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Review

Electrochemical Etching vs. Electrochemical Deposition: A Comparative Bibliometric Analysis

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Abstract: This study presents a comprehensive bibliometric analysis of scientific publications on electrochemical etching and electrochemical deposition from 1970 to 2023. Using the Science Citation Index Expanded (SCIE) database, we analysed 5166 publications on electrochemical etching and, 30,759 publications on electrochemical deposition. The analysis reveals distinct yet interconnected research landscapes for these two techniques. Electrochemical etching research has focused on themes such as porous silicon, photoluminescence, and applications in photonics, while electrochemical deposition research has centred on energy storage, catalysis, and biosensing applications. Keyword co-occurrence analysis illustrates the progression from fundamental studies to specialised applications in both fields. This study highlights the importance of international collaboration and provides insights into the historical and contemporary advancements in electrochemical methods for nanomaterial synthesis. The findings underscore the complementary nature of electrochemical etching and deposition, driving innovation and offering new opportunities in materials science and technology.

Keywords: electrochemical etching; electrochemical deposition; research landscapes; applications; nanomaterial synthesis

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1. Introduction

The nanotechnology industry is rapidly transitioning from laboratory research to industrial and market applications, revolutionising various sectors with innovative materials and processes [1,2]. Nanomaterials and nanoparticle-containing materials are now integral parts of industries ranging from electronics to healthcare, providing enhanced performance, unique properties, and new functional capabilities [3–6]. This shift highlights the growing importance of reliable, scalable methods for synthesising nanomaterials.

Traditionally, the synthesis of nanomaterials is divided into two fundamental approaches: “top-down” and “bottom-up” [7,8] (Figure 1). The top-down approach involves reducing the size of materials to create nanoscale structures [9,10]. This technology includes mechanical milling, lithography, and laser ablation, where more significant pieces of material are systematically broken down or selectively removed to achieve nanometre sizes [11–13]. Conversely, the bottom-up approach assembles nanostructures from atomic or molecular precursors. This technology encompasses processes like chemical vapor deposition (CVD), sol–gel processing, and self-assembly, which build nanomaterials atom by atom or molecule by molecule, allowing precise control over composition and structure [14–16]. In addition to these methods, plasma-based techniques for etching and deposition, such as reactive ion etching (RIE) [17,18] and plasma-enhanced chemical vapor deposition (PECVD) [19,20], play a critical role in nanostructuring. These methods are indispensable in microelectronics and enable the self-organised formation of structures, including notable examples like black silicon [21].

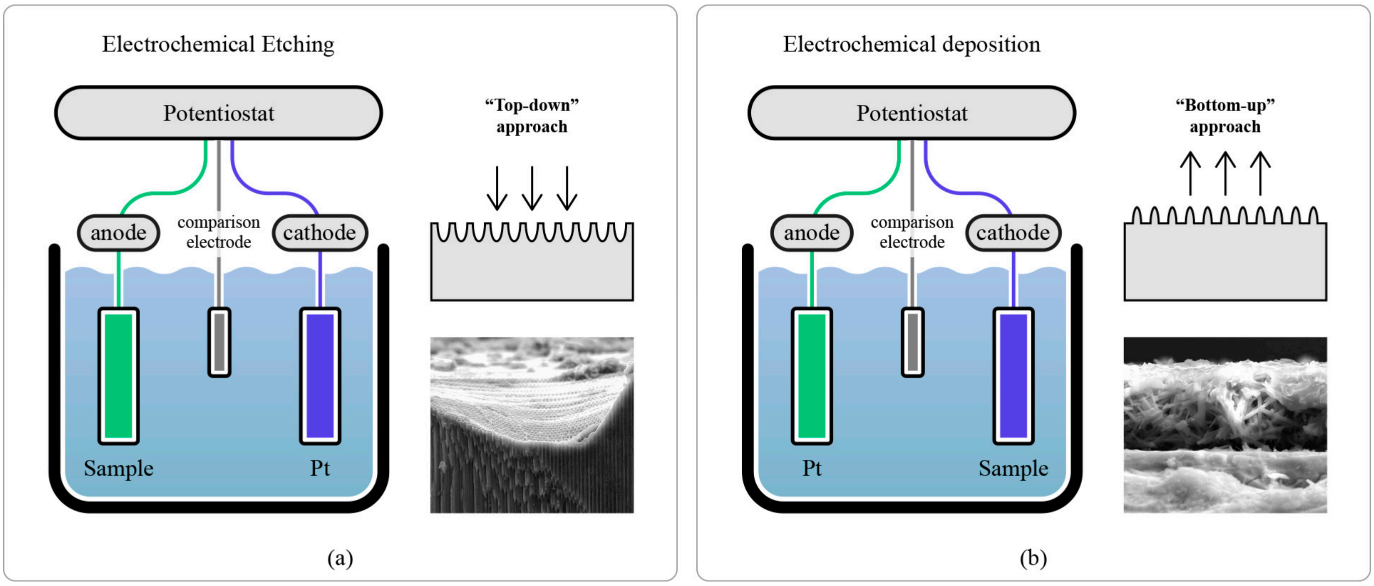


Figure 1. Schematic representation of electrochemical nanostructure synthesis: (**a**) Electrochemical etching (top-down approach); (**b**) Electrochemical deposition (bottom-up approach).

Among the various methods for synthesising nanomaterials and nanoparticles, electrochemical methods hold a significant niche [22,23]. Their simplicity, cost-effectiveness, and scalability make them attractive for industrial applications, enabling large-batch production and facilitating mass manufacturing [24]. Electrochemical methods are traditionally divided into two major categories: etching, which is an example of a top-down approach through selective material removal to create porous structures and nanostructures [25,26], and deposition, which reflects a bottom-up approach by building material from atomic or molecular precursors to form nanoscale layers and coatings [27,28].

Electrochemical etching involves the anodic dissolution of material, where an applied voltage selectively removes material from the surface, forming nanoscale features and pores (etch pits) [29]. Typical applications include the fabrication of porous silicon [30] and the creation of micro- and nanostructured surfaces for sensors and electronic devices [31]. The controlled nature of electrochemical etching allows for patterning and surface modification, making it valuable in semiconductor manufacturing and MEMS technology [32,33].

Conversely, electrochemical deposition involves the cathodic reduction of metal ions in an electrolyte solution, forming a thin film [34] or nanostructured layer on a substrate [35,36]. Electrochemical deposition is widely used for creating coatings, thin films, and metal nanoparticles, offering advantages in uniformity and thickness control [37,38], which are critical for applications in electronics, energy storage, and catalysis [39–41].

It offers advantages in uniformity and thickness control, which are critical for applications in electronics, energy storage, and catalysis [42–44]. Additionally, this method allows the synthesis of various types of nanostructures, including nanowires [45], nanorods [46], nanotubes [47], and thin films [48], spanning a wide range from zero-dimensional to three-dimensional nanomaterials [49]. For example, the deposition of gold nanoparticles by electrochemical methods has become vital in developing high-efficiency catalysts for fuel cells and other electrochemical devices [50]. Furthermore, electrochemical deposition is widely used to create protective coatings to prevent corrosion, improve the electrical conductivity of electronic components, and enhance the efficiency of catalytic processes in various industrial applications [51,52].

Both electrochemical etching and deposition share an electrochemical foundation, with the primary distinction being the type of electrochemical reaction—oxidative dissolution for etching [53] and reductive deposition for coating [54]. This distinction leads to their frequent classification as anodic [55,56] and cathodic [57,58] electrochemical treatments, respectively. Their shared nature arises from fundamental principles of electrochemistry, where controlled potential and current are used to manipulate material at the nanoscale [59].

The widespread popularity of these methods can be attributed to their practical applications and significant advancements. Electrochemical etching has played a crucial role in creating nanostructured silicon, which has found applications in photonic devices [60,61], biosensors [62], and solar energy [63,64]. The ability to produce highly porous structures with large surface areas has enhanced the performance of various silicon-based technologies [65,66]. This success has led to the adoption of this method in other semiconductors to create porous layers, particularly gaining popularity with III–V semiconductor materials such as gallium arsenide (GaAs) and indium phosphide (InP), which are essential for modern electronic and optoelectronic applications [66–71].

This study conducts a comprehensive bibliometric analysis of scientific publications on electrochemical etching and deposition, with a focus on their role in nanomaterial synthesis for electrochemical and functional applications. By analysing publication trends, international collaborations, and thematic keyword clusters, we aim to identify emerging directions and institutional contributions relevant to electrochemically active materials. This analysis contributes to understanding the strategic evolution of research on anodic and cathodic treatments, which are central to the development of advanced materials for electrochemical technologies.

We do not focus on revealing the specifics of the methods themselves; instead, we analyse the publication landscape of these topics. Until now, review articles have predominantly covered the development and applications of electrochemical methods. However, no comprehensive bibliometric analyses have been specifically concerning electrochemical methods for nanomaterial synthesis.

This study aims to map the publication landscape of electrochemical etching and deposition, uncovering key trends and insights into the research dynamics over the years. The research questions guiding this study are as follows:

- How has the volume of scientific literature on electrochemical etching and deposition evolved?
- Which countries, authors, and journals have been the most influential in advancing research in these areas?
- What are the prevalent themes and emerging trends in publications related to electrochemical etching and deposition?

Rather than focusing on the technical specifics of electrochemical processes, this study seeks to uncover how research efforts in etching and deposition have evolved over time, who the leading contributors are, and what topics have gained prominence. By adopting a bibliometric lens, we aim to provide insights into the structure and dynamics of this research domain.

2. Methodology

Bibliometric analysis is a recognised research method that applies quantitative approaches to analyse patterns in scientific publications, allowing researchers to map the structure, evolution, and emerging trends within a specific field. It has become an essential tool for systematically assessing research landscapes, identifying knowledge gaps, and informing strategic decision-making in science and technology [72,73].

The bibliometric methods applied in this study—including data extraction from the Web of Science Core Collection, co-authorship and keyword co-occurrence analysis using VOSviewer, and longitudinal trend analysis—are widely established and have been used in several bibliometric studies in natural sciences. Notable examples include analyses in nano-energy research [74], enzyme biosensors coupled to metal–organic frameworks [75], electrochemical biosensors for ocular diagnostics [76], and our recent bibliometric study on Ga_2O_3 solar-blind photodetectors [77]. These studies validate the use of similar tools and approaches for mapping research landscapes, identifying thematic clusters, and exploring international collaboration patterns. By adhering to these practices, our study ensures methodological consistency and facilitates comparability with bibliometric research across the natural sciences.

2.1. Database Selection

This study employed the Science Citation Index Expanded (SCIE) of the Web of Science Core Collection to retrieve scientific publications related to electrochemical etching and electrochemical deposition. The SCIE database was chosen for its rigorous selection process, ensuring the inclusion of high-quality, peer-reviewed articles [78]. This selection provides a robust foundation for analysing research trends and developments in these fields over an extended period.

2.2. Search Strategy

A systematic search strategy was developed to comprehensively capture the relevant literature. The following search queries were formulated to retrieve publications related to the specific topics of interest:

1. Electrochemical etching:

The search was designed to encompass a variety of terminologies used in the field, ensuring a broad and inclusive capture of the literature. The keywords used were ("electrochemical etching" OR "anodic etching" OR "electrochemical dissolution" OR "electroetching" OR "electrochemical micromachining" OR "anodic dissolution") AND ("nano*");

2. Electrochemical deposition:

Similar to the previous search, this query included terms commonly associated with electrochemical deposition processes. The keywords used were ("electrochemical deposition" OR "electrodeposition" OR "electroplating" OR "electrochemical growth" OR "cathodic deposition" OR "electrochemical coating") AND ("nano*").

2.3. Search Parameters and Filters

The search was conducted on 3 August 2024, with the application of specific filters to refine the results:

- Chronological Filter: The timeframe for the search was set from 1970 to 2023. This wide range was selected to capture the evolution and trends in electrochemical etching and deposition technologies over the last five decades, providing insights into historical and contemporary research developments;
- Language: Only publications in the English language were considered (English is the predominant language for scientific publications), ensuring access to the most widely disseminated research findings;

- Search Fields: The search was limited to the fields of "title", "abstract", and "keyword" to ensure that the retrieved articles were highly relevant to the research topics and contained pertinent information.

2.4. Data Analysis

After retrieving the publications, the data were exported for further analysis. VOSviewer 1.6.20 software was utilised for the bibliometric analysis, focusing on cooperation networks, keyword co-occurrences, and material usage [79]. The exported data included information on authors, titles, abstracts, keywords, publication years, and citations. This dataset was imported into VOSviewer to create a bibliometric map. The software reads the input files and processes the data to identify relationships between various entities within the research landscape.

Co-authorship networks were constructed to visualise the collaboration patterns among researchers and institutions. This involved mapping the connections between authors based on shared publications, highlighting the strength and frequency of collaborations.

