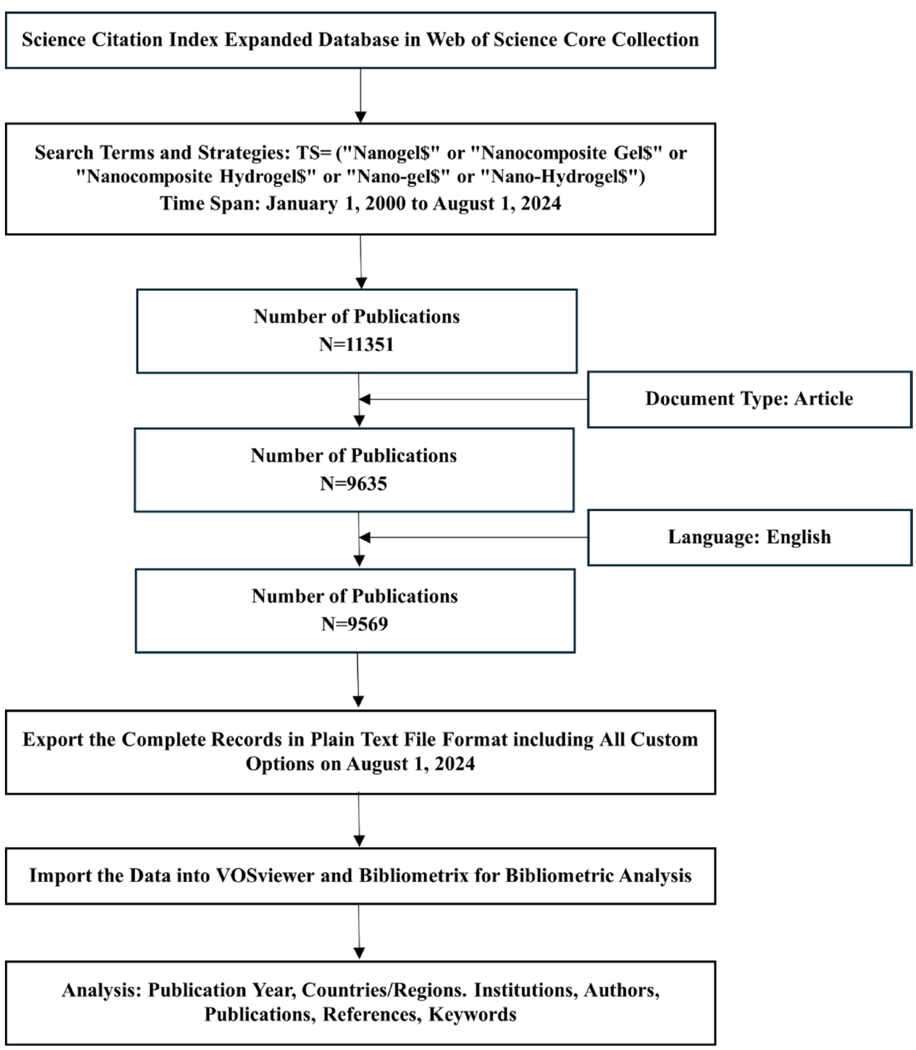

Fig. 1 A flowchart for filtering publications in nanogels research

for bibliometric analysis of the publications. VOSviewer, developed by Leiden University in the Netherlands, is a tool used for constructing and visualizing bibliometric maps; it can create maps based on co-citation data for authors or journals, or based on co-occurrence data for keywords [25, 27, 28]. The bibliometrix designed by Massimo Aria and colleagues, is a unique open-source tool written in R for comprehensive bibliometric analysis [26]. We used VOSviewer software to analyze the collaboration relationships between countries/regions, co-authorship among institutions, author collaboration, co-citation of references, keyword co-occurrence networks and temporal frequency. In VOSviewer, each node represents an item, with the size of the node corresponding to its frequency of occurrence. Lines connecting the items indicate relationships between them, with a greater number of lines reflecting a stronger relationship. The thickness of the lines represents the degree of collaboration between different items, while different colors denote different collaborative clusters [29]. Additionally, we employed Bibliometrix to count the most cited publications. By using these effective tools, we were able to visualize bibliometric data, facilitating the analysis of bibliometric data. This study used publicly available data and did not require ethical approval.

3 Results

3.1 Annual publication analysis

A total of 9,569 publications on nanogels were retrieved from the SCI-E within WoSCC. The number of publications on nanogels generally tended to increase from 2000 to 2024. This trend can be divided into two phases. The first phase (2000–2010) saw a slow increase in publication numbers, with an average annual publication count of 59.6 publications. The second phase (2011–2024) witnessed a significant increase in the number of publications, with the annual count surpassing 200 for the first time in 2011, reaching 252 publications. The number of publications subsequently increased rapidly, peaking at 948 publications in 2022, which reached 474 times the volume in 2000. The average annual publication count was 636.6 publications during the second phase, which was significantly greater than that in the first phase. In the recent five years (2020–2024), the number of publications on nanogels ($n = 4{,}130$) was accounting for 43.2% of the total. As of August 1, 2024, there were 509 publications on nanogels, while 2024 was not a full year data (Fig. 2).

