



Research Trends in IoT-Integrated Automated Titration Systems Using Peristaltic Pump: A Bibliometric Study

Adisty Mesya Triazeva Putri^{1*}, Mona Berlian Sari¹

¹ Department of Physics, Universitas Negeri Padang, Padang 25131, Indonesia

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Corresponding Author

*Author Name: Adisty Mesya Triazeva Putri

Email: adistymesya21@gmail.com

Abstract: This study examines research trends in IoT-integrated automated titration systems employing peristaltic pumps through a combined bibliometric analysis and Systematic Literature Review (SLR). Data were collected from the Scopus and Google Scholar database covering the period 2016-2026 and analyzed using VOSviewer to map publication trends, geographical distribution, journal contributions, and keyword co-occurrence networks. The result reveal a fluctuating yet overall increasing research trend, with peak publication activity observed 2019 and 2021. The united States and Brazil dominant research output, followed by emerging contributions from China, India, and Indonesia. Journal distribution indicates that publications are concentrated in a limited number of core outlets, particularly within analytical chemistry and chemical education. Keyword analysis identifies major themes such as titration, automatic titration, peristaltic pump, Arduino, and Internet of Things, indicating a convergence between analytical chemistry and digital technologies. This study provides a comprehensive overview of the field, identifies research gaps, and offers insight for future developments of intelligent, IoT-based laboratory systems.

Keywords: Automated Titration, Bibliometric analysis, Internet of Things (IoT), Peristaltic Pump, Systematic Literature Review,



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1. Introduction

Titration is a fundamental analytical technique widely used determine the concentration of chemical solutions through stoichiometric reactions between analyte and titrant [1], [2], [3]. Despite its long standing reliability, conventional titration methods remain highly dependent on manual operation, which introduces limitations in terms of precision, reproducibility, and operational efficiency [4]. To overcome these limitation some recent advancements have focus on integrating automation technology, including peristaltic pumps, microcontrollers, and sensor-based detection

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systems, enabling the transformation of traditional titration into automated and intelligent analytical platforms [5], [6], [7], [8].

In parallel the rapid development of Internet of Things (IoT) technology has further accelerated this transformation by enabling real-time monitoring, remote control, and data driven decision making in laboratory environments. The convergence of IoT and automated titration systems has led to the enhance of IoT integrated titration platforms, which enhance analytical accuracy while improving systems efficiency and flexibility. Consequently, this interdisciplinary field, which combines analytical chemistry, instrumentation, and information technology, has attracted increasing research attention in recent years [9], [10].

Several studies have discussed the development of laboratory automation and intelligent analytical systems. For instance, Olsen reviewed the historical development of laboratory automation technologies and their applications in scientific research [11]. Thurow highlighted recent strategies for automating analytical and bioanalytical to improve analytical efficiency and reproducibility [12]. Furthermore, Bezerra et al. reviewed the evolution of automated continuous-flow analysis systems and emphasized their role in enhancing analytical performance [13]. These studies have provided valuable insight into technological developments in analytical instrumentation and laboratory automation. In addition bibliometric analysis has been widely recognized as an effective approach for examining scientific development, identifying influential contributor, and revealing thematic evolution within research domains [14], [15], [16], [17]. The integration of bibliometric techniques with systematic review procedures has also been increasingly adopted to improve the transparency, reproducibility, and comprehensiveness of literature synthesis [18].

Although the number of publications related to automated titration systems and IoT applications has increased considerably, the existing body of literature remains fragmented and lacks a comprehensive understanding of its intellectual structure, thematic evolution, and collaborative patterns. Most previous studies have primarily focused on technical implementation and system development, with relatively limited efforts to synthesizing publication trends and evaluating the overall progression of the field [14]. Moreover, previous review studies have mainly addressed broader aspects of laboratory automation, analytical instrumentation, and autonomous analytical systems. However, bibliometric investigations specifically focusing on IoT-integrated automated titration systems employing peristaltic pumps remain limited. Consequently, a comprehensive understanding of publication trends, dominant research themes, and emerging research directions in this interdisciplinary field is still lacking

To address this limitation, the present study employs an integrated bibliometric analysis and systematic review (SLR) approach to investigate the development of research on IoT-integrated automated titration systems employing peristaltic pumps. Bibliometric analysis enables the quantitative assessment of publication trends, influential contributors, collaboration patterns, and thematic relationships, whereas the SLR approach provides a structured and reproducible framework for synthesizing the existing literature [15], [16], [17], [18]. By integrating these approaches, a more comprehensive understanding of the intellectual structure and thematic evolution of this research area can be achieved.