Keyword co-occurrence networks were generated to identify the main research themes and their evolution over time. Keywords from the titles and abstracts of publications were analysed to determine how frequently they appeared together. This helped in visualising clusters of related research topics.

The networks were visualised using VOSviewer's built-in functionalities. The visualisations included the following:

- Nodes represented entities such as authors, keywords, or publications. Links between nodes indicated relationships such as co-authorship, co-occurrence, or citations. The size of the nodes reflected the frequency or importance of the entity, while the thickness of the links represented the strength of the relationship;
- Nodes and links were colour-coded to indicate different clusters or thematic areas. For instance, in keyword co-occurrence networks, different colours represented distinct research themes. This colour-coding helped in quickly identifying major areas of focus within the research landscape;
- The average publication year for each node was calculated and visualised, with a colour gradient indicating the recency of the research focus. This temporal aspect allowed us to track the evolution of research topics over time.

VOSviewer's clustering algorithm was employed to group related items into clusters. These clusters represented coherent research themes or collaboration networks. The clustering algorithm maximises the intra-cluster connections while minimising inter-cluster connections, providing a clear depiction of the structure within the data.

The visualised networks and clusters were interpreted to draw meaningful insights. For example, we considered the following:

- By examining keyword co-occurrences, we identified emerging research trends, popular research topics, and shifts in research focus over time;
- Co-authorship networks revealed key researchers and institutions leading the field, as well as the extent and nature of international collaborations.

2.5. Statistical Analysis

Descriptive statistics were calculated to provide insights into publication trends. This included computing the mean, median, standard deviation, and coefficient of variation for the annual publication counts. These statistics helped to quantify the variability and growth patterns in the research output for electrochemical etching and deposition.

2.6. Temporal and Thematic Evolution Analysis

The analysis of temporal and thematic evolution was conducted by examining the keyword co-occurrence data over time. The network maps were coloured based on the average publication year, providing insights into the shifts in research focus from earlier to more recent studies. The study period was divided into specific intervals to analyse changes in research themes and the contributions of different countries during each period.

2.7. Heat Maps and Geographical Analysis

Heat maps were generated to visualise the geographical distribution of research output. These maps highlighted the leading countries in electrochemical etching and deposition research, illustrating the global landscape of scientific contributions. The visual representation of publication productivity across different countries was performed using Python 3 programming, incorporating the Pandas (Version: 1.4.3) and Plotly Express (Version: 5.10.0) libraries. The maps clearly represented the concentration of research activities and collaborations across different regions.

By employing these methodologies, the study aims to provide a comprehensive overview of the research landscape in electrochemical etching and deposition, identifying key trends, influential contributors, and evolving themes in these fields. The robust data collection and analysis approach ensures the reliability and relevance of the findings, contributing valuable insights to the scientific community.

2.8. Limitations of the Study

The primary constraint of this study is the deliberate selection of the Science Citation Index Expanded (SCIE) as the sole database for data retrieval. This strategic choice ensures the inclusion of high-quality and highly relevant sources within the field, but may inadvertently exclude significant research indexed in other databases. This approach was chosen to maintain a focused and high-standard dataset. Additionally, the keyword dataset was not standardised to merge alternative names or synonymous terms. While this methodological choice may introduce some variability, it was designed to capture a broader spectrum of the research landscape, thus reflecting the diversity in terminology and enhancing the richness of the analysis.

3. Results

3.1. Electrochemical Etching

The search conducted in the Science Citation Index Expanded (SCIE) database yielded a total of 5166 papers on electrochemical etching, with an average of 20.91 citations per document. The majority of these publications were research articles (4937, 95.57%), followed by proceeding papers (560, 10.84%) and review articles (108, 2.09%) (Table 1). Such a predominance of research articles is typical in bibliometric datasets within the natural sciences and reflects standard publishing practices in the field.

Table 1. Publications on electrochemical etching according to the Science Citation Index Expanded (SCIE) database of the Web of Science.

Document Types	Record Count *	% *
Article	4937	95.567
Proceeding Paper	560	10.840
Review Article	108	2.091
Meeting Abstract	51	0.987
Note	42	0.813
Letter	18	0.348

Table 1. *Cont.*

Document Types	Record Count *	% *
Early Access	10	0.194
Correction	5	0.097
Editorial Material	4	0.077
Book Chapters	3	0.058
News Item	1	0.019

* Note: Some publications are recorded under multiple document types, which may cause the total percentages and counts to exceed the overall total value

The number of publications on electrochemical etching began to rise significantly in the early 1990s. This growth has continued sharply to the present day, indicating a sustained interest and advancement in the field over the decades (Figure 2).

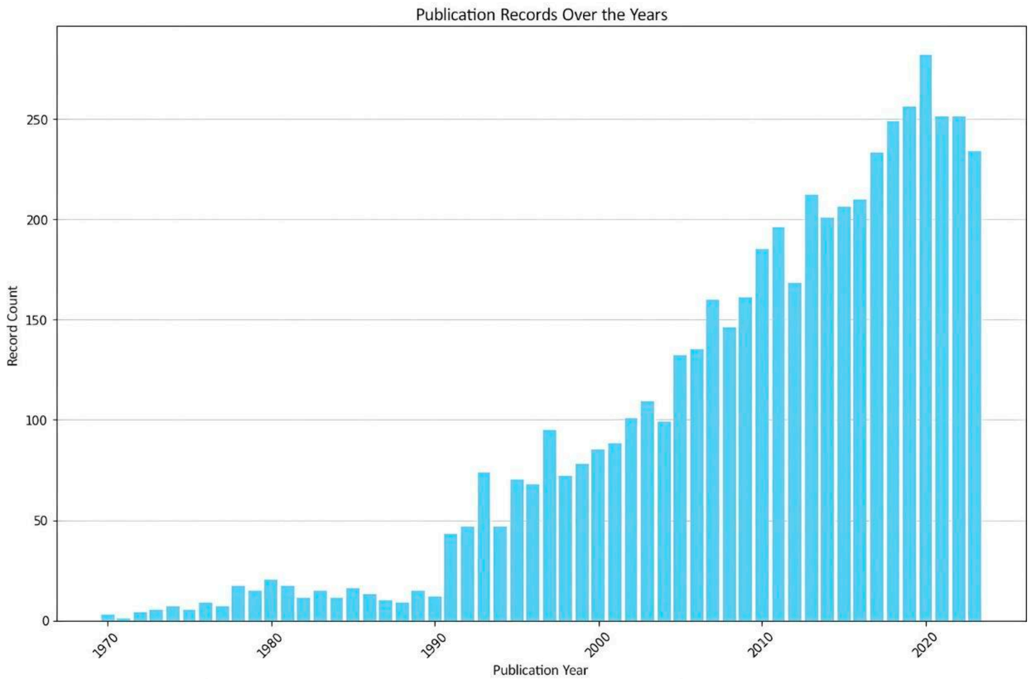


Figure 2. Trend in publications on electrochemical etching from 1970 to 2023.

The topic of electrochemical etching spans 55 research areas within SCIE. The largest proportions of publications fall under materials' science (2215, 42.88%), physics (1745, 33.78%), chemistry (1243, 24.06%), electrochemistry (915, 17.71%), and engineering (847, 16.40%) (Table 2).

Table 2. Top-20 research areas for publications on electrochemical etching according to the Science Citation Index Expanded (SCIE) database of the Web of Science.

Research Areas	Record Count	% of 5166
Materials Science	2215	42.877
Physics	1745	33.779
Chemistry	1243	24.061
Electrochemistry	915	17.712
Engineering	847	16.396
Science Technology Other Topics	711	13.763
Metallurgy Metallurgical Engineering	427	8.266
Instruments Instrumentation	318	6.156
Nuclear Science Technology	253	4.897

Table 2. *Cont.*

Research Areas	Record Count	% of 5166
Optics	211	4.084
Energy Fuels	126	2.439
Automation Control Systems	99	1.916
Environmental Sciences Ecology	80	1.549
Radiology Nuclear Medicine Medical Imaging	64	1.239
Public Environmental Occupational Health	53	1.026
Crystallography	37	0.716
Mining Mineral Processing	34	0.658
Biochemistry Molecular Biology	29	0.561
Mineralogy	25	0.484

The most prolific journals publishing on electrochemical etching include Journal of the Electrochemical Society (264, 5.11%), Electrochimica Acta (179, 3.47%), Applied Surface Science (104, 2.01%), International Journal of Advanced Manufacturing Technology (96, 1.86%), Applied Physics Letters (90, 1.74%), and Nuclear Tracks and Radiation Measurements (74, 1.43%) (Table 3).

Table 3. Top-20 journals publishing articles on electrochemical etching according to the Science Citation Index Expanded (SCIE) database of the Web of Science.

Publication Titles	Record Count	% of 5166
Journal of the Electrochemical Society	264	5.110
Electrochimica Acta	179	3.465
Applied Surface Science	104	2.013
International Journal of Advanced Manufacturing Technology	96	1.858
Applied Physics Letters	90	1.742
Nuclear Tracks and Radiation Measurements	74	1.432
Corrosion Science	63	1.220
Thin Solid Films	61	1.181
Review of Scientific Instruments	54	1.045
Journal of Electroanalytical Chemistry	53	1.026
Journal of Applied Physics	52	1.007
Journal of Physical Chemistry C	51	0.987
Journal of Applied Electrochemistry	50	0.968
ACS Applied Materials Interfaces	49	0.949
International Journal of Electrochemical Science	49	0.949
Applied Physics a Materials Science Processing	46	0.890
Journal of Materials Processing Technology	45	0.871
Journal of Alloys and Compounds	44	0.852
Journal of Micromechanics and Microengineering	44	0.852

The leading publishers in this area are Elsevier (1747, 33.82%), Springer Nature (553, 10.71%), Electrochemical Society Inc. (324, 6.27%), American Chemical Society (278, 5.39%), American Institute of Physics (241, 4.67%), Wiley (234, 4.53%), and IOP Publishing Ltd. (228, 4.41%) (Table 4).

Researchers from China (1208, 23.38%), the USA (585, 11.32%), Germany (403, 7.80%), India (338, 6.54%), Russia (338, 6.54%), and Japan (337, 6.52%) were the most active contributors to this topic (Figure 3). These nations have established themselves as leaders in electrochemical etching research, fostering significant advancements in the field.

Table 4. Top-20 publishers of electrochemical etching research according to the Science Citation Index Expanded (SCIE) database of the Web of Science.

Publishers	Record Count
Elsevier—Amsterdam, 1043 NX, Netherlands	1747
Springer Nature—Heidelberg, 69121, Germany	553
Electrochemical Soc Inc—Pennington, NJ 08534, USA	324
Amer Chemical Soc—Washington, DC 20036, USA	278
Amer Inst Physics—Melville, NY 11747, USA	241
Wiley—Hoboken, NJ 07030, USA	234
IOP Publishing Ltd.—Bristol, BS1 6BE, United Kingdom	228
Royal Soc Chemistry—Cambridge, CB4 0WF, United Kingdom	131
MDPI—Basel, 4052, Switzerland	119
Taylor & Francis—Abingdon, OX14 4RN, United Kingdom	111
Pleiades Publishing Inc—New York, NY 10012, USA	75
IEEE —Piscataway, NJ 08854, USA	51
Plenum Publ Corp—New York, NY 10013, USA (now part of Springer)	51
ESQ (EDP Sciences)—Les Ulis, 91940, France	47
Amer Scientific Publishers (ASP)—Valencia, CA 91355, USA	40
Nature Portfolio—London, W1B 3HH, United Kingdom	32
Optical Soc Amer (Optica Publishing Group)—Washington, DC 20036, USA	28
Maik Nauka/Interperiodica—Moscow, 117997, Russia	25
Sage—Thousand Oaks, CA 91320, USA	25

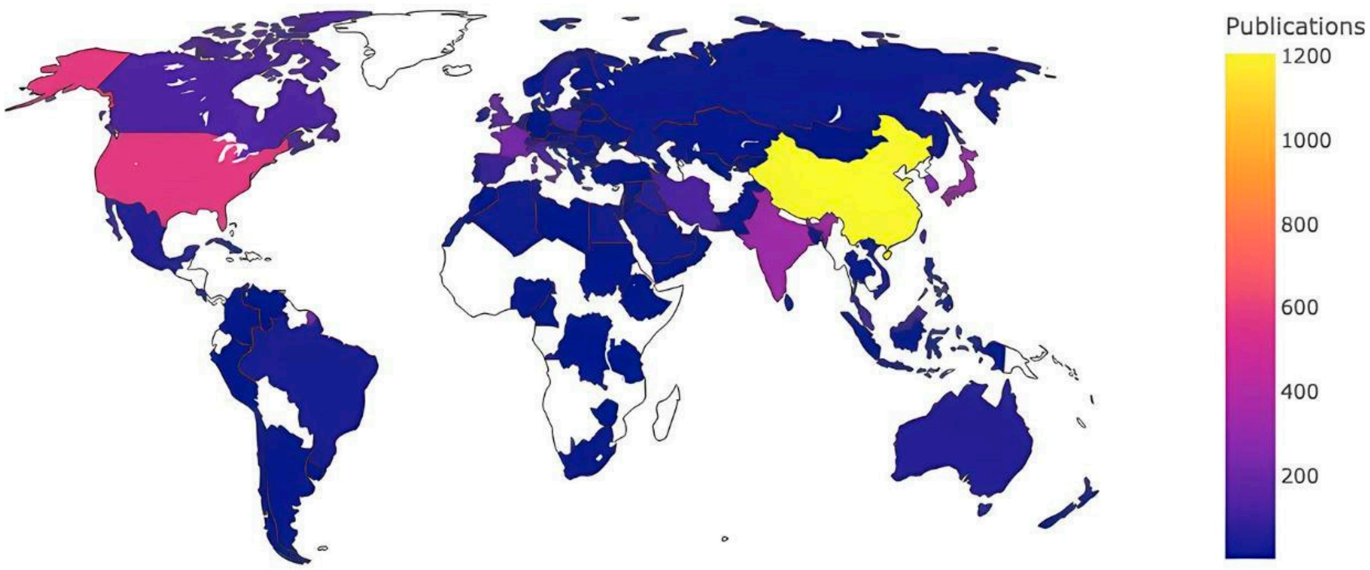


Figure 3. Global publication productivity in electrochemical etching.