3.2 Leading countries/regions

A total of 97 countries or regions have contributed to publications on nanogels. Table 1 displays the top 10 countries/regions by the number of publications from 2000 to 2024. China led with the highest number of publications, totaling 3,785. The United States of America ($n = 1{,}252$) and Iran ($n = 735$) ranked second and third, respectively. The top three countries by total citations were still China ($n = 140{,}021$), the United States of America ($n = 66{,}542$), and Iran ($n = 21{,}956$), which correlated with the high number of publications. Among the top 10 most productive countries, the United States of America had the highest average citation count for its publications ($n = 53.15$). Average normalization citation reflects the true impact of research quality, which eliminates differences related to discipline, publication year, and document type. Among the top 10 most productive countries, the United States of America had the highest average normalization citations ($n = 1.29$).

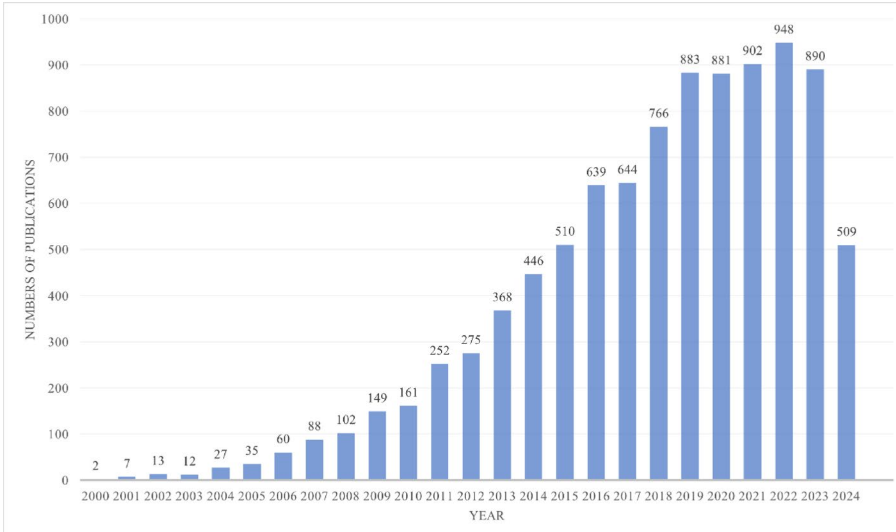

Fig. 2 Analysis of the quantity and trends of annual publications

Table 1 The top 10 countries/regions on nanogels sorted by the number of publications

Rank	Country/Region	Counts	Citations	Average citations	Average normalization citations
1	China	3,785	140,021	36.99	1.22
2	United States of America	1,252	66,542	53.15	1.29
3	Iran	735	21,956	29.87	1.10
4	India	734	19,117	26.04	0.89
5	Japan	533	23,597	44.27	0.81
6	Germany	528	17,368	32.89	0.87
7	South Korea	478	17,395	36.39	1.01
8	United Kingdom	291	10,710	36.80	1.10
9	Canada	264	12,137	45.97	1.28
10	Turkey	262	6,967	26.59	0.75

To understand the collaborative relationships between countries/regions, we selected 67 countries or regions that published at least 5 publications. The data were then visualized via VOSviewer software (Normalization method: LinLog/modularity), as shown in Fig. 3. China held a central position in international collaboration, and it had the closest connections with other countries/regions, with collaborations with 48 countries. China and the United States of America were the most common collaborators, with 275 co-published publications, highlighting both countries' significant contributions to nanogels. The largest cluster was the red one, with Germany, the United Kingdom, France, and many other European countries. The second largest cluster was the green one, which was centered by Japan, India, and South Korea. Countries/regions were close collaboration with and between clusters.

3.3 Active institutions

A total of 5,081 institutions have contributed to publications on nanogels. Table 2 displays the top 10 institutions by the number of publications. The institution with the highest number of publications was the Chinese Academy of Sciences, with 335 publications. It was followed by Sichuan University with 182 publications and Donghua University with 165 publications. In addition, the Chinese Academy of Sciences had the highest

