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# Mapping Digital Competence Research in Pre-Service Science Teacher Education through a Scopus-Based Bibliometric Analysis (2020–2025)

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**Abstract**
Post-pandemic digital transformation in education requires pre-service science teachers to have strong digital competencies. However, previous studies remain fragmented and have not fully integrated digital learning models with digital competence development. This study aims to map global research trends, identify the intellectual structure, and explore research gaps in this field. A quantitative bibliometric approach was conducted using Scopus-indexed publications from 2020–2025. A total of 30 documents were selected through the PRISMA procedure and analyzed using Bibliometrix (R). The findings show an increasing publication trend, especially in 2021 during the global shift to digital learning. Research was mainly dominated by Asian and European countries, while contributions from developing countries remained limited. Major themes included TPACK, pedagogical innovation, pre-service teacher education, and 21st-century competencies. However, the connection between digital learning design and digital competence development is still limited. This study emphasizes the need for an integrative and sustainable digital learning framework to support the transformation of science teacher education.

**Keywords:** Bibliometric analysis; Digital competence; Digital learning; Pre-service science teachers.

## INTRODUCTION

The rapid advancement of digital technology in the era of the Industrial Revolution 4.0 and Society 5.0 has fundamentally reshaped the competencies required of future teachers. In science education, this transformation is particularly important because science learning increasingly depends on digital resources, simulations, virtual laboratories, interactive platforms, data-based inquiry, and technology-supported pedagogical design. Consequently, pre-service science teachers are no longer expected merely to operate digital devices, but also to demonstrate integrated digital competence that includes technological fluency, pedagogical decision-making, information literacy, critical use of digital media, ethical awareness, and the ability to design meaningful technology-enhanced learning environments (Falloon, 2020; Starkey, 2020). Digital competence, therefore, should be understood as a multidimensional professional capacity that enables future teachers to connect scientific content, digital tools, pedagogical strategies, and students' learning needs in coherent instructional practices.

Despite the growing importance of digital competence, previous studies indicate that the preparation of digitally competent pre-service teachers remains a persistent challenge. Many teacher education programs have introduced digital tools into learning activities, yet the integration of technology often remains procedural, fragmented, and insufficiently connected to subject-specific pedagogy (Pepin et al., 2021; Thurm & Barzel, 2022). In the context of science teacher education, this problem becomes more complex because digital technology must be

aligned not only with general pedagogical goals but also with the epistemological characteristics of science learning, such as observation, experimentation, modeling, inquiry, evidence-based reasoning, and conceptual visualization. Therefore, the development of digital competence among pre-service science teachers requires more than exposure to digital media; it requires systematic learning models that integrate science content, digital pedagogy, and professional teacher development.

The post-pandemic acceleration of educational digitalization has further intensified the urgency of this issue. The global shift to emergency remote teaching during the COVID-19 crisis demonstrated both the potential and the limitations of digital learning in education (Hodges et al., 2020; Huang et al., 2022). On the one hand, digital technologies expanded access to learning resources and encouraged innovation in instructional delivery. On the other hand, the rapid transition also exposed gaps in teachers' readiness, digital pedagogical competence, infrastructure, and institutional support. As a result, research on digital learning, teacher digital competence, and science education has grown significantly in recent years. However, the expansion of this research field has not necessarily produced an integrated understanding of how digital learning models contribute to the formation of pre-service science teachers' digital competence.

Existing literature shows that studies on science learning transformation have generally focused on the use of digital technology as instructional media, learning tools, or platforms for improving student achievement (Cheng & Oon, 2022; Zhu et al., 2020). Meanwhile, research on digital learning models has tended to emphasize instructional design, learning effectiveness, and student-centered outcomes (Istenic et al., 2021). Although these studies provide important insights, they often position pre-service teachers as users or implementers of technology rather than as future professional agents whose digital competence must be systematically developed. Similarly, studies on teacher digital competence frequently discuss general teacher readiness, digital literacy, or technology acceptance, but pay less attention to the specific relationship between digital learning models and competence development in science teacher education (Bakir & Alharbi, 2024; Voogt et al., 2023). This indicates that research on digital learning and research on pre-service teachers' digital competence have developed in parallel, but have not yet been sufficiently integrated into a comprehensive conceptual and empirical framework.

