Bibliometric Analysis of International Development Trends in Liquid-Phase Laser Ablation Technology

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Date: 2017-03-01T00:00:00+00:00

Abstract

With the development of liquid-phase laser ablation technology, relevant research has evolved from early-stage explorations of fundamental principles and material synthesis processes to the discovery of new principles, design of new materials, and expansion of new applications. This paper, based on the Web of Science database and employing bibliometric methods, analyzes information related to research on liquid-phase laser ablation technology published from 1998 to 2016, including major contributing countries, total publication volume, research directions, research institutions, and research hotspots, and summarizes the main frontier research contents and development trends. This paper provides clear data support for the broad scientific research community to quickly understand and grasp the development trends and research hotspots of liquid-phase laser ablation technology.

Full Text

Bibliometric Analysis of International Development Trends in Laser Ablation in Liquids Technology

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Abstract

With the development of laser ablation in liquids (LAL) technology, related research has evolved from early-stage fundamental principle exploration and material synthesis process studies to new principle discovery, new material design, and new application expansion. Based on the Web of Science database, this paper employs bibliometric methods to analyze information related to major

contributing countries, total publication volume, research directions, research institutions, and research hotspots in LAL technology publications from 1998 to 2016, and summarizes the main frontier research content and development trends. This study provides clear data support for researchers to quickly understand and grasp the development trends and research hotspots of LAL technology.

Keywords: Laser ablation in liquids, Nanomaterials, Preparation, Application, Bibliometrics, Web of Science

In the 1960s, T. H. Maiman successfully developed the world' s first ruby solid-state laser at Hughes Research Laboratories in the United States [1], after which laser technology found widespread applications in scientific research and industrial production. In 1965, researchers discovered that laser technology could be used to prepare thin films under vacuum or specific atmospheric conditions, leading to the emergence of pulsed laser deposition (PLD) technology [2]. This marked the formal entry of laser technology as a material preparation method into the research landscape. PLD technology utilizes the high energy of lasers to instantly vaporize target materials, forming a plasma plume that ultimately deposits as a film on a fixed substrate. Using this method, researchers successfully prepared a series of highly crystalline thin films, such as ceramic oxides, nitrides, and metal multilayers [3]. Compared with methods like molecular beam epitaxy and chemical vapor deposition, PLD technology has much lower production costs and thus has received widespread attention. By the 1990s, the rise of nanotechnology ushered in a new era of microscale material synthesis and design. In 1993, Henglein and Cotton respectively attempted to use pulsed laser ablation on metal targets in water and different solvents, both successfully obtaining metal colloidal nanosolutions [4,5].

Since the ablation process involves both physical and chemical changes, encompassing complex thermodynamic and kinetic processes, the final products differ from those prepared by conventional chemical methods. This uniqueness has attracted significant scientific attention to laser ablation in liquids (LAL) technology. Typically, LAL requires laser irradiation of a target material in a liquid environment (see Figure 1 [Figure 1: see original paper]). Through "thermal effects," the target material is vaporized or evaporated, generating a plasma plume at the interface between the target and liquid (the liquid-solid interface). As the plasma plume is surrounded by liquid, its expansion is constrained, creating a large additional pressure inside the plume and ultimately forming an extreme region with high temperature, high pressure, and high density [6]. Under these conditions, the material ejected from the target through laser ablation may react with itself, with components in the liquid, or with liquid molecules at the interface, readily producing nanomaterials in metastable states [6]. Due to variations in laser parameters (wavelength, pulse width, etc.), the mechanism and product state in LAL processes can differ significantly. Additionally, changing the liquid environment or external field conditions may lead to new physical phenomena. After preliminary knowledge accumulation and technological development, LAL preparation methods have reached a critical stage of scientific principle breakthroughs and major technological innovation. Notably, Chinese researchers possess frontier advantages and distinctive features in multiple areas of LAL nanofabrication technology. In recent years, with increasing national comprehensive strength, China has also intensified its support in this technical field, with LAL exploration and applications continuously deepening. Therefore, there is an urgent need to compile and report the latest domestic and international development status of this technical field.