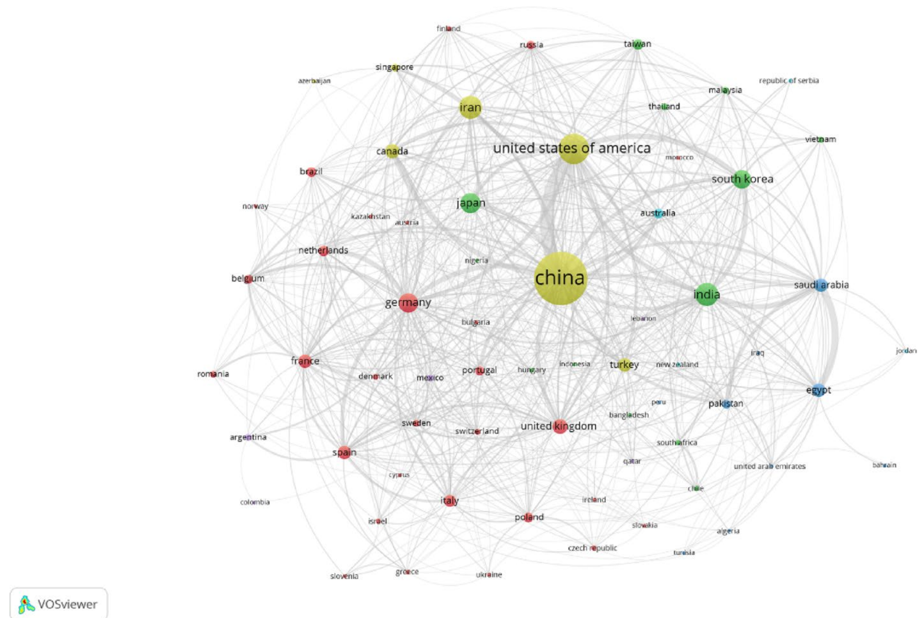

Fig. 3 Collaborative network map of countries/regions with at least 5 publications on nanogels

Table 2 The top 10 institutions on nanogels sorted by the number of publications

Rank	Institutions	Country/Region	Counts	Citations	Average citations	Average normalization citations
1	Chinese Academy of Sciences	China	335	19,993	59	1.57
2	Sichuan University	China	182	7,553	41	1.25
3	Donghua University	China	165	6,757	40	1.17
4	Shanghai jiao Tong University	China	163	4,807	29	1.34
5	Rheinisch-westfälische Technische Hochschule Aachen	Germany	117	3,508	29	0.95
6	Islamic Azad University	Iran	111	2,756	24	0.89
7	Fudan University	China	110	5,012	45	1.39
8	Zhejiang University	China	110	2,922	26	1.04
9	Kyoto University	Japan	108	3,239	29	0.68
10	Huazhong University of Science and Technology	China	105	3,682	35	1.13

average citation count ($n = 59$) and average normalization citations ($n = 1.57$), indicating that its publications were of high quality and had a significant influence on nanogels.

We filtered a total of 103 institutions with at least 30 publications and used VOSviewer to construct a collaborative network map for these institutions. We incorporated all 103 institutions into the map (Normalization method: Association strength), as shown in Fig. 4. The map revealed close collaboration among institutions, with the Chinese Academy of Sciences being the most closely connected with other institutions and having collaborations with 43 institutions. There were 6 clusters on the map, and the institutions were very closely interconnected within the clusters. The clusters marked in red primarily consisted of institutions from China, indicating close collaboration among them. Shanghai Jiao Tong University, Fudan University, and Donghua University formed a tightly connected group, indicating a strong regional collaboration.

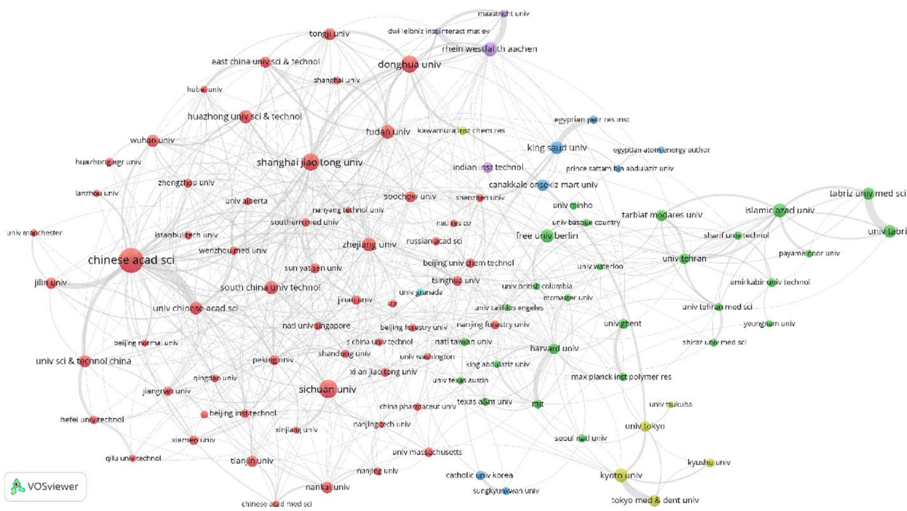

Fig. 4 Co-authorship between institutions with at least 30 publications on nanogels