This fragmentation creates an important research gap. First, there remains limited bibliometric evidence that maps how research on digital competence in pre-service science teacher education has developed during the post-pandemic period. Second, the intellectual structure of this field, including dominant themes, influential contributors, country distribution, and keyword relationships, has not been clearly synthesized. Third, the connection between digital learning models and the systematic development of digital competence among pre-service science teachers remains underexplored. These gaps are significant because teacher education institutions need evidence-based directions for designing contextual, integrative, and sustainable digital learning frameworks that can prepare future science teachers for increasingly digital learning environments.

Bibliometric analysis offers a relevant approach to address this gap because it enables researchers to examine the development of scientific publications, identify research trends, map conceptual relationships, and detect emerging themes within a specific field (Donthu et al., 2021; Zupic & Čater, 2015). Scopus is widely used as a reliable multidisciplinary database for bibliometric studies because it provides structured metadata, citation information, author affiliations, and publication sources across broad areas of scholarship (Baas et al., 2020). In addition, analytical tools such as Bibliometrix and VOSviewer allow researchers to visualize publication trends, citation patterns, author productivity, institutional contributions, country collaboration, and keyword co-occurrence networks (Aria & Cuccurullo, 2017). Through this approach, bibliometric analysis can provide a systematic overview of how digital competence research in pre-service science teacher education has evolved and where future research should be directed.

Based on this background, the present study aims to map global research trends on digital competence in pre-service science teacher education using Scopus-indexed publications from 2020 to 2025. Specifically, this study seeks to identify annual publication trends, citation patterns, productive authors and institutions, contributing countries, and dominant research themes related to digital competence and digital learning in science teacher education. Unlike previous studies that mainly discuss digital competence or digital learning separately, this study positions bibliometric mapping as a basis for identifying the conceptual gap between digital learning model development and the systematic strengthening of pre-service science teachers' digital competence. The findings are expected to provide an academic roadmap for future studies and support the development of more contextual, integrative, and sustainable digital learning frameworks for science teacher education.

## METHODS

This study employed a quantitative bibliometric approach to map and analyze the development of scientific publications related to the digital competence of pre-service science teachers and digital-based learning models. The bibliometric approach has proven effective in identifying trends, conceptual relationships, and research gaps in the field of education through the analysis of large-scale publication data (Donthu et al., 2021; Zupic & Čater, 2015). Research data were collected from the Scopus database, which is recognized as one of the largest and most reputable multidisciplinary scientific literature repositories for bibliometric analysis (Baas et al., 2020). Data collection was conducted using a search string that combined key terms such as "digital competence," "pre-service science teachers," "digital-based learning model," and "digital skills," with appropriate Boolean syntax to ensure the recall and relevance of the search results (Aria & Cuccurullo, 2017). The publication period was limited to 2020–2025 in order to capture the most recent post-pandemic research developments, a period marked by the significant acceleration of educational digitalization (Hodges et al., 2020).