International collaboration plays a critical role in scientific progress, as evidenced by the network of academic partnerships depicted in Figure 4. This figure illustrates the collaborative relationships between the most productive countries, each contributing at least 24 documents. Nodes represent different countries, and the connecting lines indicate cooperation intensity, with line thickness proportional to collaboration strength.

The diagram shows that China is the most central and interconnected node, indicating its significant role in global research collaboration. The United States also emerges as a major hub, reflecting its active participation in international research projects. Germany, Japan, and South Korea are other prominent countries with substantial collaborative links, showcasing their contributions to scientific advancements through partnerships.

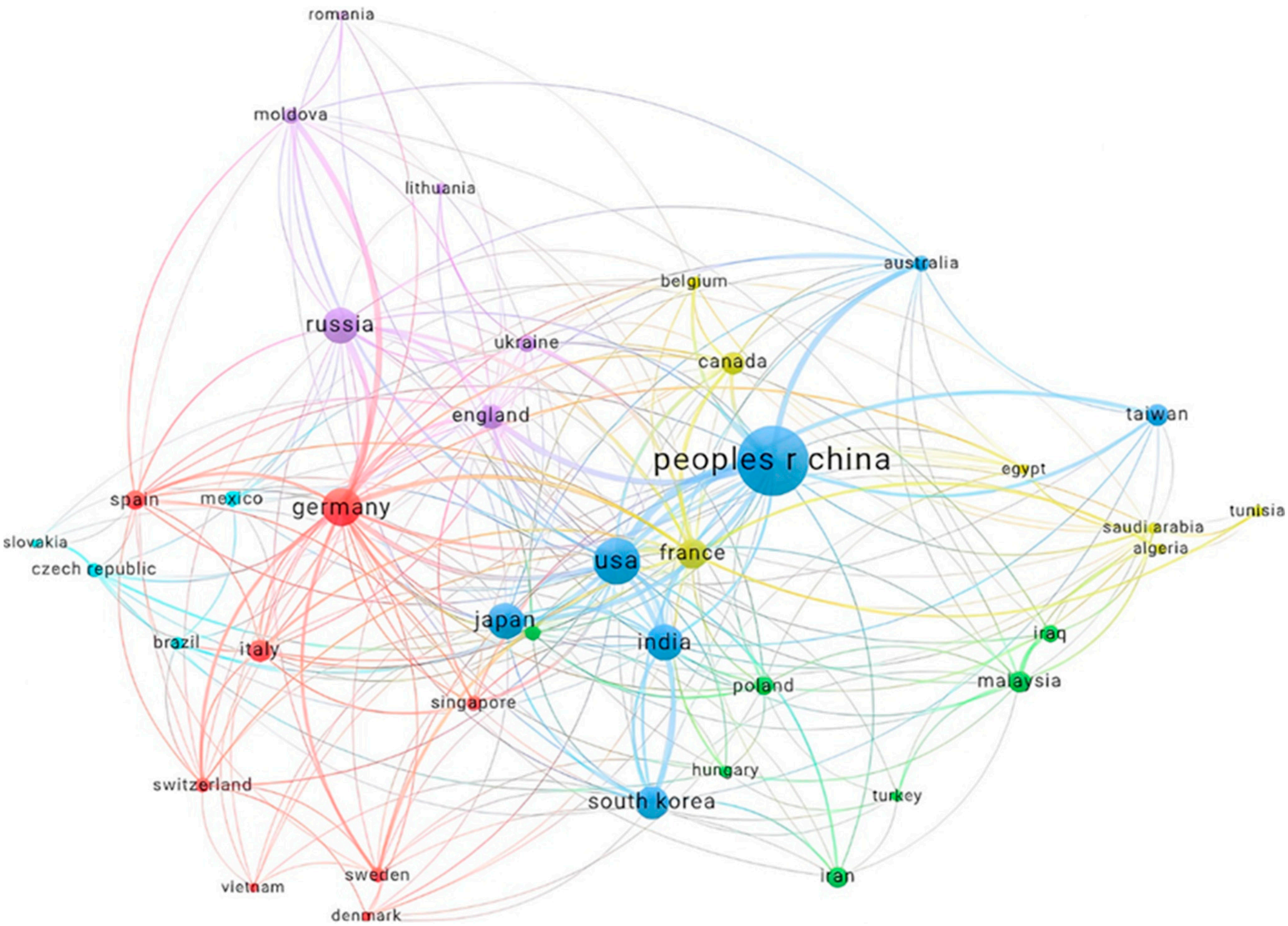


Figure 4. International collaboration network in electrochemical etching research. Nodes represent countries with at least 24 publications; link thickness indicates the strength of collaboration. China is the most interconnected node, highlighting its central role in global research partnerships. The USA, Germany, Japan, and South Korea also form major hubs, while countries like India, Malaysia, and Brazil show growing participation. Regional clusters are visible in Europe and East Asia, indicating strong intra-regional collaborations. The interactive visualisation is available at: https://tinyurl.com/mumpk5rj (accessed on 10 April 2025).

European countries such as the UK, France, and Italy demonstrate strong intra-continental collaborations, underscoring the regional emphasis on joint research initiatives. Interestingly, emerging economies like India, Malaysia, and Brazil also feature in the network, indicating their growing involvement in global research efforts. The presence of smaller countries such as Taiwan and Singapore further emphasises the inclusivity and widespread nature of international scientific collaboration.

Figure 5 demonstrates the evolution of international collaboration in electrochemical etching research over the years, highlighting the average publication year for each country involved. The colour gradient, ranging from blue to yellow, indicates the average publication year, with blue representing earlier years and yellow representing more recent years.

China stands out as the most prolific contributor, with the highest number of publications (1199 documents), and the average publication year of 2016 indicates a relatively recent surge in research output. The USA also shows a significant number of publications, maintaining a robust presence in the field over time, with an average publication year around 2013. This suggests sustained research activity and collaboration.

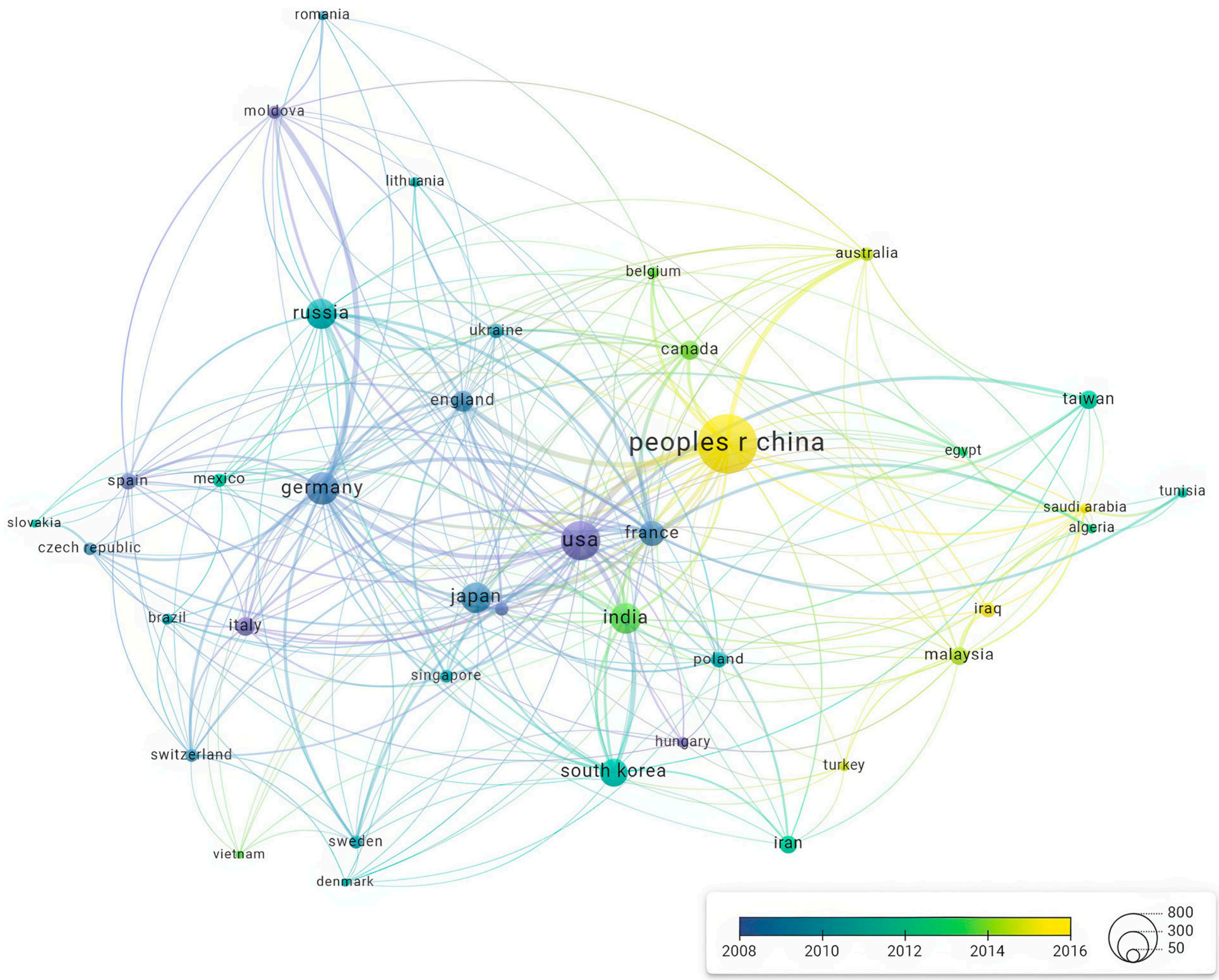


Figure 5. Evolution of international collaboration in electrochemical etching research, highlighting the average publication year for each country. The network shows international collaboration patterns, coloured by average publication year (blue: earlier; yellow: more recent). China's node, in bright yellow, indicates a recent surge in research activity. The USA and Germany show consistent activity over time, while countries like Taiwan and Malaysia are emerging contributors. Russia appears with an earlier average publication year, suggesting an earlier research focus now surpassed by others. The interactive visualisation is available at: https://tinyurl.com/mumpk5rj (accessed on 10 April 2025).

Countries like Germany, Japan, and South Korea also feature prominently, with substantial publication records and collaboration networks. Germany's average publication year is earlier than China's, reflecting its longer-term engagement in the field. In contrast, Taiwan, Malaysia, and other countries in the Asia-Pacific region show more recent average publication years, highlighting their emerging roles in electrochemical deposition research.

Russia's position in the network, with its collaborations depicted in purple, indicates earlier average publication years, reflecting a historical focus on this area. However, the recent output from other countries has surpassed it in terms of volume and recency.

The analysis underscores the dynamic nature of international collaboration in electrochemical etching research. While established leaders like China and the USA continue to drive the field, new contributors from the Asia-Pacific region are rapidly increasing their impact, fostering a more diverse and interconnected global research community. This trend highlights the importance of collaborative efforts in advancing the field and suggests a promising future for continued innovation and discovery.

The keywords in scientific papers offer valuable insights into the study's themes and focal areas. In this analysis, VOSviewer 1.6.20 software was utilised to examine the frequency and co-occurrence of keywords in publications related to electrochemical etching, using SCIE data. A total of 12,621 keywords were identified, of which only 565 appeared 10 or more times. Figure 6 presents the co-occurrence network map of the most frequent keywords, highlighting connections between terms. Each node represents a keyword, and the connecting lines indicate co-occurrence, with node size proportional to keyword linkage and line thickness reflecting co-occurrence frequency.