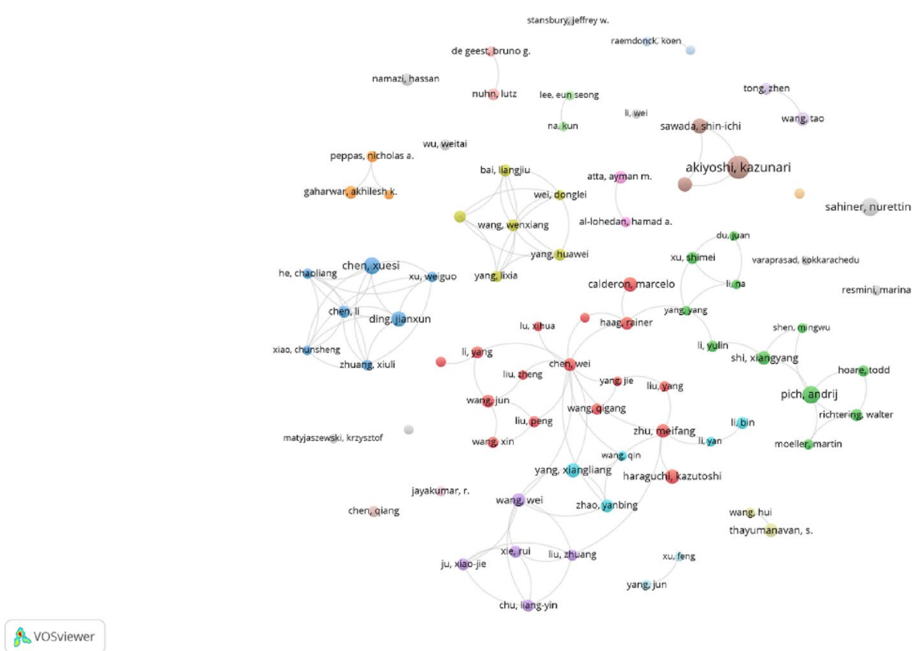

Fig. 5 Co-authorship between authors with at least 20 publications on nanogels

3.4 Prolific authors

A total of 26,159 authors have contributed to publications on nanogels. Here, we filtered for authors with at least 20 publications, resulting in a total of 82 authors, and used VOSviewer to construct a co-authorship network map for the authors. We incorporated all 82 authors into the map (Normalization method: Association strength), as shown in Fig. 5. There were a total of 27 clusters, with the largest cluster comprising 16 authors. Among them, there were more connections between the red, green, blue, and purple clusters, whereas there were less connections between the other clusters. The top three authors on nanogels according to the number of publications were Kazunari Akiyoshi ($n = 112$), Nurettin Sahiner ($n = 75$), and Andrij Pich ($n = 65$). The authors within the same cluster had close collaborations. Kazunari Akiyoshi, Sawada Shin-ichi and Sasaki Yoshihiro formed a research cluster, promoting the development of nanogels together.

3.5 Highly influential publications and references

The analysis of highly cited publications revealed significant trends and insights. Table 3 lists the top 10 most cited publications. The most cited publication was an article by Haraguchi, K. published in *Advanced Materials* in 2002, titled "Nanocomposite hydrogels: A unique organic-inorganic network structure with extraordinary mechanical, optical, and swelling/de-swelling properties", which has been cited 1,865 times. This was followed by an article by Wang, Qigang, published in *Nature* in 2010, titled "High-water-content mouldable hydrogels by mixing clay and a dendritic molecular binder" with 1,362 citations, and an article by Cheng, Ru published in *Journal of Controlled Release* in 2011, titled "Glutathione-responsive nano-vehicles as a promising platform for targeted intracellular drug and gene delivery" with 1,140 citations. Total citations per year quantifies the citation rate of a publication, reflecting its annualized impact. Among the top most cited publications, an article titled "Highly Stretchable, Elastic, and Ionic Conductive Hydrogel for Artificial Soft Electronics" had the highest total citations per year ($n = 113.17$), reflecting its timely impact on nanogels.

We conducted a visual analysis of 255,193 references from the 9,569 retrieved publications. We filtered the references that were cited at least 60 times, totaling 175 references, and used VOSviewer software to create a co-citation map of these references (Normalization method: LinLog/modularity), as shown in Fig. 6. There were 4 different clusters, and the largest cluster comprised 67 references. The article by Haraguchi, K., published in *Advanced Materials* in 2002 had the largest citation node ($n = 835$). This was followed by an article by Gong, JP, published in *Advanced Materials* in 2003 ($n = 520$) and a review by Kabanov, Alexander V., published in *Angewandte Chemie-International Edition* in 2009 ($n = 495$). They were closely linked with other references, indicating that they have made significant contributions to the foundational research on nanogels.

3.6 Core keywords and clusters

A total of 11,295 keywords were identified from 9569 publications. After standardization, 230 keywords with at least 60 occurrences were selected. We created a keyword co-occurrence network in VOSviewer (Normalization method: LinLog/modularity), as shown in Fig. 7. The most frequently occurring keyword was "nanogels" ($n = 4526$), followed by "nanoparticles" ($n = 2638$), "hydrogels" ($n = 1927$), and "drug delivery" ($n = 1685$). The keywords were divided into five clusters, each represented by a different color: red, green, blue, purple, and yellow. The five clusters were as follows: (1) nanogels and drug delivery, (2) crosslinking chemistry of nanogels, (3) nanogels in water treatment and biodegradation, (4) nanogels and scaffolds, and (5) temperature and pH-responsive nanogels.