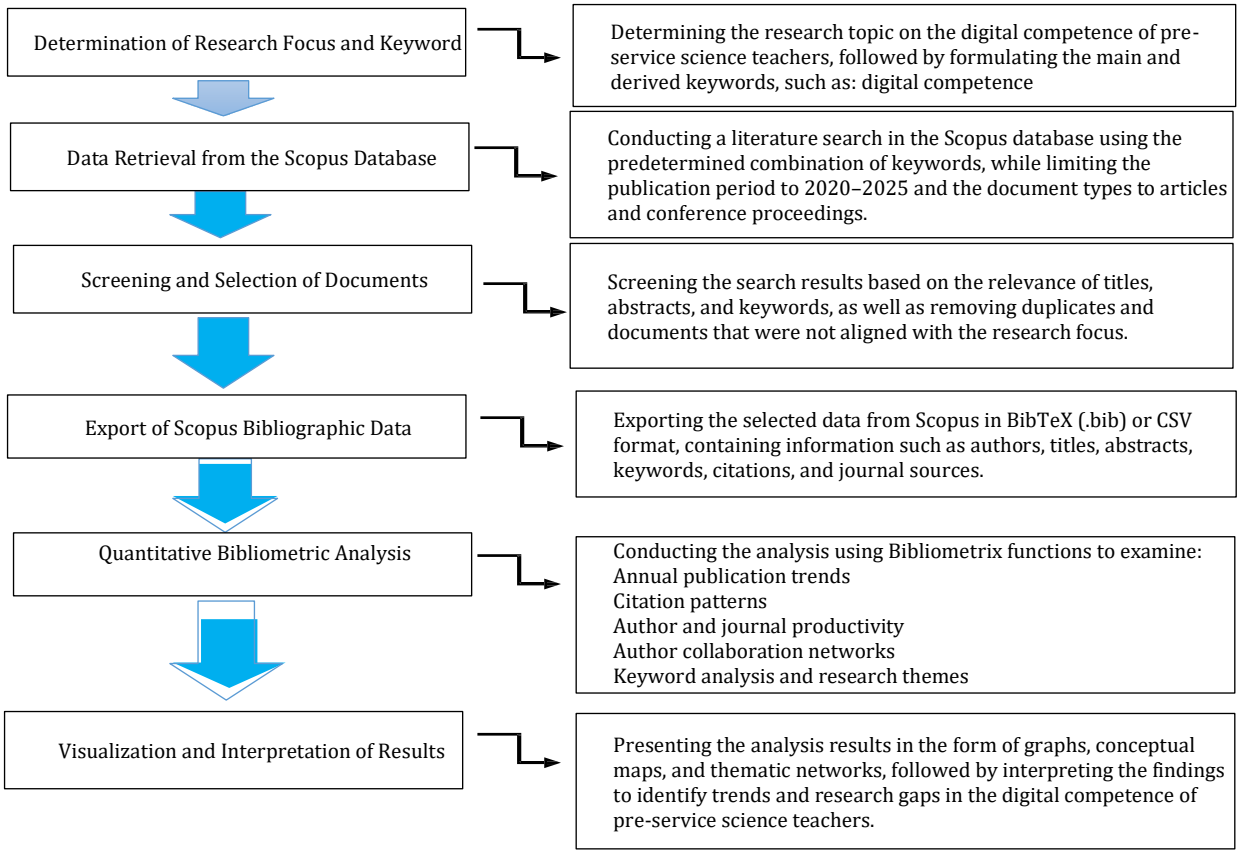


**Figure 1.** Stages of Scopus Article Analysis through Bibliometric Methods

The article selection and screening process followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to ensure transparency and reproducibility (Page et al., 2021), ensuring that only relevant journal articles were further analyzed. The search and screening process resulted in 30 selected documents relevant to the focus of the study. This final dataset constituted the core corpus for analysis, reflecting the specificity of the research topic, where a smaller but highly relevant number of documents is often appropriate for in-depth analysis in emerging research areas (Fisch & Block, 2018).

Furthermore, the data were analyzed using R Studio with the Bibliometrix package (version 4.0) to identify publication patterns, citation trends, author collaborations, and the development of research themes (Aria & Cuccurullo, 2023). The Bibliometrix package has been widely recognized as a reliable and comprehensive tool for science mapping and bibliometric analysis research (Moral-Muñoz et al., 2020).

This approach enabled a comprehensive understanding of the intellectual structure and research directions in the field of digital-based science learning transformation and the digital competence of pre-service teachers. Specifically, co-word network analysis was applied to visualize conceptual relationships among topics and identify major thematic clusters emerging in the literature (Su & Lee, 2010). Meanwhile, citation burst analysis was conducted to detect topics experiencing significant increases in scholarly attention during the study period (Chen, 2017). The combination of these analytical techniques provides a strong foundation for addressing the research gaps identified previously.