Therefore, this study aims to analyze the trends in research development on IoT-integrated automated titration systems employing peristaltic pumps through a bibliometric analysis approach using VOSviewer, complemented by a Systematic Literature Review (SLR) to ensure a structured

and comprehensive synthesis of the existing literature. The findings are expected to provide insights into publication trends, influential contributors, and emerging research themes while highlighting potential directions for future investigations. Furthermore, this study is expected to contribute to the advancement of intelligent and data driven laboratory systems by identifying research opportunities and challenges associated with the development of IoT-based automated titration technologies.

2. Method

2.1 Research Design

This study employed a combined bibliometric analysis and systematic literature review (SLR) approach to examine the development of research on IoT-integrated automated titration systems employing peristaltic pumps. The SLR approach provided a structured framework for identifying and synthesizing relevant studies, whereas bibliometric analysis enabled the quantitative evaluation of publication trends, research productivity, and thematic relationships within the field. By integrating these approaches, the study aimed to provide a comprehensive overview of the intellectual structure and research evaluation of IoT-based automated titration systems.

To ensure methodological transparency and reproducibility, this study adopted the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) 2020 framework to guide the identification, screening, eligibility assessment, and inclusion of relevant publication [19], [20], [21], [22]. Although PRISMA was originally developed for systematic reviews and meta-analyses, its application has been extended to bibliometric studies to improve the transparency and consistency of the literature selection process [23]. Accordingly, the integration of SLR and bibliometric analysis provides a systematic approach for exploring publication trends, influential contributors, collaborative networks, and thematic development in this emerging research area.

2.2 Data Sources and Search Strategy

Bibliographic data were retrieved from the Scopus and Google Scholar databases on March 18, 2026. These databases were selected because of their broad coverage of peer-reviewed literature and their extensive indexing of publications related to analytical chemistry, laboratory automation and Internet of Thing (IoT) applications. To maximize the retrieval of relevant publications, the search was performed within the title, abstract, and keyword fields using multiple combinations of search terms associated with automated titration systems, Arduino, IoT, and peristaltic pumps.

The search strategy employed several keyword combinations, including “auto-titrator using Arduino”, “automatic titration using Arduino”, “automatic titration using peristaltic pump”, “automatic titration using Arduino Uno”, and “automatic titrator”. The use of multiple search queries was intended to improve data coverage and minimize the exclusion of potentially relevant studies. Publications published between 2016 and 2026 were considered, as this period reflects the increasing adoption of IoT technologies and low-cost microcontroller platforms in laboratory automation. The retrieved records from both databases were subsequently combined to establish a comprehensive dataset for further screening and bibliometric analysis. Details of the search strategy employed in this study are summarized in Table 1.

Table 1. Search Strategy Employed in This Study

Database	Search Query	Search Fields	Search Date	Retrieved Records
Scopus	“auto titrator using Arduino” OR “automatic titration using Arduino” OR “automatic titration using peristaltic pump” OR “automatic titration using Arduino Uno” OR “automatic titrator	Title, Abstract, keywords	18 March 2026	214
			18 March 2026	232
Google Scholar	Same search terms	Title, Abstract, keywords		

2.3 Inclusion and exclusion Criteria

To ensure the relevance and quality of the retrieved literature, predefined inclusion and exclusion criteria were applied during the screening process. The inclusion criteria comprised: (1) articles published between 2016 and 2026; (2) journal articles and conference proceedings; (3) studies addressing automated titration systems, Internet of Things (IoT), Arduino-based instrumentation, sensors, or peristaltic pumps; and (4) publications with complete bibliographic information. The selected time span was intended to capture the recent development of IoT technologies and their integration into laboratory automation.

The exclusion criteria included duplicate records, publications unrelated to the scope of automated titration systems, editorials, notes, and publications with incomplete metadata. In addition, studies lacking sufficient information for bibliometric analysis were excluded. The application of these criteria ensured that only relevant and high-quality publications were retained for subsequent systematic review and bibliometric analysis.

2.4 PRISMA Screening Procedure

The literature selection process was conducted in accordance with the preferred reporting items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework to ensure transparency and reproducibility. Although PRISMA was originally developed for systematic reviews and meta-analyses, its application has increasingly been extended to bibliometric studies to improve the consistency and transparency of literature identification and selection. Accordingly, the PRISMA framework was adapted in this study to guide the identification, screening, eligibility assessment, and inclusion stages [19], [20], [21], [22].