We constructed an overlay map in VOSviewer, as illustrated in Fig. 8. In the overlay map, the color coding represents average publication year of each keyword, allowing for the visualization of trends in specific themes or research areas. Keywords shown in blue correspond to earlier research, representing foundational hotspots on nanogels, such as "volume phase-transition" (avg. pub. year:2012), "stabilization" (avg. pub. year:2013), and "core" (avg. pub. year:2013). In contrast, keywords in red represented more recently

Table 3 The top 10 most cited publications on nanogels sorted by total citations

Rank	Year	Title	First author	Journal	Total citations	Total citations per year
1	2002	Nanocomposite hydrogels: A unique organic-inorganic network structure with extraordinary mechanical, optical, and swelling/de-swelling properties	Haraguchi, K	Adv. Mater	1,865	81.09
2	2010	High-water-content mouldable hydrogels by mixing clay and a dendritic molecular binder	Wang, Qigang	Nature	1,362	90.80
3	2011	Glutathione-responsive nano-vehicles as a promising platform for targeted intracellular drug and gene delivery	Cheng, Ru	J. Control. Release	1,140	81.43
4	2012	Protein-inorganic hybrid nanoflowers	Ge, Jun	Nat. Nanotechnol	938	72.15
5	2014	Polymerization-Induced Self-Assembly of Block Copolymer Nano-objects via RAFT Aqueous Dispersion Polymerization	Warren, Nicholas J.	J. Am. Chem. Soc	898	81.64
6	2014	Nanocomposite Hydrogels for Biomedical Applications	Gaharwar, Akhilesh K.	Biotechnol. Bioeng	844	76.73
7	2017	Mussel-Inspired Adhesive and Tough Hydrogel Based on Nanoclay Confined Dopamine Polymerization	Han, Lu	ACS Nano	753	94.13
8	2015	Molecularly Engineered Dual-Crosslinked Hydrogel with Ultrahigh Mechanical Strength, Toughness, and Good Self-Recovery	Lin, Peng	Adv. Mater	740	74.00
9	2019	Highly Stretchable, Elastic, and Ionic Conductive Hydrogel for Artificial Soft Electronics	Zhou, Yang	Adv. Funct. Mater	679	113.17
10	2002	Effects of clay content on the properties of nanocomposite hydrogels composed of poly(N-isopropylacrylamide) and clay	Haraguchi, K	Macromolecules	668	29.04

topics, indicating emerging research hotspots on nanogels, including "self-healing hydrogel" (avg. pub. year:2020), "antibacterial" (avg. pub. year:2020), "antioxidants" (avg. pub. year:2020), "water purification" (avg. pub. year:2020) and "wound healing" (avg. pub. year:2021). At the same time, we divided all publications to two parts, one included the publications from 2000 to 2018 ($n = 4{,}556$), the other included the publications from 2019 to 2024 ($n = 5{,}013$). The data was shown in Supplementary Table 1. By comparing the top 100 keywords of each part, we could find the emerging research hotspots. The emerging keywords included chitosan, adsorption, scaffold, antibacterial, and self-healing. These findings indicated that the research hotspots and directions on nanogels have undergone significant changes, with an increasing number of areas being explored and investigated.

4 Discussion

This study is the first bibliometric analysis focused on nanogels. We analyzed the research hotspots and trends on nanogels.

The annual publication count reflects the development dynamics and trends in a specific field. As shown in Fig. 2, nanogels research was in its early stages from 2000 to 2010. Since 2011, publications on nanogels have exhibited a vigorous development trend. This was attributed to advances in controlled polymerization and nanoscale crosslinking strategies, which lowered the technical threshold for reproducibly preparing nanogels, thereby promoting broader participation by researchers [30, 31]. At the same time, developments in nanomedicine have increased the demand for nanogels, further stimulating researchers' enthusiasm [32].

Through the analysis of high-output countries/regions, institutions, and authors, we found that China has had a significant influence on nanogels during the past 25 years, maintaining a leading global position. The United States of America and Iran also had considerable contribution to nanogels research. The United States of America exhibited the highest quality of its publications, which was consistent with its long-standing leadership in biomedical research capacity, high-impact funding programs, and its concentration of world-class research institutions. Co-authorship network analysis can reveal the intensity, structure, and trends of collaboration among countries, institutions, and authors in a research field. China's position at the center of the collaboration network indicated its growing integrative role on nanogels, functioning as a major connector that linked multiple high-productivity countries knowledge exchange across regions. The Chinese Academy of Sciences had the closest collaboration between different institutions indicating a high level of collaboration and resource sharing on nanogels, reflecting similarities or complementarities in research themes, goals or technologies. International collaboration among different countries and institutions can accelerate the rapid development of nanogels.