This paper employs bibliometric statistical methods, relying on the Web of Science data platform, to summarize the development trends of LAL technology both domestically and internationally, objectively and quantitatively reflecting the overall layout and development trends of related disciplines, with the aim of providing reliable reference data for domestic researchers and promoting the rapid development of LAL technology in nanomaterial preparation and application fields. Figure 1 Schematic diagram of laser ablation in liquids technology principle

1. Data Sources and Retrieval Methods

This study uses the Web of Science Core Collection as the data source, retrieving relevant literature in the LAL technology field based on the SCI-Expanded database. Publications from January 1998 to December 2016 were selected as the analysis dataset, with final analysis conducted using the citation reports built into the Web of Science database. Some data items were analyzed using tools such as Excel and Origin. It should be noted that, on one hand, due to different research motivations, many researchers may not use "Laser Ablation in Liquids" as the technical term in their publications, instead employing other terms such as "Laser irradiation," "Laser fragmentation," or "Laser generation." On the other hand, "Laser Ablation" may also involve applications in techniques such as inductively coupled plasma mass spectrometry (ICP-MS), or have very similar terminology to pulsed laser deposition (PLD) technology, which are not the focus of this study. Therefore, during the retrieval process, fairly strict conditional restrictions needed to be set; otherwise, there would be a high risk of omitting research work in this technical field or including research work from other technical fields, causing statistical data to deviate from reality. Table 1 lists the search terms and conditions used in this study.

Table 1 List of search terms and retrieval conditions

Search Block	Query Terms
1 AND 2	laser* (generation OR generated OR generating OR fragmentation OR fragmentated OR fragmentating OR fabrication OR fabricated OR fabricating OR fragmenting OR ablation OR ablated OR ablating OR production OR produced OR producing) (liquid* OR water OR solvent* OR
1 AND 2 AND	hydrosol* OR colloid* OR hydro-sol* OR alkan* OR solution* OR propanol OR dispers* OR suspens* OR aqueous) (nanoparticle* OR nanocluster* OR nanocrystal* OR nanosphere*)
3 AND 4 NOT	(Inductively coupled plasma mass spectrometry OR gas phase* OR vacuum OR deposition OR pld OR laser surface OR structure* OR spectroscopy)

2.1 Country and Publication Volume Distribution in LAL Technology

Using the aforementioned retrieval method, a total of 5,622 academic papers related to nanomaterial synthesis and associated mechanisms and applications in liquid-phase systems involving laser technology were found from 1998 to 2016. After further excluding literature from closely related technical fields that are not the focus of this study, the actual number of published articles in the LAL technology field was 1,554. According to the analysis results from the citation reports built into the Web of Science database, we first analyzed the changing trends in total publications by country over the 19-year period (1998-2016). Figure 2 [Figure 2: see original paper] lists the top 11 countries or regions by total publication volume and their respective publication counts. The statistical results show that China is the country with the highest total publication volume, reaching 370 papers, with the United States, Japan, and Germany ranking second, third, and fourth, respectively. According to statistics from Barcikowski' s research group in 2009 [7], both Japan and the EU had publication volumes exceeding China, with the United States ranking fourth. This situation demonstrates that in recent years, China' s paper output in the LAL technology field has been continuously increasing. Figure 3 [Figure 3: see original paper] further analyzes the annual fluctuations in publication volume for the above countries and regions. Before 2003, the main publishing countries were the United States, Japan, Germany, France, Italy, etc., indicating that these countries started research in LAL technology earlier. Starting from 2003, paper output from China, the United States, Japan, Germany, South Korea, India, Russia, France, Italy, Taiwan, Canada, and other countries or regions has gradually increased, indicating that research in this technical field has received increasing attention from these countries and regions. Notably, starting from 2011, China' s publication volume has been able to match that of the most active research countries such as the United States, Japan, and Germany, and by 2015, it had surpassed the publication volume of other countries or regions, becoming the top-ranked country in annual publication volume.

2.2 Publishing Institutions and Geographical Distribution

Figure 3 [Figure 3: see original paper] Annual publication volume data by country from 1998-2016. Based on statistics of research institutions affiliated with the retrieved literature, we also compiled a list of the top 50 research institutions by publication volume (see Table 2) and their corresponding geographical distribution (see Figure 4 [Figure 4: see original paper]). These 50 research institutions contributed a total of 906 publications, accounting for 57.85% of all publications, indicating that they dominate frontier research in the LAL technology field. We note that since the citation report analysis results built into the Web of Science database count all research institutions involved in each publication, some institutions may have been collaborative units rather than first-affiliation units. Therefore, although some countries (such as Russia, Italy, etc.) in Figure 2 do not have particularly high publication volumes, their research institutions still have relatively high publication counts, demonstrating that these institutions play important roles in international cooperation and exchange activities in related fields. In Figure 4, we conducted statistical analysis of the distribution of these research institutions according to different geographical regions. Globally, the main active regions for LAL technology research are concentrated in China, Southeast Asia, Europe, and North America. In China, the main institutions engaged in related research are the Chinese Academy of Sciences and universities in certain coastal provinces and cities (such as Sun Yat-sen University, Zhejiang University, Tianjin University, etc.). In Southeast Asia, universities and research institutes in Japan and Singapore have consistently led related research activities in the region. In Europe, Germany and France show significantly stronger research activity than other countries. In North America, primarily U.S. government agencies (Department of Defense, Department of Energy, etc.) have demonstrated considerable enthusiasm for research in related fields.