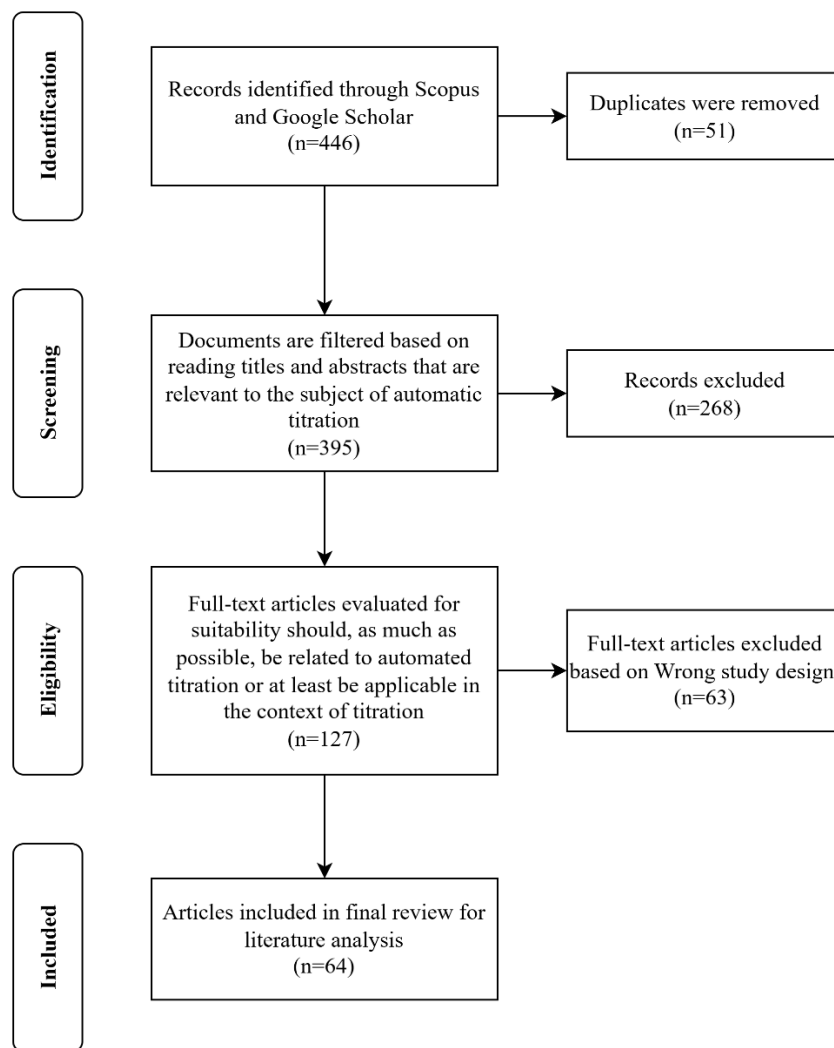


Figure 1. Systematic Literature Review Process Using PRISMA 2020

Based on the search process illustrated in Figure 1, a total 446 records were initially identified from Scopus and Google Scholar databases. Following the removal of 51 duplicate records, 395 unique documents were retained for the screening stage. During this stage, the titles and abstracts of the retrieved publications were systematically evaluated to determine their relevance to the research topic, resulting in the exclusion of 268 records that did not satisfy the predefined inclusion criteria, consequently, 127 articles were considered eligible for full-text assessment. After evaluating the full texts, 63 articles were excluded due to insufficient relevance to the scope of the study and incomplete information required for bibliometric analysis. Ultimately, 64 publications were retained for systematic literature review and bibliometric analysis. The complete article selection procedure is illustrated in Figure 1, whereas the number of records identified, screened, excluded, and included at each stage is summarized in Table 2.

Table 2. Screening Process Based on PRISMA 2020

Stage	Number of Records
Records identified from Scopus and Google Scholar	446
Duplicate records removed	51
Records screened	395
Records excluded	268
Ful-text articles assessed for eligibility	127
Full-text articles excluded	63
Studies included in the bibliometric analysis	64

2.5 Data Cleaning and Duplicate Removal

The bibliographic records retrieved from the Scopus and Google Scholar databases were merged to establish a comprehensive dataset for subsequent analysis. Duplicate records were identified and removed using the Covidence web platform, which facilitated an efficient and systematic deduplication process based on bibliographic metadata. This process resulted in the removal of 51 duplicate records, thereby retaining only unique publications for further screening and analysis.