The author with the greatest number of publications was Professor Kazunari Akiyoshi from the Graduate School of Medicine, Kyoto University, who was dedicated to the design and functionalization of nanomaterials and their applications in biomedical and environmental sciences [2]. This indicated his high activity and expertise on nanogels. As shown in Fig. 5, a research group by Kazunari Akiyoshi, Sawada Shin-ichi and Sasaki Yoshihiro mainly collaborated on developing polysaccharide self-asssembled nanogels and applied them artificial chaperones, drug delivery, and vaccine delivery systems [33,

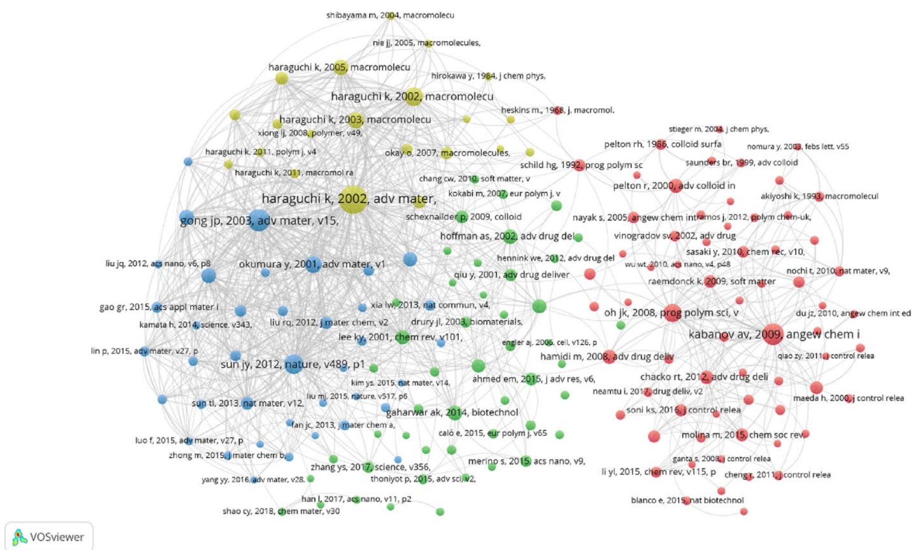

Fig. 6 Co-citation map of references cited at least 60 times on nanogels

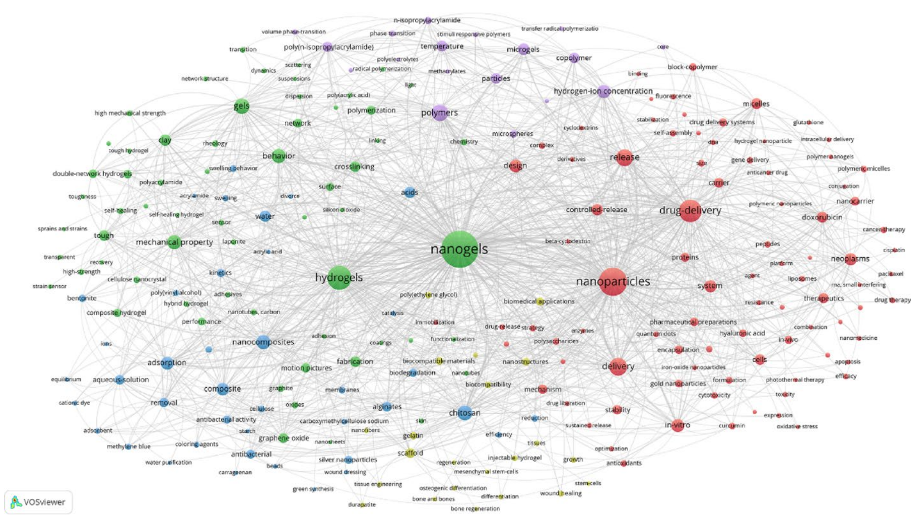

Fig. 7 Co-occurrence network map of keywords with at least 60 occurrences on nanogels

34]. A relatively low degree of collaboration among authors suggested limited resource sharing and communication between researchers. To enhance collaboration among researchers and advance research on nanogels, it is important to promote interdisciplinary exchanges and establish collaborative research platforms.

Examining highly cited publications and co-cited references helps in understanding crucial research methods or theoretical frameworks within a specific field. The most cited publication and the most co-cited reference were both a publication titled "Nanocomposite hydrogels: A unique organic- inorganic network structure with extraordinary mechanical, optical, and swelling/de-swelling properties." This publication introduced a novel type of nanocomposite hydrogel that combines organic polymers with inorganic nanoparticles to greatly enhance the mechanical strength, optical properties, and swelling/de-swelling responsiveness [35]. This study illustrated the wide applicability