Table 2 Publication volume data of world research institutions

Institution
Chinese Academy of Sciences
Russian Academy of Sciences

Institution
French National Center for Scientific Research
National Institute of Advanced Industrial Science and Technology (Japan)
University of Duisburg-Essen
Laser Center Hanover (Germany)
University of Science and Technology of China
U.S. Department of Energy
National University of Singapore
University of Montreal
Italian National Research Council
Indian Institute of Technology
Shanghai Jiao Tong University
Polytechnique Montréal
Hokkaido University
Nanyang Technological University (National Institute of Education)
Nanyang Technological University
Max Planck Society for the Advancement of Science
Japan Science and Technology Agency
Islamic Azad University
Tohoku University
Pohang University of Science and Technology
Pennsylvania State University
Spanish National Research Council
University of Catania
Aix-Marseille University
Universiti Putra Malaysia
U.S. Department of Defense
Academia Sinica (Taiwan)
University of Missouri
Tokyo Institute of Technology
Swiss Federal Institute of Technology
Pierre and Marie Curie University (Paris VI)
National Research Nuclear University - Moscow Engineering Physics Institute
Moscow Institute of Physics and Technology
Korea Advanced Institute of Science and Technology

2.3 Research Direction Analysis in LAL Technology

Figure 4 [Figure 4: see original paper] Geographical distribution of world research institutions. Using the "Research Direction" option in the "Analyze Results" function of the Web of Science database, we conducted statistical analysis of the research directions of all literature and listed the top 10 results in Figure 5 [Figure 5: see original paper]. The analysis shows that LAL technology research is mainly concentrated in three directions: chemistry, physics, and materials science. The number of papers involving these three directions is significantly higher than that of other research directions, even by an order of magnitude. Additionally, analysis reveals that in the five-year period from 2012 to 2016, the publication volume in each research direction was significantly higher than the total volume in the previous 14 years (1998-2011). This result indicates that in recent years, the enormous potential of LAL technology to promote future social development has gained increasing recognition from the international community, with significantly elevated attention and more active related scientific research. It is worth mentioning that the development speed of this technology in the biomedical field cannot be underestimated. Since the Web of Science database divides the biomedical field into numerous subdirections such as biochemistry and molecular biology, pharmacology, cell biology, biotechnology and applied microbiology, biophysics, genetics, toxicology, immunology, etc., the publication volume information for the entire biomedical field is not presented in Figure 5. After further statistical analysis, the total publication volume for the entire biomedical field is 214 papers, accounting for 13.77% of the total. According to statistics from Barcikowski' s research group [7] in 2009, the proportion of publications in the biomedical field was only about 1%, indicating that application research on nanomaterials prepared or modified by LAL technology in the biomedical field has gained attention in recent years and should be noted by Chinese researchers.

2.4 Applications of LAL Technology in Materials Science

Researchers generally use Science Citation Index (SCI) data to evaluate the impact of academic papers and journals and to obtain information on related research hotspots and development trends. To analyze research hotspots in the LAL technology field, we list the 15 most highly cited papers and their related information (including publication journal, publication year, citation frequency, etc.) in Table 3 . The analysis shows that the most studied materials are noble metal (Au, Ag, etc.) systems, with a few papers focusing on transition metal oxide materials (CuO, ZnO, etc.) systems. Research content is mainly concentrated in three aspects: 1) study of the formation process and size/morphology control of colloidal nanoparticles; 2) study of surface activity and reactivity of colloidal nanoparticles; and 3) study of performance applications of colloidal nanomaterials. These papers are cited at least 13 times per year on average, with the highest reaching 135 times, indicating that they have received widespread attention since publication. To further analyze current research trends, we conducted statistical analysis of the research directions of all citing papers of these 15 papers and listed the top 10 research directions in Figure 6 [Figure 6: see original paper]. The analysis shows that although chemistry, materials science, and physics remain the main research directions, compared with the results in Figure 5, the proportion of literature in materials science has exceeded that in physics, indicating that in citing papers, related research work is more concentrated in chemistry and materials science, and citers may be more concerned with material synthesis strategies of LAL technology and their involved chemical processes. In addition, research work in electrochemistry and spectroscopy has also increased significantly, indicating that research on colloidal nanomaterials prepared by LAL technology in other related application fields has been expanded.