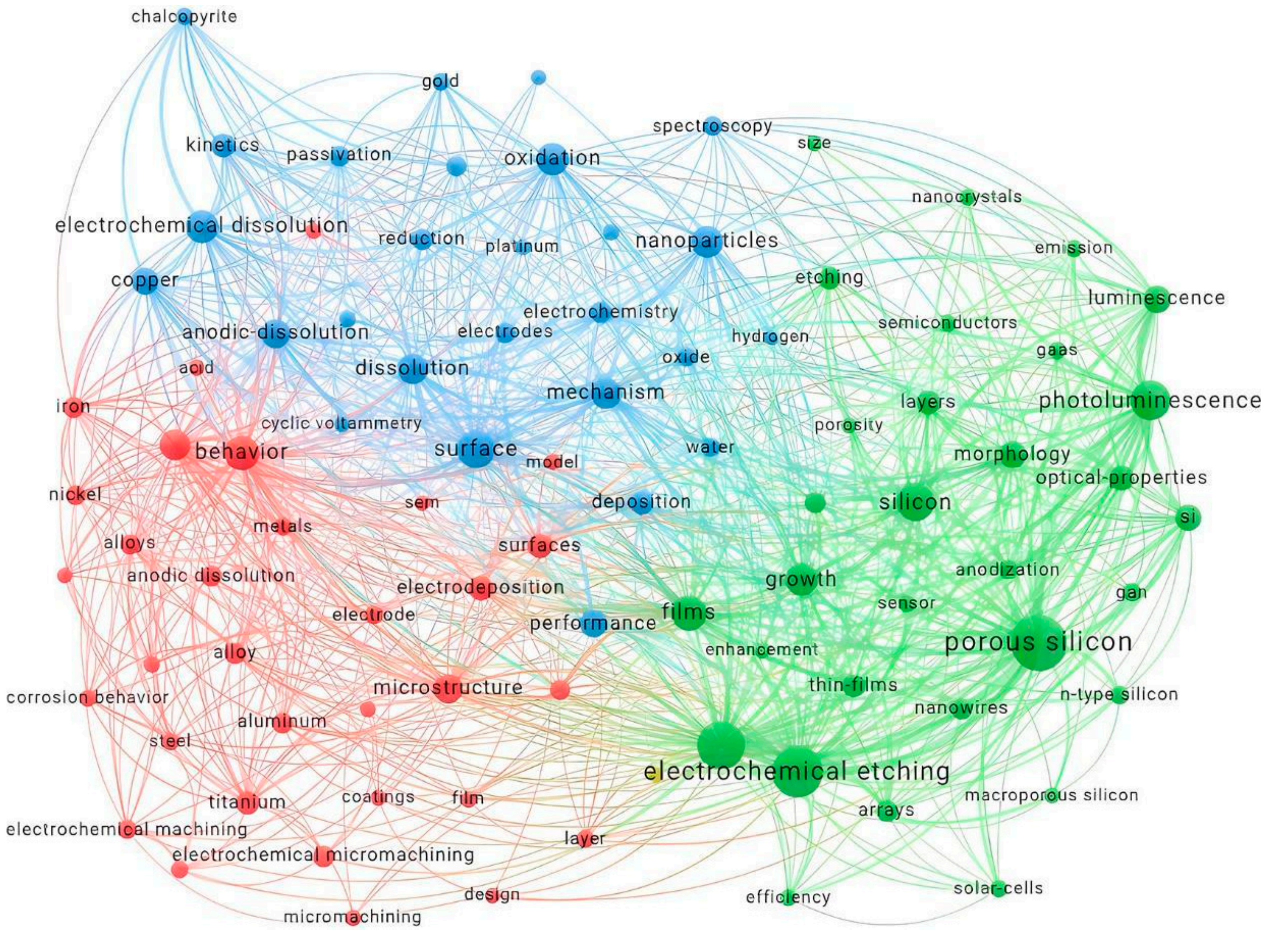


Figure 6. Keyword co-occurrence network in electrochemical etching publications. The interactive visualisation is available at https://tinyurl.com/4c2fkcbe (accessed on 10 April 2025).

For this map, keywords with a minimum of 50 occurrences were selected, resulting in 91 keywords. "Electrochemical etching" emerged as the central keyword, exhibiting 564 co-occurrences. Notably, strong associations were observed with "porous silicon" (677 co-occurrences), "fabrication" (494 co-occurrences), and "photoluminescence" (343 co-occurrences).

The co-occurrence analysis revealed three clusters of closely related keywords, each marked with different colours (Figure 5). Cluster 1, represented in red, comprises 32 keywords, focusing on electrochemical dissolution and behaviour. The theme of this cluster centres around the processes and mechanisms of electrochemical dissolution and the resulting behaviours of materials. The publications in this cluster mainly reflect research on interactions at the surface level during electrochemical etching, including the dissolution of different metals and alloys and the effects on microstructure and corrosion resistance.

Cluster 2, shown in green, comprises 31 keywords primarily related to silicon and other semiconductors. This cluster emphasises the use of silicon and other semiconductor materials in various applications. The strong association with photoluminescence and optical properties indicates that the publications mainly reflect a focus on the photonic applications of silicon and other semiconductors. The research concerned the structural and functional modifications of these materials, highlighting the use of nanowires, thin films, and semiconductors for enhanced performance in sensors and solar cells.

Cluster 3, depicted in blue, contains 28 keywords, with an emphasis on nanoparticles and oxidation processes. This cluster concentrates on the oxidation and reduction processes involving nanoparticles. The publications in this cluster show attention to surface interactions and dissolution behaviours of metals and nanoparticles during electrochemical processes. The research emphasises the kinetics of these reactions and their implications for material performance, particularly in terms of passivation and oxidation resistance.

In summary, the keyword co-occurrence network analysis provides a comprehensive overview of the major thematic areas within electrochemical etching research. The identified clusters highlight the focus on electrochemical dissolution processes and material behaviours, the applications and modifications of silicon-based materials, and the oxidation and reduction processes involving nanoparticles. These clusters represent distinct but interconnected areas of research, offering a detailed understanding of the various aspects of electrochemical etching and the materials involved.

The analysis of keywords in the publications also shed light on the most frequently studied materials, including porous silicon (677 occurrences), silicon (303), copper (160), titanium (117), aluminium (96), iron (96), nickel (86), gold (68), stainless steel (58), platinum (53), graphene (48), and silver (41). These materials play pivotal roles in electrochemical etching research and are central to ongoing scientific exploration.

The analysis of keyword co-occurrence data over time for electrochemical etching offers insights into the shifting research trends and focal points within this field (Figure 7). The network map, coloured based on the average publication year, illustrates how different research themes have emerged and evolved from 2010 to 2016. This can be attributed to the year of the appearance of these specific graphs and themes. After 2016, no new dominant themes emerged that had a minimum of 50 occurrences. This may indicate a diversification of research topics, leading to a broader field with a more extensive network that does not exhibit the same dense connections as before.

In the early years, from 2010 to 2012, research primarily focused on fundamental aspects of electrochemical etching. Key topics included “dissolution,” “oxidation,” and “surface” as researchers sought to understand the basic mechanisms and behaviours involved in electrochemical processes. The emphasis was on developing a foundational understanding that could be built upon in subsequent years.

From 2013 to 2014, the focus of research expanded to include more applied aspects, such as “nanoparticles”, “thin films”, and “fabrication”. This period saw significant advancements in the practical applications of electrochemical etching, with an increased emphasis on creating nanostructures and improving fabrication techniques. Researchers explored new materials and methods to enhance the efficiency and effectiveness of electrochemical etching.

In the later years, from 2015 to 2016, the research landscape diversified further, incorporating advanced applications and emerging technologies. Keywords like “photoluminescence”, “optical properties”, and “porous silicon” became more prominent, indicating a growing interest in using electrochemical etching for photonic and optoelectronic applications. The development of "porous silicon" and its integration into various technological applications became a major research focus.

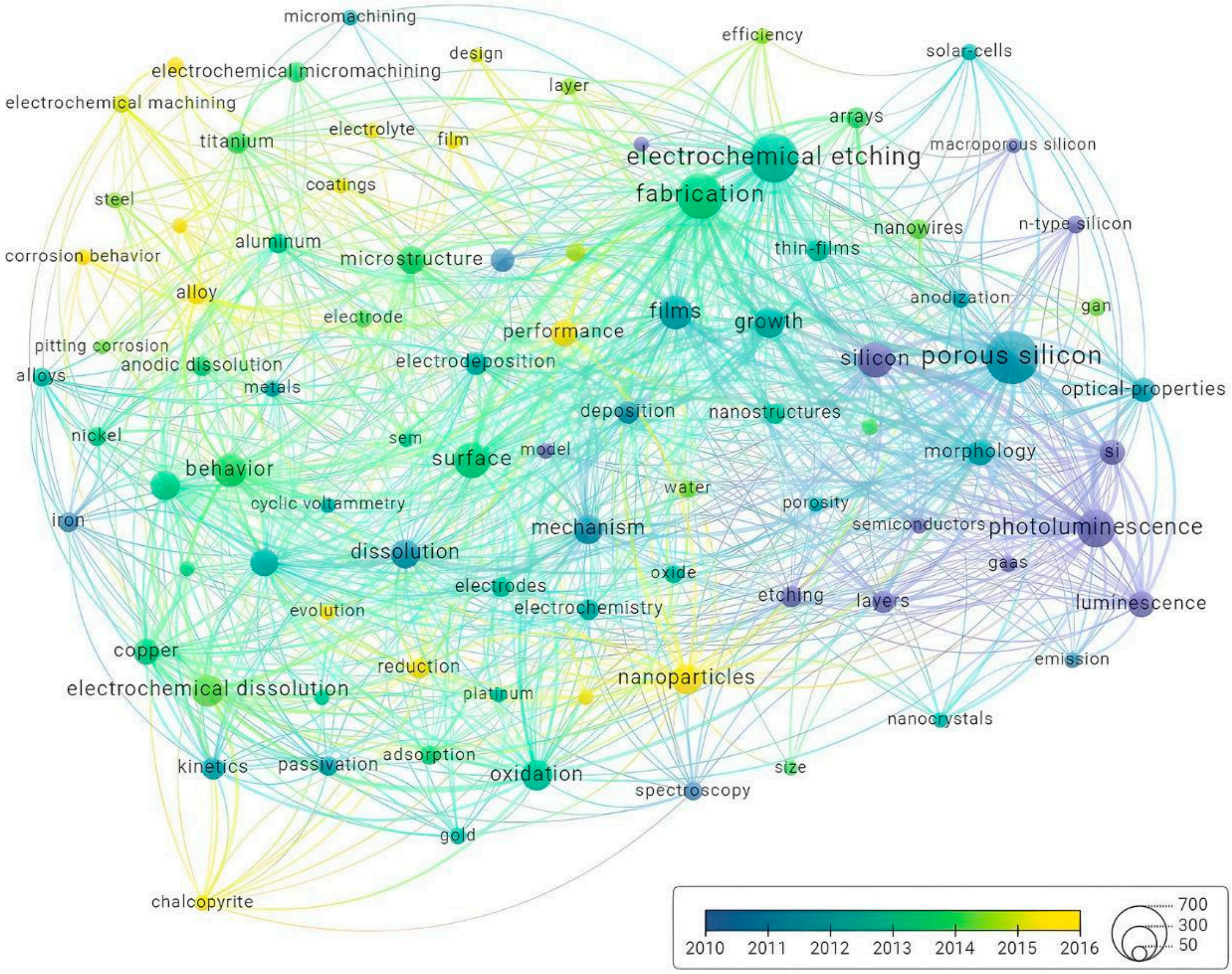


Figure 7. Temporal and thematic evolution of electrochemical etching research. The interactive visualisation is available at https://tinyurl.com/4c2fkcbe (accessed on 10 April 2025).

The interconnectedness of different keywords, represented by the strength of the links between them, highlights the collaborative nature of research in this field. Strong connections between keywords such as "electrochemical etching", "fabrication", and "porous silicon" demonstrate the multidisciplinary approach adopted by researchers to address complex challenges and innovate within the field.

In summary, the temporal and thematic analysis of electrochemical etching research reveals a dynamic and evolving field. Early research focused on fundamental mechanisms, followed by a shift towards practical applications and advanced technologies. This progression reflects the ongoing efforts of researchers to push the boundaries of what is possible with electrochemical etching and its applications in various industries.

3.2. Electrochemical Deposition

A comprehensive search in the Science Citation Index Expanded (SCIE) database identified a total of 30,759 papers dedicated to electrochemical deposition. The majority of these publications are research articles (29,801, 96.89%), followed by proceeding papers (1451, 4.72%) and review articles (781, 2.54%) (Table 5). The publication trend, as depicted in Figure 8, indicates that interest in electrochemical deposition began to surge in the early 2000s and has maintained a robust growth trajectory to the present day.

Table 5. Document types for electrochemical deposition publications according to the Science Citation Index Expanded (SCIE) database of the Web of Science.