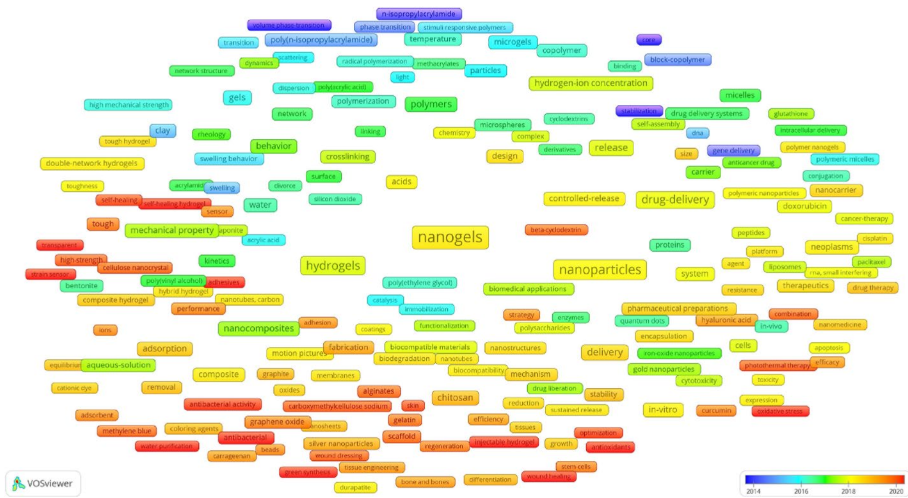

Fig. 8 Overlay map of keywords with at least 60 occurrences on nanogels

potential of these hydrogels in biomedical research and in environmental protection and laid a foundation for further study on nanogels.

Cluster analysis helps to group similar topics to discover hot topics and trends in a research field. By using VOSviewer software, 230 keywords were categorized into five clusters. Cluster 1 focused on the application of nanogels in drug delivery systems, with keywords such as nanoparticles, drug delivery, release, and design. nanogels, made up of natural or synthetic material are engineered for targeted drug delivery, providing a huge boost to bioavailability [36]. The two dominant mechanisms highlighted in this cluster are physical encapsulation through non-covalent forces and covalent drug-network conjugation, mirroring key technological turning points in drug delivery: the transition from passive carrier to stimuli-responsive platforms capable of controlled, site-specific drug activation [37]. These mechanisms innovations directly support real-world applications, including precision delivery in oncology, neuro-regeneration, and inflammatory disease, where nanogels have improved therapeutic indices and reduced systemic toxicity [38]. Their versatility is underscored by recent applications in the treatment of spinal cord injury, cancer, cardiovascular diseases, ischemic stroke, bone regeneration, wound healing, psoriasis, and inflammatory disorders [39, 40]. This cluster captures a substantive technological trajectory, that is the convergence of nanogels and precision medicine to form the foundation of next-generation pharmaceutical platforms.

Cluster 2 focused on the cross-linking chemistry of nanogels and its impact on performance and applications, with keywords such as cross- linking, polymerization, and mechanical properties. Typical crosslinking chemistry involves covalently linking together polymer chains to give gels increased mechanical strength and stability [41]. These cross-links can be achieved via chemical reactions, e.g. click chemistry [42], or through physical interactions [37]. These resultant cross-linked structures show sustained release capabilities, biocompatibility and tunable drug release profiles. Novel redox- responsive hydrogels based on poly(N-isopropylacrylamide) or polyacrylamide, utilizing redox- sensitive crosslinkers create new opportunities for analyte exchange in microfluidic applications for sensing and separation [43]. Furthermore, nanogel cross-linking-based Belousov-Zhabotinsky (NCBZ) self- oscillating polyacrylamide (PAAm) gels show potential for applications in smart soft robotics, actuators, sensors, and tissue engineering [44]. Recent advances increasingly favor biocompatible and biologically relevant backbones, such as poly (ethylene glycol) (PEG), hyaluronic acid (HA), and polypeptide-based networks, which use click chemistry or dynamic covalent cross-links to achieve both material stability and improved biological performance. PEG- and HA-based nanogels exhibit superior cytocompatibility and tunable degradation profiles, supporting controlled drug delivery and enhanced tissue regeneration [45]. Similarly, peptide-based hybrid nanogels employing thiol-ene or Schiff-base cross-linking demonstrate adaptive mechanical properties and efficient loading of bioactive molecules [46, 47]. These systems highlight cross-linking chemistry is increasingly leveraged not only to modify mechanics or release kinetics but also to match biological environments and promote cell-material interactions.

Cluster 3 focused on nanogel-based water treatment and biodegradation, with primary keywords including nanocomposites, chitosan, water, and biodegradation. This cluster reflects a coherent technological trajectory in which polymer-inorganic hybrid structures are engineered to couple high-affinity pollutant capture with environmentally benign degradation pathways. The prominence of chitosan and clay-based nanocomposites illustrates how surface chemistry, porosity, and functional group density have been deliberately optimized to remove heavy metals, acidic dyes, and organic pollutants with far greater efficiency than conventional sorbents [48, 49]. Dendritic architectures, for instance, exemplify how nanoscale branching enhances diffusion, increases accessible binding sites, and enables rapid adsorption kinetics [50].Moreover, these nanocomposites are also biodegradable, breaking down into harmless substances and thus minimizing their environmental impact [51]. This dual functionality—effective pollutant removal and subsequent harmless degradation—positions dendritic nanocomposites as promising candidates for sustainable water treatment solutions.