The finalized dataset was exported in comma-separated values (CSV) format and organized using Microsoft Excel prior to bibliometric analysis. Data preprocessing was subsequently performed to improve the accuracy and consistency of bibliometric mapping. This process included metadata verification, removal of incomplete records, and keyword normalization to minimize inconsistencies arising from variation in terminology, abbreviations, and writing styles. The cleaned dataset was then imported into VOSviewer version 1.6.20 to generate network, overlay, and density visualizations for subsequent bibliometric analysis.

2.6 Bibliometric Analysis Using VOSviewer

Bibliometric analysis was performed using VOSviewer version 1.6.20 to visualize and analyze the bibliographic data retrieved from the selected databases. The software enables the construction of bibliometric networks, facilitating the examination of citation relationships, author collaborations, and keyword co-occurrence patterns. This approach allows for the identification of the intellectual structure and thematic evolution of research on IoT-integrated automated titration systems employing peristaltic pumps.

The integration of bibliometric techniques with systematic literature review provides a comprehensive framework for synthesizing existing knowledge while mapping publication trends, influential contributors, collaborative networks, and emerging research themes [24]. Such a combined approach contributes to a deeper understanding of the development trajectory and historical evolution of this interdisciplinary research area, while also highlighting potential directions for future investigations [25]. Furthermore, bibliometric analysis provides valuable insights into the structure and dynamics of scientific research, thereby supporting the identification of research gaps and opportunities for further development. Network visualization was employed to identify relationships among keywords and research themes, whereas overlay visualization was used to illustrate the temporal evolution of research topics. In addition, density visualization was utilized to determine the prominence and concentration of specific themes within the field. The results obtained from these visualizations provide insights into publication and thematic development and are discussed in the subsequent sections.

3. Results and Discussion

The results of this study are based on 64 articles retrieved from the Scopus and Google Scholar database using keywords related to IoT- integrated automated titration systems employing peristaltic pumps. The analysis was conducted to quantitatively and structurally map the development of research, encompassing publication trends, geographical distribution, author collaborations, publication sources, as well as the relationships and evolution of research keywords. By leveraging VOSviewer to map the evolution of research output, this study provides an overview of the growth, patterns, and current direction of research on IoT- based automated titration systems.

3.1. Annual Scientific Production

The annual scientific production of research related to IoT-integrated automated titration systems employing peristaltic pumps demonstrates a fluctuating yet generally increasing trend throughout the 2016-2026 period. Based on the 64 publications included in the final dataset, the field has experienced gradual growth despite variations in publication output across individual years. The earliest publication identified within the selected timeframe appeared in 2016, marking the initial stage of integrating IoT technologies into automated titration systems. The annual distribution of publications is presented in Table 3.

Table 3. Progress of Scopus and Google Scholar Database Publication

Year of Publication	Count of Published Year
2016	6
2017	1
2018	5
2019	10
2020	7
2021	10
2022	4
2023	4
2024	7
2025	8
2026	2
Total	64

As shown in Table 3, publication activity reached notable peaks in 2019 and 2021, with 10 publications recorded in each year. This increase may be attributed to the growing adoption of low-cost microcontrollers, such as Arduino and ESP32, as well as the increasing accessibility of sensors, wireless communication technologies, and IoT platforms. These technological advancements have facilitated the development of affordable, customizable, and remotely accessible analytical systems, thereby attracting greater research interest from both academic and industrial communities. Similar trends have been reported in studies on laboratory automation and IoT-enabled analytical technologies, which highlight the increasing role of interconnected devices and intelligent instrumentation in modern analytical laboratories [12].

The fluctuations observed during the study period reflect the interdisciplinary nature of the research field, which lies at the intersection of analytical chemistry, instrumentation, electronics, automation, and information technology. Consequently, publication activity is strongly influenced by technological developments, research funding priorities, and the emergence of new laboratory automation paradigms. The decline observed in 2022 and 2023 does not necessarily indicate a reduction in research interest; rather, it may reflect publication cycles, shifts in research focus, or delays in the dissemination of research outputs. Similar fluctuations have also been observed in emerging interdisciplinary research fields, where publication growth is often affected by technological maturity and the availability of research resources [11].

A moderate recovery in publication output was observed during 2024 and 2025, suggesting renewed interest in the development of intelligent laboratory systems. This trend is consistent with the increasing demand for real-time monitoring, remote accessibility, autonomous operation, and data-driven analytical platforms associated with industry 4.0 and smart laboratory initiatives. The integration of IoT technologies with automated analytical instrumentation has become increasingly relevant as laboratories seek greater efficiency, accuracy, and operational flexibility. Recent studies have emphasized that laboratory automation and autonomous analytical systems are expected to play an increasingly important role in supporting future smart laboratory environments and analytical operations [12].