Document Types	Record Count *	% *
Article	29,801	96.885
Proceeding Paper	1451	4.717
Review Article	781	2.539
Early Access	103	0.335
Meeting Abstract	83	0.270
Letter	49	0.159
Editorial Material	18	0.059
Correction	17	0.055
Book Chapters	8	0.026
Note	4	0.013
News Item	3	0.010

* Note: Some publications are recorded under multiple document types, which may cause the total percentages and counts to exceed the overall total value

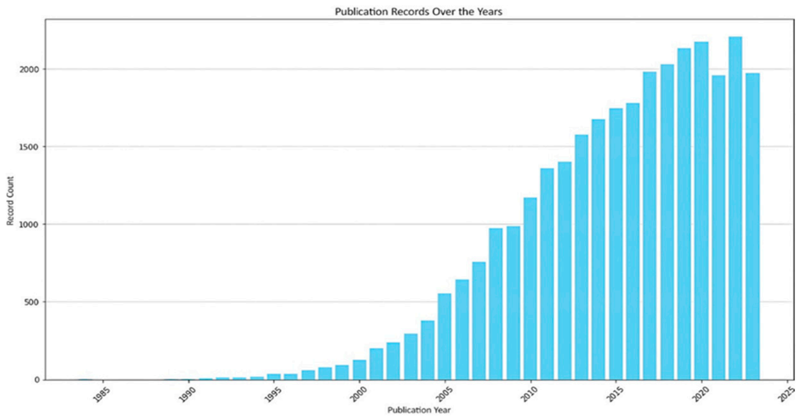


Figure 8. Trend in publications on electrochemical deposition from 1970 to 2023.

Electrochemical deposition research spans 63 distinct areas within the SCIE, with the most substantial contributions coming from materials science (15,354, 49.92%), chemistry (13,623, 44.29%), physics (8763, 28.49%), electrochemistry (6813, 22.15%), and other topics in science and technology (5234, 17.02%) (Table 6).

Table 6. Top-20 research areas of electrochemical deposition publications according to the Science Citation Index Expanded (SCIE) database of the Web of Science.

Research Areas	Record Count	% of 30,759
Materials Science	15,354	49.917
Chemistry	13,623	44.289
Physics	8763	28.489
Electrochemistry	6813	22.150
Science Technology Other Topics	5234	17.016
Engineering	2870	9.331
Metallurgy Metallurgical Engineering	2290	7.445
Energy Fuels	1940	6.307
Instruments Instrumentation	709	2.305
Polymer Science	430	1.398
Environmental Sciences Ecology	394	1.281

Table 6. *Cont.*

Research Areas	Record Count	% of 30,759
Optics	323	1.050
Biophysics	298	0.969
Biotechnology Applied Microbiology	286	0.930
Biochemistry Molecular Biology	283	0.920
Crystallography	276	0.897
Nuclear Science Technology	127	0.413
Spectroscopy	120	0.390
Food Science Technology	110	0.358

The most prolific journals publishing on electrochemical deposition include Electrochimica Acta (1558, 5.07%), Journal of the Electrochemical Society (941, 3.06%), Applied Surface Science (752, 2.45%), Journal of Alloys and Compounds (743, 2.42%), Surface Coatings Technology (579, 1.88%), and Journal of Electroanalytical Chemistry (554, 1.80%) (Table 7). These journals are at the forefront of disseminating significant research findings in this field.

Table 7. Top-20 journals publishing articles on electrochemical deposition according to the Science Citation Index Expanded (SCIE) database of the Web of Science.

Publication Titles	Record Count	% of 30,759
Electrochimica Acta	1558	5.065
Journal of the Electrochemical Society	941	3.059
Applied Surface Science	752	2.445
Journal of Alloys and Compounds	743	2.416
Surface Coatings Technology	579	1.882
Journal of Electroanalytical Chemistry	554	1.801
RSC Advances	532	1.730
ACS Applied Materials Interfaces	510	1.658
International Journal of Electrochemical Science	501	1.629
International Journal of Hydrogen Energy	465	1.512
Materials Letters	456	1.482
Journal of Physical Chemistry C	422	1.372
Nanotechnology	372	1.209
Electrochemistry Communications	344	1.118
Journal of Solid State Electrochemistry	330	1.073
Journal of Power Sources	321	1.044
Journal of Materials Chemistry A	310	1.008
Sensors and Actuators B Chemical	300	0.975
Journal of Nanoscience and Nanotechnology	298	0.969

Leading publishers in the domain of electrochemical deposition are Elsevier (12,396, 40.30%), the American Chemical Society (2805, 9.12%), Springer Nature (2696, 8.77%), the Royal Society of Chemistry (2332, 7.58%), Wiley (2029, 6.60%), Electrochemical Society Inc. (1142, 3.71%), and MDPI (897, 2.92%). These publishers are instrumental in curating and advancing the scientific discourse on electrochemical deposition (Table 8).

Researchers from China (12,168, 39.56%), the USA (3500, 11.38%), India (2118, 6.89%), South Korea (2083, 6.77%), Iran (1701, 5.53%), Japan (1432, 4.66%), and Germany (1406, 4.57%) have been the most active contributors to this research area (Figure 9). These countries have established themselves as leaders in electrochemical deposition research, demonstrating a strong commitment to advancing the field.

Table 8. Top-20 publishers of electrochemical deposition research according to the Science Citation Index Expanded (SCIE) database of the Web of Science.

Publishers	Record Count
Elsevier—Amsterdam, 1043 NX, Netherlands	12,396
American Chemical Society (ACS)—Washington, DC 20036, USA	2805
Springer Nature—Heidelberg, 69121, Germany	2696
Royal Soc Chemistry (RSC)—Cambridge, CB4 0WF, United Kingdom	2332
Wiley—Hoboken, NJ 07030, USA	2029
Electrochemical Soc. Inc.—Pennington, NJ 08534, USA	1142
MDPI—Basel, 4052, Switzerland	897
IOP Publishing Ltd.—Bristol, BS1 6BE, United Kingdom	812
Taylor & Francis—Abingdon, OX14 4RN, United Kingdom	589
ESQ (EDP Sciences)—Les Ulis, 91940, France	447
American Institute of Physics (AIP)—Melville, NY 11747, USA	438
American Scientific Publishers (ASP)—Valencia, CA 91355, USA	393
Science Press—Beijing, 100710, China	217
IEEE (Institute of Electrical and Electronics Engineers)—Piscataway, NJ 08854, USA	195
Nature Portfolio—London, W1B 3HH, United Kingdom	175
World Scientific—Singapore, 609433, Singapore	145
Pleiades Publishing Inc.—New York, NY 10012, USA	122
Hindawi Publishing Group—London, WC1X 8HB, United Kingdom	106
Peking Univ. Press—Beijing, 100871, China	100

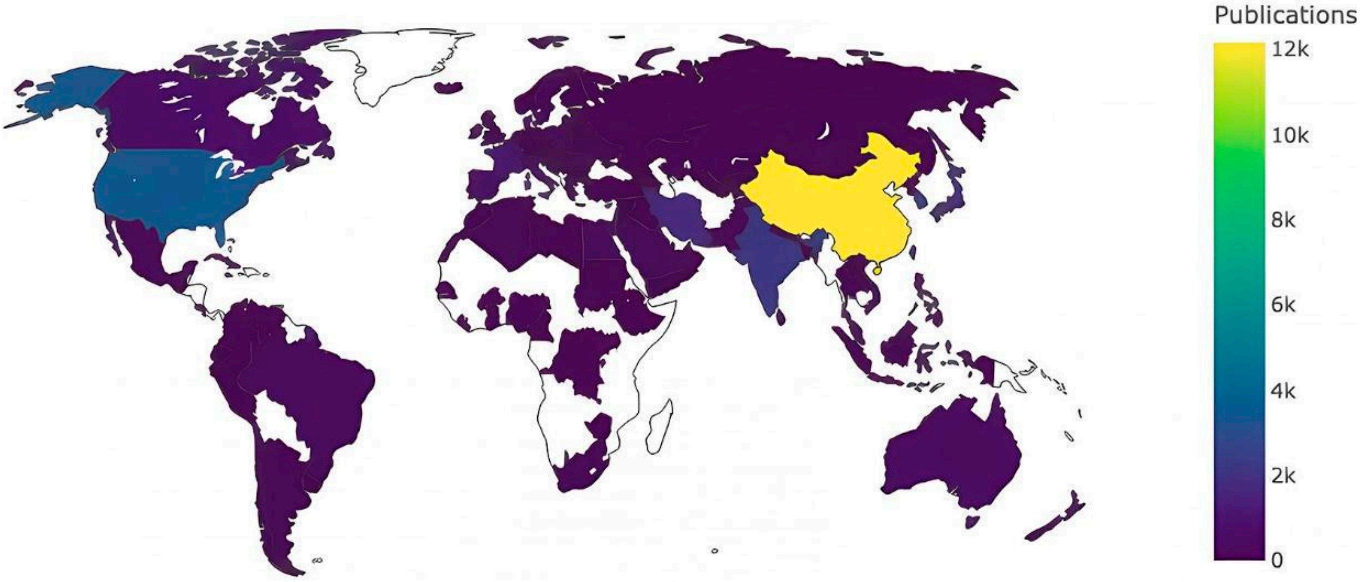


Figure 9. Global publication productivity in electrochemical deposition.

Figure 10 illustrates the international collaboration network among the most prolific countries, each contributing at least 24 documents. China emerges as the most prominent node, reflecting its substantial contribution and central role in global research collaboration. The USA, while also significant, shows fewer connections compared to China, suggesting a more selective collaboration approach.

European countries, particularly Germany, France, and Italy, display dense intra-continental collaboration networks, emphasising the strong regional research partnerships within Europe. Countries like India, South Korea, and Iran are also well-integrated into the global network, showcasing their active participation in international research projects.

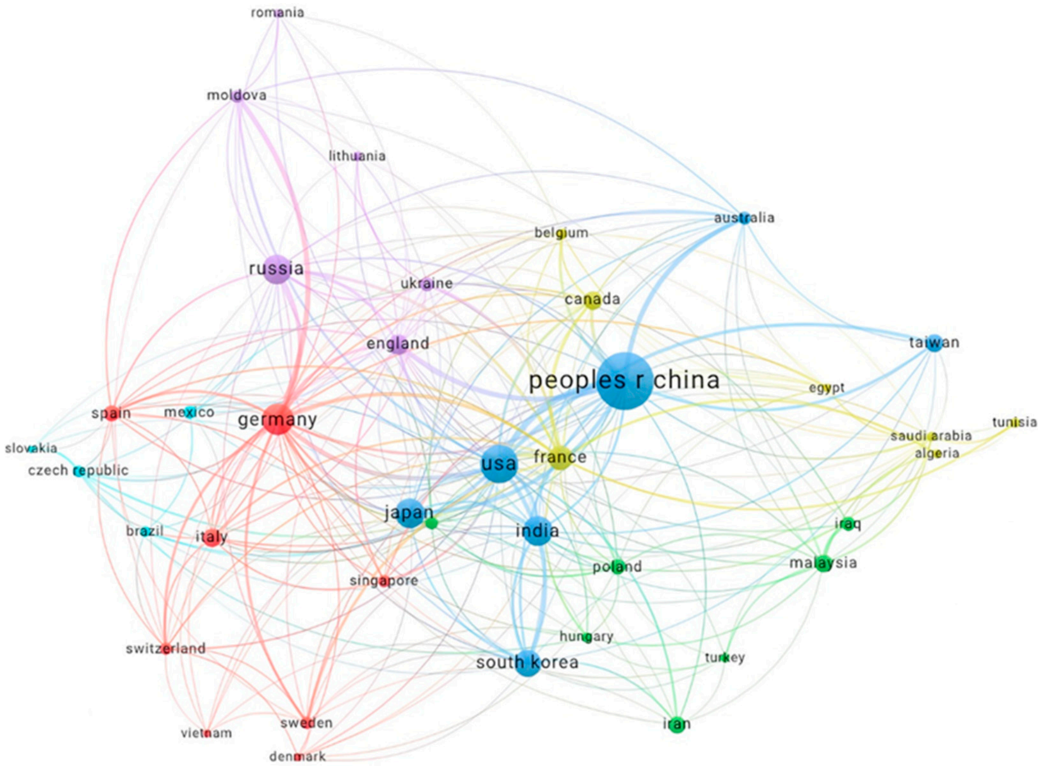


Figure 10. International collaboration network in electrochemical deposition research. Countries contributing at least 24 publications are displayed, with link thickness denoting collaboration strength. China is the dominant hub, with extensive collaborations across Asia, Europe, and North America. The USA and major European countries (e.g., Germany, France, Italy) also form strong collaboration cores. New research economies such as Malaysia, Egypt, and Saudi Arabia are increasingly active in international networks. The interactive visualisation is available at https://tinyurl.com/25vvaxz5 (accessed on 10 April 2025).