Cluster 4 focused on the use of biocompatible nanogels combined with scaffolds in biomedical applications, with primary keywords including scaffold, biomedical applications, and biocompatible materials. These keywords collectively indicate nanogels have moved from being drug carriers to becoming functional components of engineered microenvironments. Nanogels are widely used in drug delivery, tissue engineering, and regenerative medicine. Nanogels possess excellent drug-loading capacity, enabling sustained drug release through scaffolds. This synergy not only enhances the bioavailability of the drug but also prolongs its release time in the body, thereby improving its therapeutic efficacy [52]. The high controllability of nanogels allows for the embedding of drugs or growth factors, promotes tissue regeneration, and allows scaffolds to serve a structural support role in tissue engineering [53]. Nanogel-based scaffolds can be applied in tissue engineering to provide a conducive microenvironment for tissue repair [54]. Research indicates that both standalone nanogels and those integrated with scaffolds significantly enhance the healing of chronic wounds and critical-sized bone fractures [9]. Moreover, cross-linked nanogels employed in innovative scaffold designs have been shown to induce bone growth, further illustrating the substantial potential of nanogels in tissue engineering and regenerative medicine [55]. Owing to their versatility, nanogels are promising tools for advancing therapeutic strategies in drug- delivery, tissue repair and regeneration [56, 57]. Overall, the cluster reflects an emerging paradigm in which nanogels act as modular bioactive units within scaffold systems, driving integrated therapeutic strategies in drug delivery, tissue repair, and regenerative medicine.

Cluster 5 focused on temperature- and pH-responsive nanogels, with primary keywords including polymers, temperature, and hydrogen-ion concentration. Stimulus-responsive polymers are materials that exhibit dramatic changes in performance in response to slight or moderate environmental changes, such as changes in temperature, light, salt concentration, or pH [58]. These nanogels demonstrate excellent responsiveness in smart materials because of their reversible swelling or shrinking behaviors at specific temperatures or pH values [59]. Poly(N-isopropylacrylamide) (pNIPAAm) have enabled precise control over nanogels swelling kinetics, thereby supporting innovations in on-demand drug release, intracellular delivery, and microenvironment-triggered therapies [60–63], and its combination with nanoparticles has potential applications in smart drug delivery systems [64]. This cluster's prominence indicates that researchers are increasingly leveraging environmental cues such as local acidity or body-temperature fluctuations to achieve spatiotemporally controlled therapeutic action. Cluster analysis provides a clear and rapid understanding of the diverse applications and potential of nanogels across various fields, guiding future research directions.

The overlay map and the shift of top 100 high frequency keywords revealed that early research focused primarily on the fundamental physicochemical properties of nanogels, the development of synthesis techniques, and their stability [3, 65, 66]. This foundational research established the basis for nanogels technology and facilitated the exploration of its applications. As the field matured, the temporal shift of keywords highlights the emergence of more functionally sophisticated systems. Self-healing nanogels have gained prominence due to their intrinsic plasticity and autonomous repair capability, enabling robust performance in tissue engineering and controlled drug-delivery context [67]. Additionally, some newly synthesized nanogels have demonstrated excellent antioxidant and antibacterial properties [68], and can be used for pathogen detection and antibacterial treatments [69, 70], offering new perspectives for sterile treatments of infectious diseases. The emergence of these novel nanogels has elevated the field to greater complexity and broader applications. This trend not only reflects advancements in technology but also highlights potential future opportunities and challenges in nanogel applications. This provides researchers with new directions and ideas for future investigations.

5 Conclusion

This study provided a comprehensive bibliometric analysis of nanogels research from 2000 to 2024, revealing rapid growth in publication output. Collaboration networks among countries, institutions, and authors have accelerated research progress. High-impact publications have focused on nanogels mechanisms and functional design, supporting applications in drug delivery, environmental remediation, smart materials, and biomedicine. Future research should focus on enhancing nanogel stability, biodegradability, and responsiveness under complex physiological and environmental conditions to facilitate clinical and industrial translation. International strategic agendas in advanced materials and emerging biomedical technologies increasingly highlight nanogels for precision therapeutics and sustainable innovation, suggesting broader social relevance of nanogels. The bibliometric analysis will improve the ability to identify emerging hotspots and guide evidence-based development of next-generation nanogels technologies.

6 Limitations

This study also has certain limitations. First, the data were sourced purely from the SCI-E database of the WoSCC, and a small number of publications may have been overlooked. Second, the publication selection was restricted to English language and article type publications, potentially introducing selection bias. Thirdly, citations included self-citations, they might introduce a self-citation effect. Finally, in the analysis of institutions and authors, irregularities in author affiliations might lead to discrepancies in identifying authors and institutions.

Supplementary Information

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Supplementary Material 1

Author contributions

Yulai Liu: Writing—original draft, Data curation, Formal analysis. Zhiying Cui: Writing—original draft, Conceptualization, Methodology. Shuping Jia: Writing—original draft, Software, Investigation. Jiuyue Wang: Writing—original draft, Project administration. Xin Tian: Writing—original draft, Resources. Lang Guo: Writing—review and editing, Validation, Visualization. Zhongqing Wang: Writing—review and editing, Funding acquisition, Supervision.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

Not applicable.

Consent for publication

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