Table 3 Summary of the 15 most highly cited papers in LAL technology

Authors	Journal	Title	Publication Year	Citations/Year	Total Citations
Link S.; El-Sayed M.A. et al.	J. Phys. Chem. B	Spectral properties and relaxation dynamics of surface plasmon electronic oscillations in gold and silver nanodots and nanorods			

Authors	Journal	Title	Publication Year	Citations/Year	Total Citations
Mafune F.; Kohno J. et al.	J. Phys. Chem. B	Formation and size control of silver nanoparticles by laser ablation in aqueous solution			
Kamat P.V.; Flumiani M. et al.	J. Phys. Chem. B	Picosecond dynamics of silver nanoclusters. Photoejection of electrons and fragmentation			

Authors	Journal	Title	Publication Year	Citations/Year	Total Citations
Mafune F.; Kohno J. et al.	J. Phys. Chem. B	Formation of gold nanoparticles by laser ablation in aqueous solution of surfactant			
Hayakawa K.; Yoshimura T. et al.	Langmuir	Preparation of gold-dendrimer nanocomposites by laser irradiation and their catalytic reduction of 4-nitrophenol			

Authors	Journal	Title	Publication Year	Citations/Year	Total Citations
Link S.; Burda C. et al.	J. Phys. Chem. A	Laser photothermal melting and fragmentation of gold nanorods: Energy and laser pulse-width dependence			
Sylvestre J.P.; Poulin S. et al.	J. Phys. Chem. B	Surface chemistry of gold nanoparticles produced by laser ablation in aqueous media			

Authors	Journal	Title	Publication Year	Citations/Year	Total Citations
Hodak J.H.; Henglein A. et al.	J. Phys. Chem. B	Laser-induced interdiffusion in AuAg core-shell nanoparticles			
Zeng H.B.; Cai W.P. et al.	J. Phys. Chem. B	Composition/structural evolution and optical properties of ZnO/Zn nanoparticles by laser ablation in liquid media			

Authors	Journal	Title	Publication Year	Citations/Year	Total Citations
Kabashin A.V.; Meunier M. et al.	J. Appl. Phys.	Synthesis of colloidal nanoparticles during femtosecond laser ablation of gold in water			
Yeh M.S.; Yang Y.S. et al.	J. Phys. Chem. B	Formation and characteristics of Cu colloids from CuO powder by laser irradiation in 2-propanol			

Authors	Journal	Title	Publication Year	Citations/Year	Total Citations
Dolgaev S.I., Simakin A.V. et al.	Appl. Surf. Sci.	Nanoparticles produced by laser ablation of solids in liquid environment			
Tsuji T.; Iryo K. et al.	Appl. Surf. Sci.	Preparation of silver nanoparticles by laser ablation in solution: Influence of laser wavelength on particle			
Link S.; Wang Z.L. et al.	J. Phys. Chem. B	How does a gold nanorod melt?			

Authors	Journal	Title	Publication Year	Citations/Year	Total Citations
Sylvestre J.P.; Kabashin A.V. et al.	J. Am. Chem. Soc.	Stabilization and size control of gold nanoparticles during laser ablation in aqueous cyclodextrins			

Figure 6 [Figure 6: see original paper] Research direction classification of all citing papers of the 15 most highly cited papers in LAL technology

3. Analysis of Main Research Content in LAL Technology

Although we briefly analyzed the popular research content in the LAL technology field based on the 15 most highly cited papers (Table 3), this is still insufficient to summarize the entire research landscape. By analyzing the abstracts of the retrieved literature, we found that research related to process control, mechanism analysis, and material performance applications of nanomaterial preparation using LAL technology under different conditions has always been a core concern for researchers. Therefore, based on the retrieved literature, we further summarized the main popular research content in the LAL technology field and categorized it into three aspects: "Research Methods," "Material Systems," and "Application Directions" (see Figure 7 [Figure 7: see original paper]).