The presence of emerging research nations, such as Malaysia, Saudi Arabia, and Egypt, indicates their growing involvement in electrochemical deposition research, contributing to a more diverse and inclusive global research community.

Figure 11 presents an analysis of the international collaboration network in electrochemical deposition research over the years, highlighting the evolution of these collaborations. The nodes are coloured based on the average publication year, with blue indicating earlier years and yellow representing more recent years. This temporal gradient allows us to observe the shifting dynamics of research activity and collaboration intensity.

China stands out as the most prominent node, indicating its significant and recent surge in research output. The concentration of publications around the average year 2016 underscores China's rapid ascension and dominant role in the field. The USA, while also maintaining a substantial presence, displays a broader range of collaboration over a longer period, with its average publication year around 2013. This suggests a more sustained and consistent research effort.

European countries such as Germany, France, and Italy exhibit dense intra-continental collaboration networks with average publication years indicating a long-term engagement in the field. Germany, with its earlier average publication year, reflects its established history and foundational role, whereas countries like Spain and the UK show a more recent focus, indicating ongoing and evolving research activities.

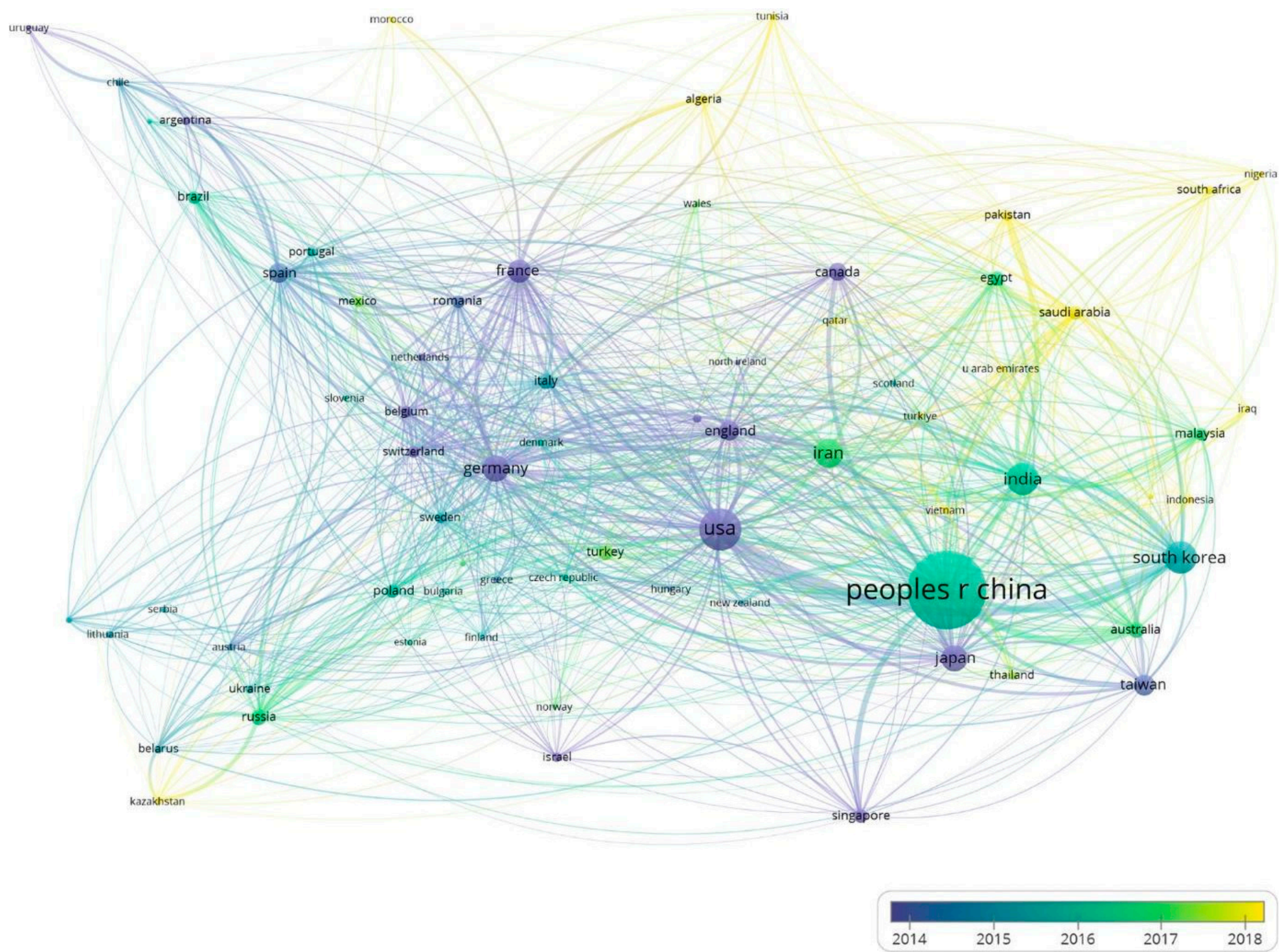


Figure 11. Evolution of international collaboration in electrochemical deposition research, highlighting the average publication year for each country. Nodes are coloured by the average year of publication, showing temporal dynamics of international collaboration. China (yellow) has rapidly risen in prominence, with most output concentrated in recent years. The USA maintains a broad collaboration profile over time (light green), while countries like Egypt, Saudi Arabia, and Malaysia show recent research growth. Earlier contributors such as Japan and Russia appear in darker colours, reflecting longer-established participation. The interactive visualisation is available at https://tinyurl.com/25vvaxz5 (accessed on 10 April 2025).

Emerging research nations, including Malaysia, Saudi Arabia, and Egypt, display more recent average publication years, highlighting their growing involvement and increasing contributions to global research efforts. This trend signifies a broadening of the research community, with new players adding to the diversity and depth of electrochemical deposition research.

In terms of keyword analysis, the VOSviewer software was utilised to evaluate the frequency and co-occurrence of keywords within the publications. This analysis revealed a total of 50,508 keywords, with 3338 occurring 10 times or more. Figure 12 presents a co-occurrence network map of the most frequently occurring keywords, constructed from keywords with at least 50 occurrences, resulting in a network of 850 keywords.

The term "electrodeposition" is notably central within this research field, exhibiting 12,544 co-occurrences with other keywords, indicating its pivotal role in electrochemical deposition studies. Prominent associations are observed with "nanoparticles" (4995 co-occurrences), "fabrication" (3682 co-occurrences), and "films" (2976 co-occurrences), reflecting key themes in the research.

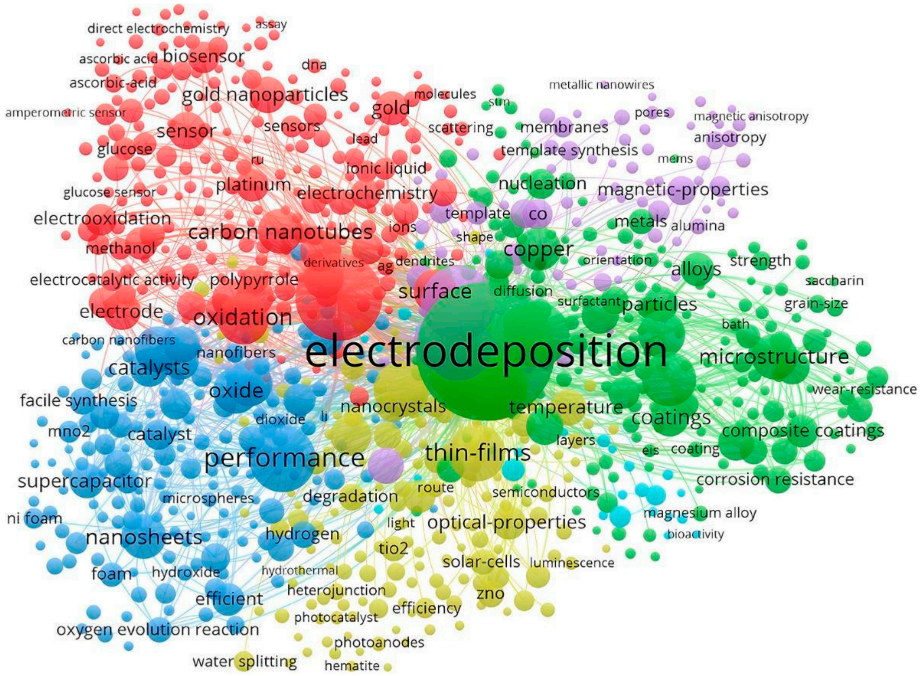


Figure 12. Keyword co-occurrence network in electrochemical deposition publications. The interactive visualisation is available at https://tinyurl.com/25oa2yxq (accessed on 10 April 2025).

Keywords with strong interconnections were categorised into six distinct clusters, each depicted in different colours (Figure 12). Cluster 1 (red) comprises 226 keywords centred on carbon-based materials and their applications, including carbon nanotubes and graphene. This highlights significant research interest in these materials for their unique properties. Cluster 2 (green) includes 188 keywords related primarily to the surface properties and microstructure of materials, indicating a strong emphasis on understanding and manipulating material surfaces and structures at the microscopic level. Cluster 3 (blue) contains 162 keywords associated with the performance and efficiency of various materials and processes, reflecting the importance of optimising performance metrics in electrochemical deposition. Cluster 4 (yellow) comprises 159 keywords connected to thin films and their optical properties, suggesting a research focus on the fabrication and application of thin film materials in various technologies. Cluster 5 (purple) consists of 86 keywords related to the magnetic properties and related applications of materials, indicating an interest in magnetic materials and their potential uses. Cluster 6 (light blue) includes 29 keywords associated with specific electrochemical processes and techniques, reflecting detailed studies on particular methods within the broader field.

The analysis of keywords also highlighted the materials most frequently studied within electrochemical deposition research. These include copper (1247 occurrences), graphene (1435), nickel (1507), carbon (886), gold (767), graphene oxide (616), silver (523), cobalt (523), silicon (346), and titanium (326). These materials are integral to the research and applications in electrochemical deposition, underscoring their significance in ongoing scientific endeavours.

The analysis of keyword co-occurrence data over time using VOSviewer software reveals the evolution of research trends in electrochemical deposition (Figure 13). The network map, coloured based on the average publication year, provides insights into the shifts in research focus from earlier to more recent studies.

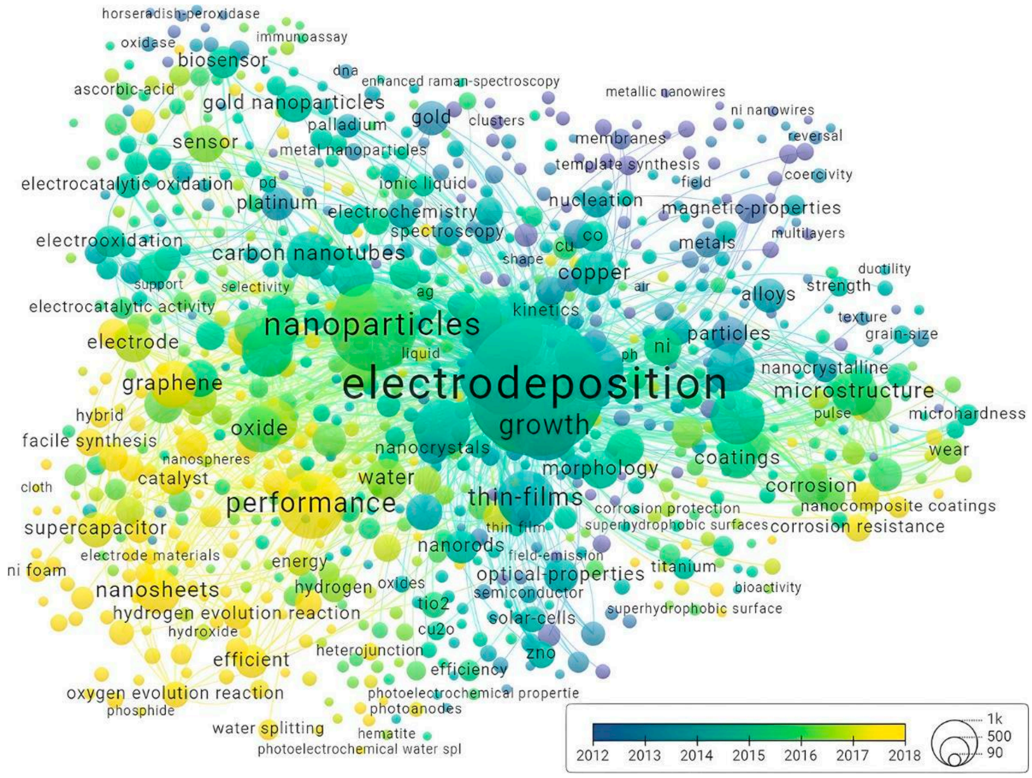


Figure 13. Evolution of research trends in electrochemical deposition, coloured by average publication year. The interactive visualisation is available at https://tinyurl.com/25oa2yxq (accessed on 10 April 2025).