Overall, the publication trend indicates that research on IoT- integrated automated titration systems employing peristaltic pumps remains an emerging but steadily developing field. The increasing number of publications over the past decade reflects growing recognition of the potential of intelligent automation technologies to transform conventional analytical procedures into more efficient, connected, and adaptive laboratory systems. Furthermore, the sustained research interest observed during the study period suggests that the integration of IoT technologies with automated titration systems will continue to evolve, driven by ongoing advances in sensing technologies, wireless communication, and intelligent data processing capabilities.

3.2. Distribution of Publications by Country

The geographical distribution of publications indicates that research on IoT- integrated automated titration systems employing peristaltic pumps is conducted across several countries, although the research output remains concentrated within a limited number of nations. As presented in Figure 2, the United States emerged as the most productive country with 11 publications, followed by Brazil with 10 publications. China, India, and Indonesia each contributed four publications, while Portugal produced three publications. Germany, Canada, Malaysia, Spain, and Sri Lanka each contributed two publications.

The prominent contribution of the United States and Brazil may reflect their established research activities in analytical chemistry, laboratory automation, and instrumentation technologies. Previous studies have shown that countries with strong scientific infrastructure and active research institutions tend to contribute more significantly to emerging interdisciplinary fields involving automation and analytical technologies [11], [12]. The substantial publication output from these countries suggests their active involvement in advancing intelligent analytical systems and laboratory automation applications.

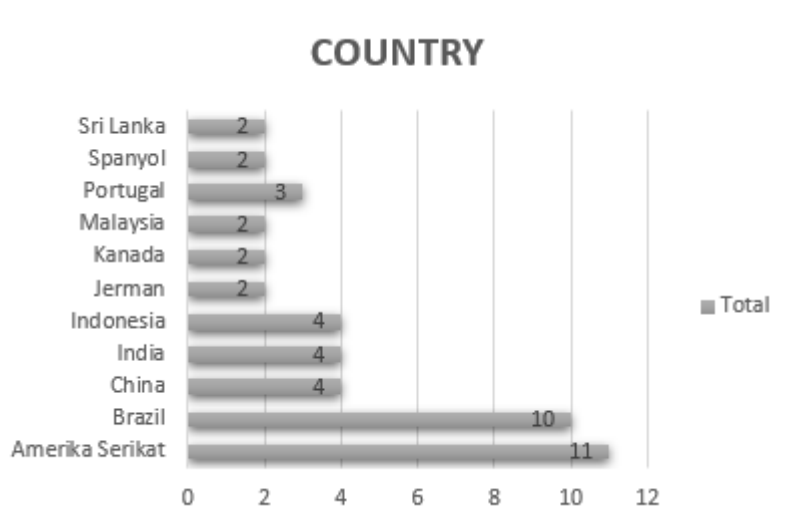


Figure 2. Articles by country

The contributions from China, India, and Indonesia demonstrate that research interest in this field is not limited to traditionally dominant scientific nations. The increasing accessibility of low-cost microcontrollers, sensors, and open-source development platforms has enabled researchers from developing and emerging economies to participate more actively in the development of automated analytical systems [26]. This trend may explain the growing geographical diversity observed in the publication dataset.

Although publication output remains unevenly distributed, the participation of countries from different regions highlights the interdisciplinary and globally relevant nature of IoT-based automated titration research. The integration of analytical chemistry, automation, electronics, and IoT technologies addresses challenges that are common across various scientific and industrial sectors, thereby encouraging broader international engagement. Furthermore, the geographical distribution identified in this study suggests opportunities for future international collaboration. Collaborative research among institutions, innovation, and methodological standardization. Therefore, strengthening international research networks may support the continued advancement of IoT automated titration technologies in the future.

3.3. Distribution of Publications by Journal

The distribution of publications across journals provides valuable insights into the disciplinary orientation and dissemination patterns of research on IoT-integrated automated titration systems employing peristaltic pumps. As illustrated in Figure 3, the *Journal of Chemical Education* emerged as the most productive publication source, contributing the highest number of articles within the analyzed dataset. This finding suggests that a substantial portion of the research has been conducted within educational and instructional contexts, where automated titration systems are increasingly utilized as practical learning tools to support laboratory activities, enhance students' understanding of analytical chemistry concepts, and promote the adoption of digital technologies in science education.