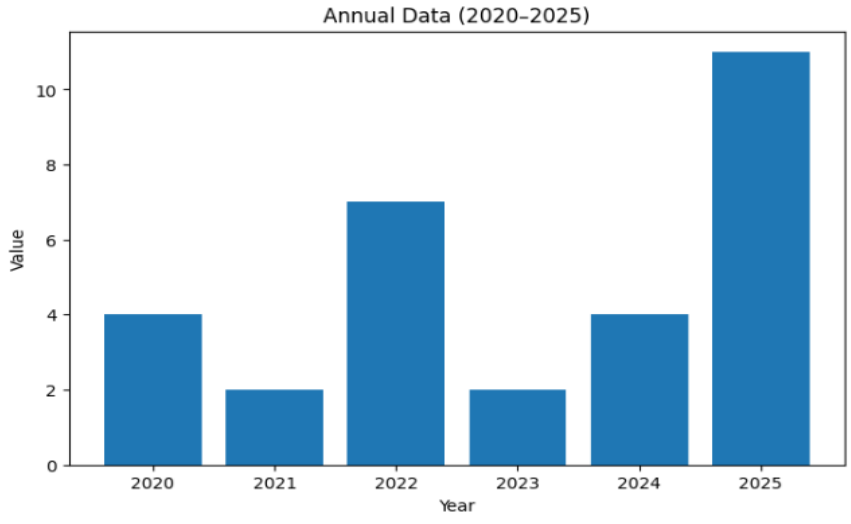


**Figure 2.** Number of Documents Related to Digital Competence (2020–2025)

Figure 2 illustrates the development in the number of scientific publication documents per year during the 2020–2025 period. This development pattern is characteristic of emerging research fields or those experiencing acceleration due to external disruptions, such as the post-pandemic digital transformation in education (Marinoni et al., 2020). Based on the graph, the number of publications in 2020 was still relatively limited, followed by a decline in 2021. This decrease may reflect the temporal gap between the onset of the crisis (the pandemic) and the processes of conducting research, writing, and publishing, which require considerable time (Aguilar et al., 2021).

Entering 2022, the number of documents increased significantly, indicating growing scholarly attention to the studied topic, in line with academic consolidation and reflection on emergency learning practices (Trust & Whalen, 2023). In 2023, the number of publications declined again, but an increase reappeared in 2024. Such fluctuations are part of the normal research cycle and may be influenced by factors such as funding cycles, educational policy

priorities, or the focus of major international conferences (Leydesdorff et al., 2016).

The peak number of documents occurred in 2025, indicating a strong publication growth trend in the most recent period. This peak confirms that the topics of teachers' digital competence and digital learning models have reached a mature phase within the global educational research agenda (Instefjord & Munthe, 2017; Scherer et al., 2021). Overall, the graph demonstrates that research interest and productivity on these topics have tended to increase in recent years, reflecting the growing relevance of these issues in the context of educational development and digital technology advancement.

## RESULT AND DISCUSSION

The analysis results from the Scopus database using the keywords *digital competence* and *pre-service science teachers* identified 30 documents. Based on the scientific fields, the distribution is presented in Figure 3 below.

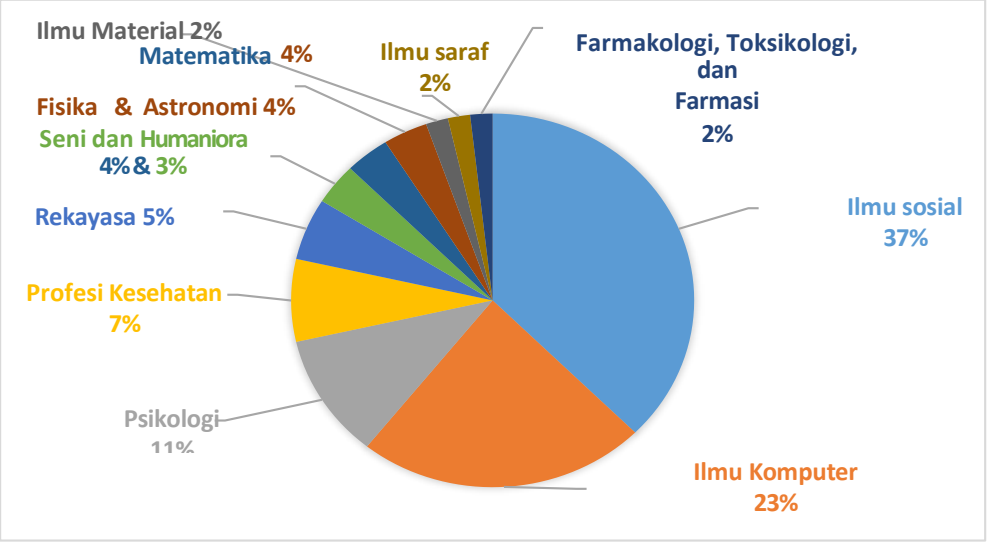


**Figure 3.** Territorial Distribution of Contributing Countries

The findings indicate that research on digital competence and pre-service science teachers is multidisciplinary in nature, with the main contributions coming from Social Sciences (37%), Computer Science (23%), and Psychology (11%), alongside supporting contributions from fields such as engineering, health sciences, and pure sciences (Voogt et al., 2013; Koehler & Mishra, 2009). The dominance of Social Sciences suggests that the primary focus of the studies lies in pedagogical aspects, educational policy, and the social context of teacher competence development, where technology is viewed as a tool for achieving broader educational goals. Meanwhile, the substantial contribution from Computer Science reflects the fundamental need for technical foundations and technological innovation to support digital transformation in learning processes (Kirkwood & Price, 2014). The contribution of Psychology further emphasizes that successful technology adoption strongly depends on internal individual factors, such as self-confidence, motivation, and pre-service teachers' acceptance of new technologies in their teaching practices (Scherer et al., 2019).