Figure 7 [Figure 7: see original paper] Classification of main popular research content in LAL technology

3.1 Research Methods in LAL Technology

Since the laser ablation process in liquid systems determines the size, morphology, composition, and other properties of the obtained nanomaterials, and these not only indirectly provide feedback on formation mechanisms but are also directly related to material performance and application potential, exploring the laser ablation process using different methods to achieve mechanism summary, synthesis process control, and application performance improvement of related nanomaterials is one of the most concerning research topics in the LAL technology field. For early-stage research methods, the main focus was on adjusting laser parameters such as wavelength, pulse frequency, and energy density to obtain special nanomaterials in liquid systems and summarize the corresponding formation mechanisms [8,9]. This research approach is the most common "target ablation" method (see Figure 7). Previous studies have shown that laser pulse widths can be divided into three categories: ultra-short pulse lasers (ultrafast lasers, i.e., femtosecond lasers), short pulse lasers (nanosecond lasers), and long pulse lasers (millisecond lasers), and these three types of pulsed lasers have fundamentally different ablation processes [6]. Building upon this foundation, new research methods have continuously emerged, such as direct "solution irradiation" of salt solutions and colloids [10-13], or "external field-assisted" laser ablation under electric/magnetic fields [14-16]. Both research methods provide opportunities for precise control of nanomaterial structure and performance. Additionally, two other methods have also received widespread attention: "solvent induction" [17-19] and "post-processing" [20-22]. The former regulates the surface properties and growth processes of colloidal nanoparticles by changing solvent types, providing new analytical approaches for colloidal interface property research. The latter mainly applies colloidal nanomaterials to different fields through hydrothermal, spin-coating, and other methods, helping to further broaden the application areas of colloidal nanoparticles, such as biosensing and energy catalysis. Controlling the morphology, size, and performance of colloidal nanomaterials based on the above methods has greatly enriched the research scope of LAL technology.

3.2 Material Systems in LAL Technology

Researchers are also very concerned with summarizing the variation patterns of composition, structure, and other parameters of different materials under LAL conditions. This research content focuses more on the evolution of various parameters of the materials themselves. Through analysis and comparison, the most extensively studied material systems are "noble metals," "semiconductors," and "magnetic materials" (see Figure 7). For the "noble metal" system, the most representative are Au, Ag, Pt, and their alloys. Previous studies have shown that noble metals have low reactivity and rarely react with liquid or gas media after laser ablation [23-25]; therefore, related work has mainly focused on observing the evolution of size, morphology, and composition of colloidal nanoparticles under changing conditions such as laser parameters and solvent types. In recent years, as colloidal nanomaterials prepared by LAL technology have increasingly highlighted advantages such as being green and highly active, how to graft various biomolecules onto the surface of noble metal nanoparticles or composite them with other materials to achieve multifunctional and high-efficiency new materials has gradually become the most concentrated research topic [26-28]. For the "semiconductor"system, the coverage is very broad, such as oxides (ZnO [29], CuO [30], TiO2 [31], SnO2 [21], etc.), sulfides (PbS [32], etc.), selenides (ZnSe [33], CdSe [34], etc.), nitrides (InN [35], GaN [36], GaAs [37], etc.), and carbides (SiC [38], etc.). For these materials, the research focus is on how to construct different microstructures or form composite systems to enhance their performance in optical, electrical, chemical, and other aspects, such as the electrical conductivity of SnO2 nanoparticles after compositing with graphene [21]. Another material system is "magnetic materials," mainly including metals such as Co [39] and Ni [40], oxides such as Mn3O4 [41] and FeOx [42], and alloy materials such as FeNi [43] and AuCo [44]. Researchers are concerned with both the relationship between the magnetic properties and structural dimensions of these materials and whether magnetism can be used to assist in controlling the synthesis of new materials, discovering new mechanisms, and broadening the application scope of related materials. Through the above analysis, it can be found that LAL technology has a wide range of material research objects, fully demonstrating the universal applicability of this technology.

3.3 Application Directions of LAL Technology

After years of development, researchers have reached a consensus that LAL technology has become an effective method for preparing highly active, green nanomaterials, and whether related materials can be promoted for application development in various fields is also one of the most concerning research topics currently. For literature research on "application directions," we summarized three main application areas from all retrieved literature: "biomedicine," "energy catalysis," and "environmental protection" (see Figure 7).