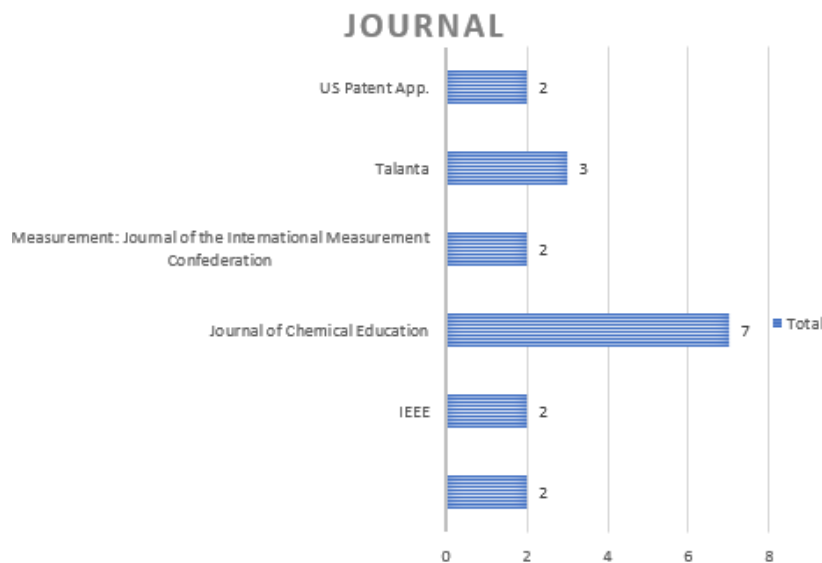


Figure 3. Number of Scientific Publications by Journals

The prominence of the Journal of Chemical Education also reflects the growing interest in incorporating automation, sensors, and Internet of Things (IoT) technologies into laboratory-based learning environments. Recent studies have highlighted that laboratory automation not only improves analytical performance but also provides educational benefits by facilitating hands-on experimentation, real-time data acquisition, and interactive learning experience [12]. Consequently, automated titration systems have become increasingly relevant in chemistry education as examples of modern analytical instrumentation and smart laboratory technologies.

In addition to educational journals analytical chemistry journals such as *Talanta* also contributed significantly to the publication output. The presence of publications in *Talanta* indicates that research on automated titration systems is increasingly recognized within the broader analytical chemistry community. As one of the leading journals in analytical science, *Talanta* frequently published studies related to analytical methodologies, sensor technologies, measurement systems, and laboratory automation. This observation suggest that research in the field is evolving beyond educational applications and is increasingly focused on improving analytical accuracy, operational efficiency, and autonomous analytical capabilities.

Furthermore, the presence of publications across journals specializing in instrumentation, engineering, automation, and measurement science demonstrates the inherently interdisciplinary nature of the research area. The development of IoT-integrated automated titration systems requires the integration of knowledge from analytical chemistry, electronics, embedded systems, automation engineering, and information technology. Such multidisciplinary characteristics explain why publications are distributed across various scientific domains rather than concentrated within a single journal category [12].

The observed publication pattern also indicates that the field remains in a relatively early stage of development. In emerging research areas, scientific outputs are often disseminated through multiple specialized journals before a well-defined publication ecosystem is established. Similar patterns have been reported in other interdisciplinary fields involving laboratory automation and intelligent analytical technologies, where research dissemination occurs across chemistry, engineering, and technology oriented journals [12].

Overall, the journal distribution highlights that research on IoT- integrated automated titration systems employing peristaltic pumps is characterized by strong interdisciplinary engagement. The dominance of chemistry education and analytical chemistry journals suggest that current research efforts are directed toward both educational implementation and analytical innovation. This combination reflects the dual role of automated titration technologies as educational tools and advanced analytical systems, thereby supporting the continued development of smart laboratory environments and data-driven analytical practices.

3.4. Research Cluster on Keyword Evolution (Co-Occurrence)

To identify the conceptual structure and thematic evolution of research on IoT-integrated automated titration systems employing peristaltic pumps, a keyword co-occurrence analysis was conducted using VOSviewer. The analysis was performed on publications retrieved from the Scopus and Google Scholar databases covering the period from 2016 to 2026. As illustrated in Figure 4, the resulting network visualization consists of several interconnected clusters, each representing a distinct yet related research theme within the field.