This multidisciplinary distribution also highlights and confirms the previously identified research gap. Although the context of science education (represented by contributions from Mathematics, Physics, and Chemistry) constitutes a specific niche, the deep and specific integration between science content, digital pedagogy from the perspective of Social Sciences, and technical solutions from Computer Science remains limited and fragmented (English, 2016).

Many studies in the dominant field of Social Sciences tend to discuss digital competence in general terms; therefore, further studies are needed to explicitly design and examine learning models that are seamlessly integrated with the epistemological and practical characteristics of each branch of science education. Accordingly, future research is encouraged to adopt a design-based research approach that intentionally integrates expertise from these three major pillars—designing technical solutions (Computer Science) to support pedagogical strategies (Social Sciences) that align with the context of science content, while continuously considering users' psychological aspects (Psychology)—in order to create holistic and effective interventions for improving the digital competence of pre-service science teachers.

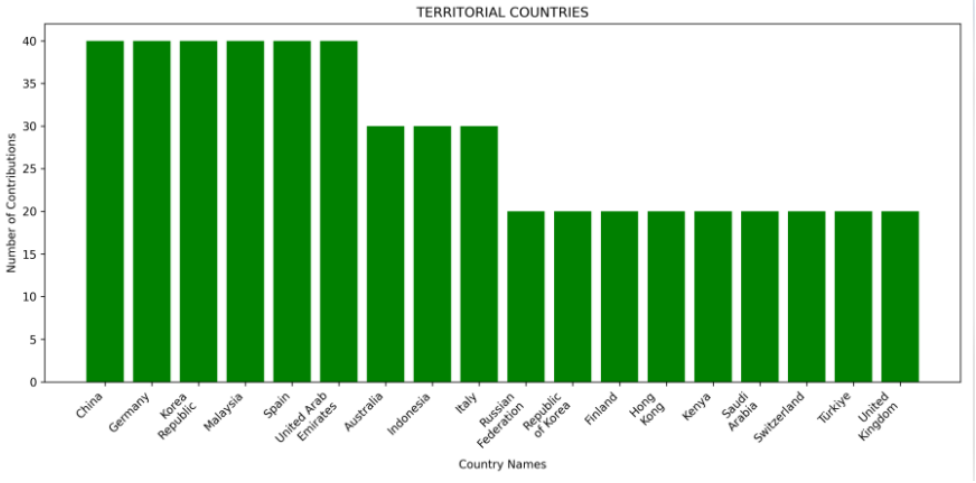


**Figure 4.** Contributing Countries

The analysis of country distribution in Figure 4 reveals that research on the digital competence of pre-service science teachers and digital-based learning models has developed globally, although with uneven patterns of productivity and contribution across regions (Huang et al., 2022; Starkey, 2019). The dominance of contributions from countries such as China, Germany, Malaysia, Spain, and the United Kingdom, each contributing approximately three documents, reflects regional leadership and a strong commitment to research in education and technology. In Europe, the active involvement of countries such as Germany and Spain aligns with the European Union's research agenda focused on digital transformation and strengthening educational system resilience, as reflected in the Horizon Europe research program, which funds innovative projects for risk management and capacity building (European Commission, 2024). Meanwhile, the leading positions of China and Malaysia represent the dynamics of research in Asia, which strongly emphasizes the integration of Information and Communication Technology (ICT) in education, driven by ambitious national policies aimed at modernizing teaching and learning systems.

At the intermediate level of contribution, countries such as Australia, Indonesia, Italy, Peru, and the Russian Federation demonstrate consistent participation. This involvement indicates that the research topic has gained attention across diverse socio-cultural contexts and varying levels of economic development. For example, research in Indonesia may focus more on developing digital learning models to address infrastructure challenges and digital divides, as reflected in global efforts to measure and strengthen system resilience through contextual approaches (UNDRR, 2024). The participation of countries from Latin America (Peru) and Central Europe (Hungary and Slovakia) further reinforces the finding that building resilience and digital capacity requires inclusive cross-sectoral and cross-regional approaches (European Civil Protection and Humanitarian Aid Operations, 2025).