In the "biomedicine" field, the toxicological effects of nanomaterials have always received significant attention. Nanomaterials prepared by conventional chemical methods typically have residual components of surfactants or other synthetic precursors on their surfaces, making it difficult to directly determine the toxicity of the nanomaterials themselves, which has become a primary obstacle for application research of nanomaterials in the "biomedicine" field. However, nanomaterials prepared by LAL technology do not require any surfactants or reaction precursors, fundamentally solving the above problems. Therefore, research on "toxicological analysis"of nanomaterials obtained through this technology is very active [45,46]. Studies have shown that direct laser ablation of metal targets (such as gold, etc.) in solutions containing biomolecules can achieve coupling between colloidal nanomaterials and biomolecules in one step [47], or colloids can be prepared first and then biomolecules can be modified on their surfaces [48]. Therefore, researchers can design multifunctional, highly active biological materials without contact with other substances, showing great application potential in "bioimaging," "biosensing," and "biopharmaceuticals" [49-52]. The positive role played by LAL technology in these four aspects of "toxicological analysis," "bioimaging," "biosensing," and "biopharmaceuticals" has gradually elevated the status of this technology in the "biomedicine" field. Currently, in this field, research groups with prominent work are mainly concentrated abroad, such as the Barcikowski Stephan group in Germany and the Kabashin Andrei V. and Meunier Michel groups in Canada.

In the "energy catalysis" field, catalyst activity is crucial for energy conversion, material decomposition, electron transfer, and other aspects. Nanomaterials prepared by LAL technology are often in metastable states with clean surfaces and active properties, and have begun to make their mark in this field. Existing studies show that nanocatalysts prepared by LAL technology (such as Au-CeO2, AuPt, PtCo, Pt-rGO, etc.) have higher activity compared with nanocatalysts prepared by conventional chemical methods [53-56]. Catalysts obtained using this technology are mainly applied in three aspects: "water splitting," "batteries," and "industrial catalysis." In "water splitting," the Liang Changhao group from the Chinese Academy of Sciences successfully combined this technology with energy research. They used colloids obtained by LAL technology as doping precursors, and the hematite thin films prepared on conductive glass substrates could achieve a photocurrent density of 1.4 mA/cm2 [57]. The Yang Guowei group from Sun Yat-sen University simultaneously achieved TiO2 reduction and its compositing with graphene oxide through the LAL method, greatly improving the efficiency of hydrogen production from water splitting [58]. The Du Xiwen group from Tianjin University developed a highly active Co3O4 catalyst based on LAL technology, whose oxygen evolution efficiency from water splitting reached the highest level for cobalt oxide materials, even exceeding the noble metal catalyst RuO2 [59]. These research works were published in top international journals and have received widespread recognition from peers. In "battery" research, reports have proven that TiO2 [60] and SnO2 [61] prepared by LAL technology can be used as cathode materials for lithium-ion batteries; Au colloids can replace biological enzymes to oxidize glucose molecules and thus achieve biofuel cell functions [62]; with the assistance of electrophoresis technology, CuSe2 colloids can be formed into films and used in solar cells [63]. Additionally, in "industrial catalysis," the main research objects are hydrocarbon compounds such as methanol, ethanol, and formic acid [64-66]. It is worth mentioning that the Liang Changhao group from the Chinese Academy of Sciences developed a highly dispersed ultrafine platinum-based catalyst that is at the international advanced level in methanol oxidation [56]. The above analysis shows that Chinese scientists have begun to advance into world frontier research in promoting the application of LAL technology in the "energy catalysis" field.

Since colloids prepared by LAL technology can be used to detect and monitor industrial wastewater and automobile exhaust emissions, as well as residues of heavy metals and pesticide components, research on its "environmental protection" applications often receives keen attention from industrial production departments. Existing studies show that colloidal nanomaterials prepared by this technology can widely achieve trace detection of heavy metal ions, pollutants in food and water (such as xanthine, pathogens, phenylhydrazine, etc. [67-69]), and flammable and explosive gases (such as CO, ethanol, HCl, H2, etc. [70-73]). In these studies, the research focus is on, on one hand, how to improve the selectivity of nanomaterials, and on the other hand, how to achieve simultaneous detection and discrimination of multiple pollutants. The technical advantages of LAL in related fields have attracted the attention of researchers worldwide.

The potential of LAL technology in fields with major application demands such as "biomedicine," "energy catalysis," and "environmental protection" has already begun to emerge. This study conducted an in-depth analysis of the development trends and research hotspot content of related technical fields from a bibliometric perspective. Relying on the Web of Science data platform, we summarized information on major publishing countries, total publication volume, research directions, research institutions, research hotspots, and main research content in related technical fields, providing detailed data to enhance researchers' in-depth understanding of related fields, with the aim of further promoting the development of LAL technology.

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