In the early stages of electrochemical deposition research, around the years 2012 to 2014, the focus was predominantly on fundamental aspects and core techniques. Keywords such as "electrodeposition," "copper," "nickel," and "nanoparticles" were central, indicating a primary interest in the basic mechanisms and materials used in electrochemical deposition processes. Studies during this period emphasised understanding the fundamental properties and behaviours of these materials, as well as optimising the deposition techniques for better control and efficiency.

Between 2014 and 2016, there was a noticeable shift towards exploring the applications and performance of deposited materials. Keywords like "performance," "thin films," "microstructure," and "coatings" began to emerge more prominently. This shift reflects a growing interest in applying electrochemical deposition techniques to create advanced materials with specific properties for various applications, such as corrosion resistance, mechanical strength, and electrical conductivity. Research during this period also started to focus on composite materials and the enhancement of material properties through innovative deposition methods.

From 2016 onwards, especially noticeable from 2017 to 2019, the research focus has expanded to include more diverse and application-oriented studies. Keywords such as "nanostructures," "graphene," "carbon nanotubes," "biosensor," "electrocatalysis," and "supercapacitor" have become more prevalent. This indicates a strong interest in the functional applications of electrochemically deposited materials in fields such as energy storage, catalysis, and biosensing. The emergence of terms like "facile synthesis," "efficient," and "hydrogen evolution reaction" highlights a trend towards developing more efficient and sustainable deposition processes, as well as exploring the potential of these materials in renewable energy technologies.

In summary, the temporal analysis illustrates the dynamic nature of research in electrochemical deposition, with evolving priorities reflecting technological advancements and emerging global challenges. Researchers have progressively moved from foundational studies to application-driven investigations, paving the way for innovative solutions in various high-impact areas.

4. Discussion

4.1. One Technology, Two Modes: Anodic vs. Cathodic Operation

Although this article primarily focuses on bibliometric trends, it is important to briefly outline the technological context in which electrochemical etching and electrochemical deposition are applied. Understanding both methods' fundamental principles, typical conditions, and materials helps to interpret long-term publication patterns, keyword dynamics, and research trajectories.

It is also important to emphasise that electrochemical etching and electrochemical deposition are two modes of a single technological approach: electrochemical processing. The difference between them lies in electrode polarity and process objective—removing material versus accumulating material.

As noted at the beginning of the article, during electrochemical etching, the substrate is connected as the anode, where oxidation and controlled material dissolution occur. During electrochemical deposition, the substrate acts as the cathode, where reduction leads to the accumulation of material on its surface.

Despite the differences in outcomes, both processes rely on a standard set of key parameters (Table 9).

Table 9. Core process parameters and their influence.

Parameter	Description
Voltage or current density	Determines the kinetics of the electrochemical reaction, influencing etching rate or deposition thickness.
Treatment time	Directly affects structural characteristics such as pore depth (etching) or film thickness (deposition).
Power supply regime	Direct current (DC), alternating current (AC), and pulsed modes are applied depending on the desired morphology and structural quality.
Electrolyte composition and concentration	Defines the reaction mechanism, conductivity, and structural features. Strong acids and metal salt solutions are commonly used, with concentration significantly affecting uniformity and porosity.

These parameters are not only fundamental but also strongly interdependent, with each one influencing the outcome of the process in combination with the others. For example, during electrochemical etching, increasing the applied voltage—especially when working with silicon in hydrofluoric acid (HF) electrolytes—accelerates the reaction kinetics, resulting in faster pore formation [80–82]. This typically leads to mesoporous structures at moderate voltages, whereas higher voltages can induce a transition to macroporous morphology due to enhanced dissolution rates and local heating effects [83,84].

In electrochemical deposition, the choice of power supply mode plays a crucial role in determining the structural quality of the deposited layer [85,86]. Pulsed current modes, in particular, have proven effective in controlling grain size and suppressing dendritic growth [87,88]. This is especially important when working with metals such as copper or nickel, where uniform layer formation and mechanical stability are essential for applications in microelectronics and energy devices [89,90].

Electrolyte composition and concentration further influence the process outcomes in both methods. In the case of etching, a higher concentration increases the dissolution rate, which may be desirable for fast processing but can also lead to the collapse of delicate porous structures if not carefully controlled [91]. Conversely, in deposition processes, the concentration of metal ions in the electrolyte determines the availability of reactive species at the cathode surface, directly affecting the resulting film's deposition rate, surface roughness, and thickness uniformity [92].

While external process parameters such as voltage, electrolyte, and current mode play an essential role in shaping the outcomes of electrochemical treatment, the intrinsic properties of the material being processed are often equally decisive. Material-specific factors can significantly alter reaction dynamics, structural outcomes, and functional performance in both etching and deposition.

Silicon (Si) remains the most thoroughly studied and widely used substrate for electrochemical etching. Its predictable behaviour under anodic conditions, compatibility with HF-based electrolytes, and well-understood pore formation mechanisms make it a model system [93]. The ability to form stable and uniform mesoporous and macroporous structures has enabled its use in a wide range of applications, from photonic devices to biosensors and drug delivery systems [94,95].

Complex III–V semiconductors such as gallium arsenide (GaAs) and indium phosphide (InP) have also demonstrated good responsiveness to electrochemical etching, although their behaviour is more sensitive to processing conditions [96]. These materials can form porous layers with large surface areas, making them suitable for optoelectronic and sensing applications [97]. In contrast, II–VI compounds, such as cadmium telluride (CdTe) and zinc selenide (ZnSe), are generally more resistant to electrochemical dissolution, resulting in lower process control and reproducibility [98].

Several intrinsic properties influence how a material responds to electrochemical treatment. The type of conductivity (n-type vs. p-type) strongly affects charge carrier dynamics during etching [99,100]. Doping concentration is another critical factor. Heavily doped substrates often result in thinner, more branched porous structures, while lightly doped materials tend to form more profound and more uniform pores [101]. The crystallographic orientation of the substrate also plays an important role. For instance, Si(100) and Si(111) surfaces exhibit distinct differences in pore shape and propagation due to the atomic arrangement at the surface [102].

These structural differences affect not only the morphology but also the functional properties of the resulting materials. For example, the photoluminescence of porous indium phosphide is highly sensitive to pore size, surface termination, and internal surface area, which are, in turn, governed by the interplay of voltage, doping, and crystal orientation [103]. In deposition processes, the choice of substrate material similarly influences nucleation behaviour, adhesion strength, and film morphology. Surface roughness, chemical compatibility, and lattice mismatch between the deposited material and the substrate determine the structural integrity of the resulting film [104,105]. Thus, electrochemical etching and deposition are highly sensitive to material-related variables that must be considered alongside external process parameters.

The technical overview above highlights the shared foundations and distinct electrochemical etching and deposition behaviour. Despite their different objectives—removal or accumulation of material—these processes rely on a common electrochemical framework governed by voltage, electrolyte chemistry, current regime, and time. However, their performance strongly depends on the processed material's properties, including conductivity type, doping level, and crystallographic orientation.

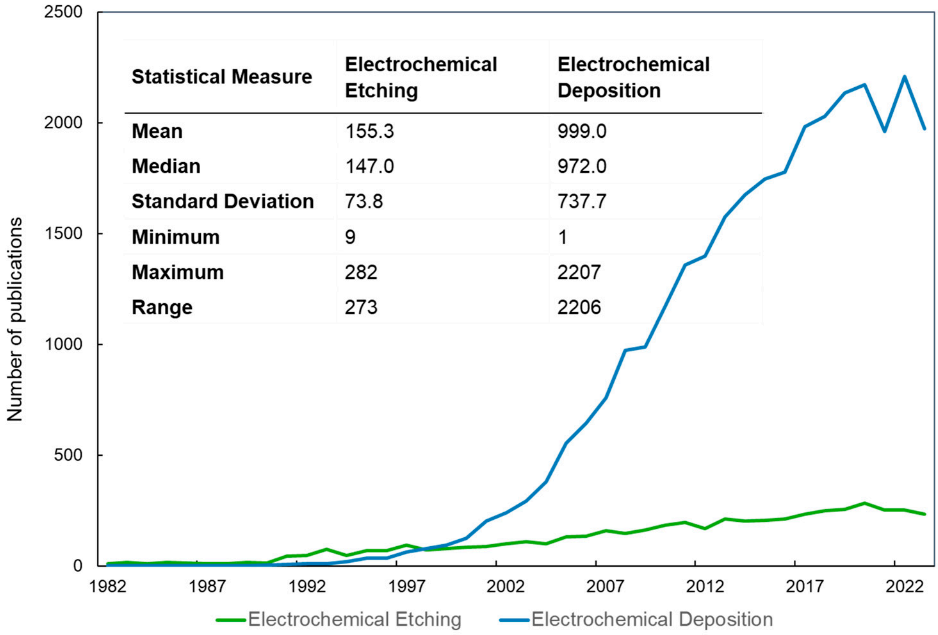
This background helps to contextualise specific bibliometric patterns observed in our analysis. For example, the frequent co-occurrence of terms such as porous silicon, photoluminescence, or HF etching can be linked to silicon anodisation's technological specificity and scientific significance. Similarly, the prominence of copper, nickel, and pulsed deposition in keyword networks reflects ongoing interest in controllable electroplating techniques for electronics, catalysis, and energy storage.

Moreover, international research trends and collaborative clusters may be influenced by thematic interest, material availability, local expertise in semiconductor processing, or access to specialised electrochemical equipment. Recognising the technical underpinnings of these processes thus provides a more informed lens for interpreting the quantitative and qualitative outputs of bibliometric mapping.

While this section is not intended as an exhaustive review of the physical chemistry of electrochemical methods, it serves as a bridge between bibliometric data and the field's technological reality. It underscores the importance of grounding data-driven analysis in domain-specific knowledge to ensure meaningful interpretation and understanding.

4.2. Comparative Analysis of Research Trends in Electrochemical Etching and Electrochemical Deposition

The comparative analysis of publication trends in electrochemical etching and deposition reveals distinct differences in their respective research outputs over the years. The dataset provides a clear picture of the historical growth and the relative popularity of these two methods in the scientific community (Figure 14).



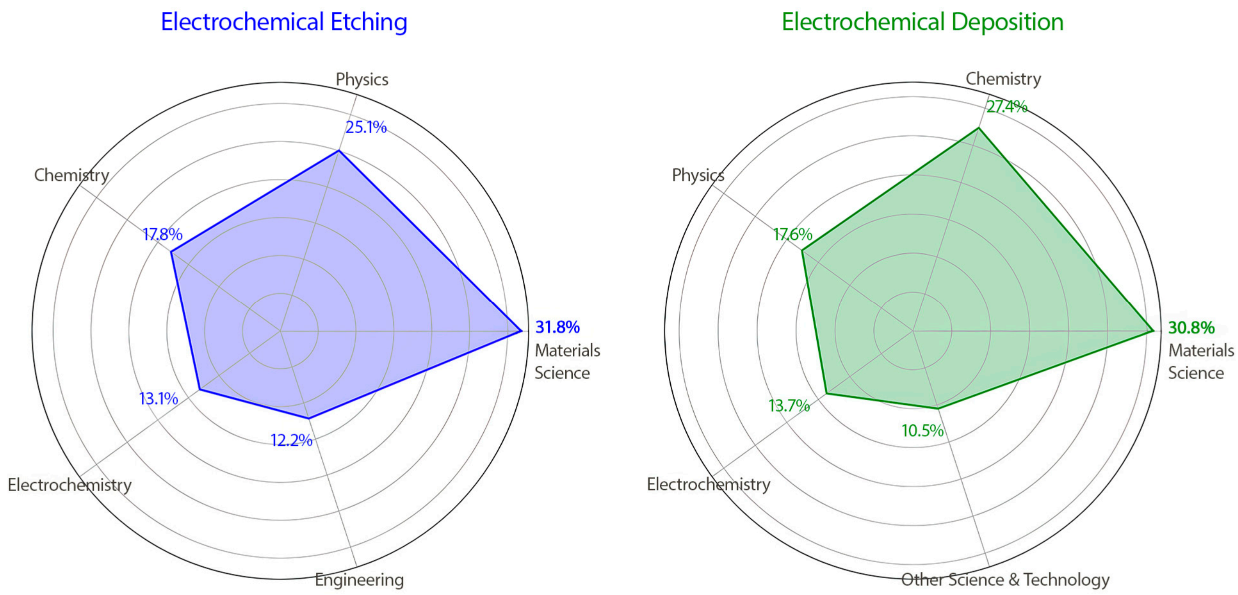
Statistical Measure	Electrochemical Etching	Electrochemical Deposition
Mean	155.3	999.0
Median	147.0	972.0
Standard Deviation	73.8	737.7
Minimum	9	1
Maximum	282	2207
Range	273	2206

Figure 14. Distribution of publications by year and statistical summary of annual publications on electrochemical etching and electrochemical deposition.