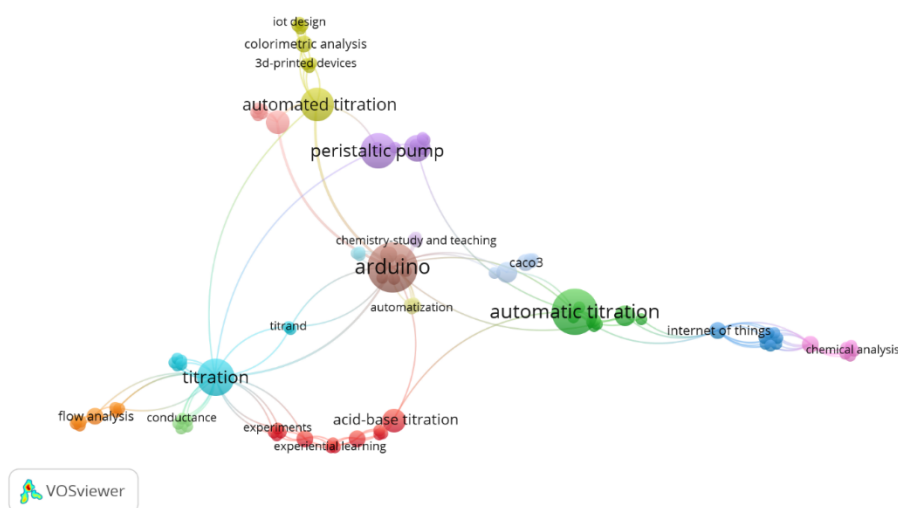


Figure 4. Representation of Keyword Terms

The size of each node reflects the frequency of keyword occurrence, while the links between nodes indicate the strength of co-occurrence relationships. Larger nodes represent topics that have received greater research attention, whereas stronger connections indicate closer conceptual relationships between research themes. Keyword such as *titration*, *automation titration*, *Arduino*, *peristaltic pump*, and *Internet of Things* appear as central nodes within the network, highlighting their fundamental role in the development of intelligent titration systems. The prominence of these keywords suggest that recent research efforts have focused on integrating automation technologies, embedded systems, and digital communication frameworks to enhance analytical performance and operational efficiency.

The network structure reveals a strong interaction between traditional analytical chemistry concepts and emerging digital technologies, the red cluster which includes keywords such as *acid-base titration*, *experiments*, and *experiential learning*, reflect the continued importance of laboratory-

based educational applications. The presence of these keywords suggest that automated titration systems are increasingly being adopted as instructional tools to improve practical laboratory experiences and facilitate technology enhanced chemistry education.

The green cluster is centered on *automatic titration* and is strongly connected to *Internet of Things*, indicating that smart connectivity has become a major research direction within the field. The close relationship between these keywords demonstrates the growing emphasis on remote monitoring, data acquisition, and intelligent process control. This trend is consistent with the broader implementation of industry 4.0 principles in laboratory environments, where analytical instruments are increasingly designed to operate as interconnected systems capable of real-time communication and autonomous operation [12].

The blue cluster highlights *titration* as the core analytical concept linking multiple research themes. The association of this keyword with terms such as *conductance*, *flow analysis*, and *CaCO₃* indicates that automated titration technologies continue to be applied across diverse analytical chemistry applications. This finding suggest that technological innovation is being developed not as a replacement for conventional analytical methods but as an enhancement that improves precision, reproducibility, and operational efficiency. Another notable cluster is represented by the keyword *peristaltic pump*, which appears closely associated wit *Arduino* and automation-related terms. This relationship highlights the critical role of low-cost microcontrollers and fluid handling systems in the development of automated titration platforms. The widespread appearance of these keywords reflects the increasing adoption of open-source hardware and embedded control systems, which have significantly reduced the cost and complexity of laboratory automation.

Furthermore, the yellow cluster includes keywords such as *IoT design*, *colorimetric analysis*, and *3D-printed devices*, representing emerging technological innovations within the field. The presence of these keywords suggest that recent research is expanding beyond conventional automation toward the development of more flexible, customizable, and cost-effective analytical systems. The integration or additive manufacturing technologies and IoT-based sensing platforms indicates a growing interest in creating portable and accessible analytical instruments suitable for educational, industrial, and field applications [26].

Overall, the keyword co-occurrence network demonstrates a clear transition from conventional titration practices toward intelligent and interconnected analytical systems. The strong relationships among automation, IoT, embedded electronics, and analytical chemistry keywords indicate that future research is likely to focus on autonomous operation, real-time monitoring, advanced sensing technologies, and smart laboratory environments. These findings confirm that the field is evolving toward more adaptive, data-driven, and digitally integrated analytical platforms capable of supporting the next generation of laboratory automation.