Electrochemical etching, with a mean publication count of approximately 143.71 and a median of 135, shows a relatively steady output over the years. The highest number of publications in a single year is 282 in 2020, while the lowest is 9 in 1988. The standard deviation is 63.85, indicating moderate variability in the annual publication counts. The coefficient of variation is 0.44, reflecting a consistent but modest fluctuation in research interest.

In contrast, electrochemical deposition exhibits a much higher mean publication count of approximately 623.75 and a median of 642. The highest number of publications in a single year is 2207 in 2022, highlighting a significant peak in research activity. The lowest count is 1, recorded in both 1989 and 1984. The standard deviation is substantially higher at 669.72, indicating a wide range of publication counts across the years. The coefficient of variation is 1.07, showing considerable relative variability, which can be attributed to the dynamic growth in this field.

The publication trends over the years illustrate that electrochemical deposition has consistently garnered more research attention compared to electrochemical etching. The cumulative publication count for deposition has shown a steep increase, particularly from the early 2000s onwards, reflecting its growing importance and widespread application in various industries. Figure 15 provides a visual comparison of the research areas associated with these fields, highlighting both shared and unique domains.



(**a**) (**b**)

Figure 15. Keyword co-occurrence networks representing research areas in (**a**) electrochemical etching and (**b**) electrochemical deposition. While both maps display overlapping terminology (e.g., nanostructures, thin films), notable distinctions are visible: etching research is more centred on surface modification, patterning, and photonic applications, whereas deposition research focuses on electrocatalysis, energy conversion, and composite coatings. This comparison highlights the thematic divergence and the specific application areas emphasised within each subfield.

The SCIE indicates that electrochemical etching is primarily explored within the realms of materials science, physics, and chemistry, with a strong focus on innovations in nanostructuring and surface modifications. In contrast, electrochemical deposition covers a wider scope, emphasising electrochemistry and engineering, indicative of its extensive applications in electronics, corrosion protection, and catalysis. While materials science remains a key focus for both processes, electrochemical deposition research includes a broader array of topics, such as thin-film technology and energy storage solutions, showcasing its diverse applications.

An analysis of international contributions reveals that both electrochemical etching and deposition are primarily driven by researchers from leading nations like China, the USA, and Germany. However, the level of contribution and collaboration differs between the fields. China leads in publications in both areas, with a particularly strong influence in electrochemical deposition. Meanwhile, the USA and Germany maintain significant positions, each emphasising different aspects of these processes based on their research priorities.

The comparative analysis of publication trends in electrochemical etching and electrochemical deposition reveals distinct yet interconnected research landscapes, based on our bibliometric analysis (Figure 16).

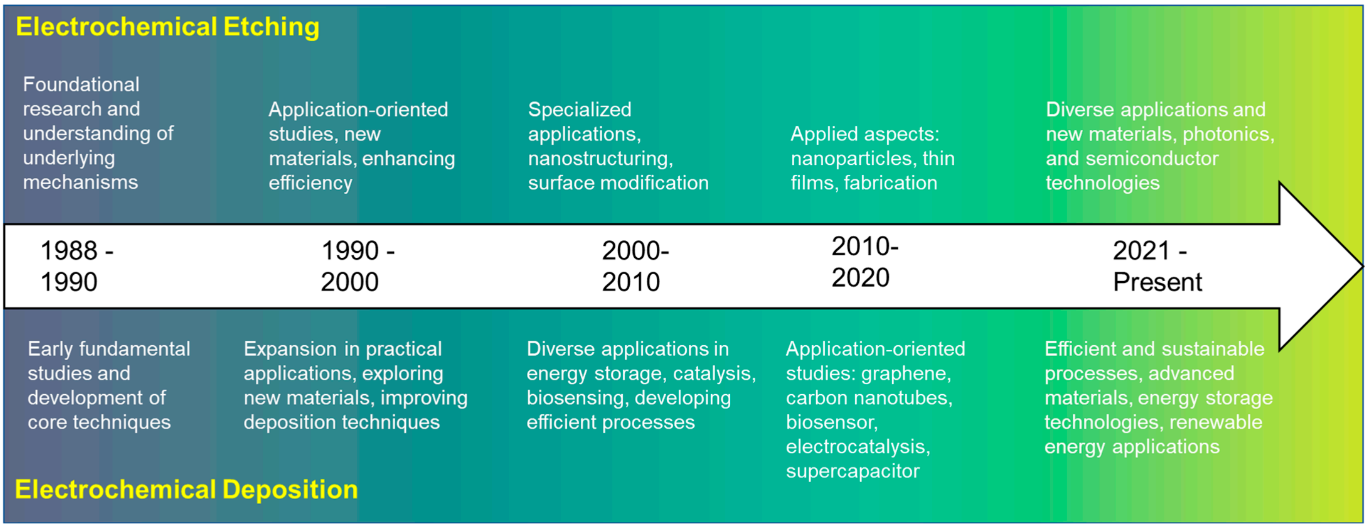


Figure 16. Evolution of research trends in electrochemical etching and electrochemical deposition.

In the early stages from 1988 to 1990, Germany, the USA, and Japan were prominent in electrochemical etching research, focusing on foundational studies and understanding underlying mechanisms. Similarly, early research in electrochemical deposition during this period centred on fundamental studies and developing core techniques, with significant contributions from the USA and Japan. As our bibliometric analysis shows, the research activities during this period were foundational, setting the stage for future advancements.

From 1990 to 2000, China emerged as a significant player in electrochemical etching research, focusing on application-oriented studies and new materials. During this period, our analysis of publication trends indicates that research in electrochemical deposition saw increased contributions from European countries like Germany and France, with a focus on practical applications, exploring new materials, and improving deposition techniques.

From 2000 to 2010, the research landscape for electrochemical etching diversified, with substantial contributions from India, South Korea, and Taiwan. The bibliometric analysis highlights a shift towards specialised applications, nanostructuring, surface modification, and novel etching techniques. For electrochemical deposition, this period was characterised by a broader range of applications in energy storage, catalysis, and biosensing, with China becoming a central figure in the field. The analysis of keyword co-occurrence during this period shows a clear focus on developing efficient processes and exploring new materials.

Between 2010 and 2020, electrochemical etching research expanded to applied aspects, focusing on nanoparticles, thin films, and fabrication, with leading contributions from China, Germany, and the USA. Our analysis of publication data reveals that electrochemical deposition research during this period included performance and material properties, exploring thin films, microstructure, and coatings. Keywords like "graphene," "carbon nanotubes," "biosensor," "electrocatalysis," and "supercapacitor" became prevalent, reflecting the trend towards renewable energy technologies and efficient deposition processes.

From 2021 to the present, the research focus in electrochemical etching included diverse applications and new materials in photonics and semiconductor technologies, with China, the USA, and Germany leading the field. As our bibliometric analysis demonstrates, electrochemical deposition research emphasised efficient and sustainable processes, advanced materials, energy storage technologies, and renewable energy applications.

This categorisation, while somewhat arbitrary due to the continuous nature of research progress, provides a broad overview of the shifts in research focus and contributions over time. The analysis underscores the adaptive and innovative nature of scientific inquiry, driven by both foundational studies and application-oriented research. The comparative study highlights the importance of international collaboration and the diverse contributions of different countries, emphasising the global effort to advance electrochemical techniques.

4.3. Future Research Directions

The comparative bibliometric analysis of electrochemical etching and electrochemical deposition reveals that these methods, while historically significant, are currently experiencing a decline in popularity compared to more technologically advanced alternatives, such as atomic layer deposition (ALD) [106], chemical vapour deposition (CVD) [107], and molecular beam epitaxy (MBE) [108]. This trend is reflected in the relatively modest publication landscape (5166 publications for electrochemical etching and 30,759 publications for electrochemical deposition). However, we are convinced that electrochemical methods possess substantial potential due to their undeniable advantages, which position them uniquely in nanostructure synthesis.

Firstly, electrochemical methods have a significant advantage in terms of simplicity of implementation [109,110]. Due to their straightforward nature, these techniques are often referred to as "kitchen" or "bench-top" methods [111–113]. Unlike many nanofabrication techniques, electrochemical processes do not require complex procedures or high levels of expertise, making them accessible to a broader range of researchers and industries.

Secondly, electrochemical methods are time-efficient. The processes typically occupy much less time than other high-precision techniques, enabling rapid prototyping and experimentation [114,115]. This time efficiency is particularly beneficial in research settings where quick iterations and adjustments are necessary.

Additionally, electrochemical methods do not require high-vacuum conditions, extreme temperatures, or other unique environments. This lack of stringent requirements makes these processes more accessible to set up and maintain, significantly reducing operational complexity and costs [116,117]. The absence of the need for high-tech equipment further enhances their practicality and economic viability.

Another critical advantage is electrochemical methods' low cost and economic efficiency [118,119]. Given their simplicity and minimal equipment requirements, the overall expense associated with these processes is relatively low [120,121]. This cost-effectiveness is crucial, especially for industrial applications where large-scale production and budget constraints are important considerations [122].

Electrochemical methods also offer remarkable versatility in forming a wide variety of nanostructures [123,124]. Whether etching intricate patterns [125] or depositing uniform thin films [126], these methods can be tailored to produce diverse nanostructured materials with specific properties. This adaptability is a significant asset in research and industrial applications, where different nanostructures are required for different functionalities.

Furthermore, electrochemical methods' scalability and adaptability make them suitable for the industrial-scale synthesis of nanostructures [127]. These processes can be easily scaled up from laboratory settings to full-scale production without substantial changes to the methodology [128]. This scalability ensures that the benefits of nanostructured materials can be leveraged in commercial applications effectively and economically.

Additionally, in recent years, combined methods of electrochemical etching and electrochemical deposition have gained traction [129]. Porous layers formed by electrochemical etching can serve as reliable buffer "soft" substrates for subsequent electrochemical deposition [130,131]. This approach mitigates the elastic stresses that typically arise at the interface between two materials, facilitating the formation of high-quality heterostructures [132]. Such combined techniques leverage the strengths of both processes, offering enhanced control over material properties and structural integrity, which is crucial for advanced applications in electronics and photonics [133]. The integration of these methods presents a promising avenue for further research, aiming to optimise and expand their application scope in synthesising nanostructured materials.

Given these advantages, we believe that electrochemical etching and deposition methods are promising for future research and industrial applications. By focusing on optimising these methods and exploring new applications, researchers can continue to unlock their potential. Emerging trends, such as integrating electrochemical techniques with machine learning algorithms for process optimisation and aligning with green chemistry principles to minimise environmental impact, may rejuvenate interest in these methods and expand their applicability across disciplines. Future research should enhance the efficiency, precision, and range of materials and structures produced using electrochemical methods.

In conclusion, despite declining popularity, the inherent advantages of electrochemical methods—such as simplicity, time efficiency, minimal requirements, low cost, versatility, and scalability—underscore their enduring value and potential for future advancements. By capitalising on these strengths, the scientific community can ensure that electrochemical methods remain a vital tool in the synthesis of nanostructures, driving innovation and technological progress.

5. Conclusions

This bibliometric study offers a retrospective and comparative overview of the development of electrochemical etching and electrochemical deposition methods over the period from 1970 to 2023, providing a structured mapping of their research landscapes, key contributors, and thematic evolution.

Our analysis reveals that electrochemical deposition has experienced significantly higher publication activity compared to electrochemical etching, with a notable surge since the early 2000s. Nevertheless, both fields demonstrate sustained scientific interest, reflecting their essential roles in nanomaterial synthesis and functional applications.

The keyword co-occurrence analysis identified how each field evolved: electrochemical etching research moved from fundamental investigations of porous silicon and photoluminescence to photonic and sensing applications, while electrochemical deposition expanded towards energy storage, catalysis, and biosensor technologies. These trends illustrate the gradual specialisation of research topics and the diversification of practical applications.

By analysing the evolution of collaboration networks, we demonstrated the growing importance of international partnerships, with China, the USA, Germany, and emerging research economies playing central roles. The comparative analysis also highlighted shifts in regional leadership over time and the dynamic entry of new contributors.

An important outcome of this work is the comparative perspective: despite operating under a shared electrochemical framework, etching and deposition exhibit distinct thematic trajectories and strategic focuses. Electrochemical etching retains a niche in surface modification and photonics, while electrochemical deposition increasingly supports fields such as renewable energy and advanced coatings.

Although newer fabrication technologies are gaining prominence, electrochemical methods maintain substantial advantages—including simplicity, cost-effectiveness, and scalability—that ensure their relevance for future applications. Especially promising are integrated approaches that combine electrochemical etching and deposition to engineer complex nanostructures.

Thus, this study not only charts the historical development of two fundamental electrochemical techniques but also identifies promising directions for further research and technological innovation. By grounding bibliometric findings in a technological and historical context, we offer insights that can guide future efforts in advancing electrochemical processing for nanomaterials and functional devices.

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