This study presents a comprehensive bibliometric and systematic analysis of research concerning IoT-integrated automated titration systems utilizing peristaltic pumps. The results indicate that the number of publications in this field has gradually increased over time, although fluctuations in annual output suggest that the research area is still developing and has not yet reached full maturity. Such a trend reflects the interdisciplinary nature of the field, which combines analytical chemistry, instrumentation, electronics, control systems, and Internet of Things technologies. The growing interest in low cost ang open-source automation platforms further demonstrates the increasing relevance of intelligent laboratory systems in both educational and industrial applications [27].

The analysis of publication sources indicates that scientific contributions are concentrated within a relatively small number of core journals and conference proceedings. These publication venues play a significant role in shaping the development of the field by disseminating advancements related to laboratory automation, analytical instrumentation, and intelligent monitoring systems. The dominance of specialized journals demonstrates that research on automated titration systems remains strongly connected to analytical chemistry and engineering disciplines. Furthermore, the increasing appearance of studies in interdisciplinary journals highlights the growing integration of chemistry with information technology and embedded systems [27]. Keyword co-occurrence analysis provides insights into the intellectual structure and thematic evolution of the research domain. The identified clusters demonstrate a strong relationship between conventional analytical chemistry concepts and modern technologies such as Arduino microcontrollers, IoT communication, pH sensors, peristaltic pumps, and automated control systems. These findings indicate that current research trends are increasingly directed toward real-time monitoring, remote accessibility, data acquisition, and intelligent decision-making processes. The integration of cloud computing and wireless communication technologies has further enhanced the capability of automated analytical systems to support smart laboratory environments and industry 4.0 applications [28].

Another important finding is that recent studies emphasize the developments of cost-effective and customizable systems. Open-sources platforms based on Arduino and ESP32 have significantly reduced the financial barriers associated with commercial auto titrators, thereby enabling wider implementation in educational laboratories and small scale research facilities. Several studies have demonstrated that peristaltic pumps combined with microcontrollers can achieve satisfactory accuracy while maintaining systems flexibility and ease of maintenance. These advantages have contributed to the increasing popularity of low-cost automated titration systems among researchers seeking practical and scalable analytical solutions [27]. Despite these advancements, several research gaps remain evident. The lack of standardization in systems architecture, calibration procedures, and communication protocols presents challenges for reproducibility and interoperability among different platforms. In addition, scalability issues and variations in sensor performance may affect the reliability and accuracy of automated titration processes in diverse laboratory conditions. The absence of universally accepted design guidelines also limits the transferability of developed systems from research prototypes to commercial and industrial applications [29].

Future studies should therefore focus on improving systems robustness, enhancing measurement accuracy, and developing standardized frameworks that facilitate compatibility among hardware and software components. Greater attention should also be directed toward cybersecurity, cloud integration, machine learning algorithms, and predictive control techniques to enable intelligent and adaptive titration systems. Moreover, interdisciplinary collaboration involving chemists, electrical engineers, computer scientists, and automation specialists will be essential for addressing exiting challenges and accelerating technological innovation. Such collaboration efforts are expected to contribute significantly to the realization of fully autonomous smart laboratories [28].

4. Conclusion

Overall, this study provides a deeper understanding of the scientific landscape surrounding IoT-based automated titration systems employing peristaltic pumps. The findings not only reveal current research trends and major contributors but also identify opportunities and challenges that require further investigation. By highlighting the evolution and intellectual structure of the field, this study offers valuable guidance for future researchers and developers. Ultimately, the advancement of intelligent titration systems is expected to support the development of more efficient, accurate, and sustainable laboratory technologies in the era digital transformation. The geographical distribution of scientific publications reveals that research activities are concentrated in a relatively limited number of countries, particularly the United States and Brazil, which have long established infrastructures and research capabilities in analytical chemistry and automation technologies. Nevertheless, several emerging countries have recently shown increasing contributions, indicating that the accessibility of microcontrollers, sensors, and IoT platforms has facilitated wider participation in this research area. This trend suggest that technological democratization through open-source hardware and software has enabled institutions with limited resources to develop affordable automated analytical systems. Consequently, international collaboration is expected to become increasingly important for accelerating innovation and promoting knowledge exchange among researchers worldwide. Future studies should therefore focus on improving systems robustness, enhancing measurement accuracy, and developing standardized frameworks that facilitate compatibility among hardware and software components.

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