Meanwhile, contributions from several other countries, each contributing approximately one document—such as Austria, the Czech Republic, Egypt, Finland, and the United States—indicate that academic interest in this topic is widespread, although it may still be in an early or

incidental stage in some regions. This broad geographical distribution is consistent with the principles of global frameworks such as the Sendai Framework for Disaster Risk Reduction, which emphasizes the importance of knowledge sharing, international collaboration, and capacity strengthening at all levels to address complex challenges (UNDRR, 2015). In the context of educational research, this means that solutions for improving teachers' digital competence need to consider and synthesize insights from diverse local and national contexts to create approaches that are truly effective and adaptable.

Overall, this map of country contributions not only illustrates research productivity but also highlights potential collaboration networks and existing knowledge gaps. The dominance of certain countries suggests the presence of well-established research ecosystems supported by funding and policy frameworks. On the other hand, the more limited participation of many other countries, including some with very large educational systems, indicates substantial opportunities for further research capacity development, knowledge transfer, and more equitable international collaboration. Future research should actively bridge these geographical gaps by establishing inclusive partnerships, so that innovations in teacher education can accommodate and address the diverse needs of global contexts.

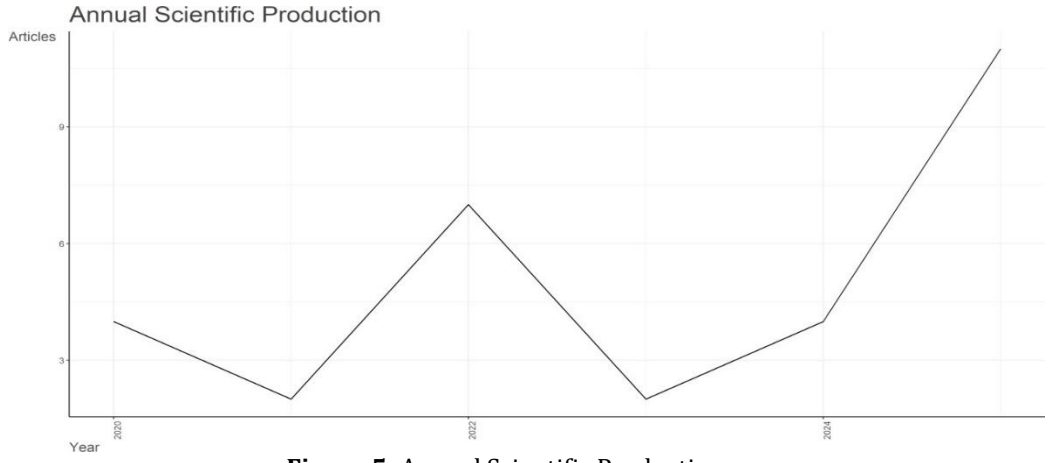


**Figure 5.** Annual Scientific Production

The analysis of annual scientific production data in Figure 5 demonstrates a growth pattern that has been strongly influenced by external disruptions and recent policy responses. The graph, which shows stable production during 2020–2021, followed by a significant increase in 2022, a decline in 2023, and a gradual upward trend through 2025, reflects global and national dynamics in the field of digital-based educational research.

The annual scientific production pattern presented in Figure 5—showing stable production in 2020–2021, followed by a surge in 2022, a decline in 2023, and a recovery trend leading up to 2025—directly reflects the dynamic response of the research community to external disruptions and accelerated policy developments (Sánchez et al., 2022). The relatively low volume during the initial phase (2020–2021) indicates that the topic of digital competence among pre-service science teachers was still an emerging field, where early studies tended to be exploratory before gaining momentum that stimulated rapid growth (Bouchrika, 2026). The significant increase in 2022 was most likely a direct consequence of the COVID-19 pandemic, which acted as a global catalyst accelerating the adoption of technology in education and creating urgent research opportunities to address the challenges of remote learning (Maphoto & Moloi, 2025).

The decline in production in 2023 can be understood as a phase of correction and intellectual consolidation following the previous surge, during which researchers shifted from rapid-response studies toward more in-depth examinations of earlier findings and the preparation of more structured investigations. The recovery and continued growth observed in 2024 and peaking in 2025 mark the transition of this field into a phase of institutionalization and sustainable innovation. This growth has been supported by the convergence of several driving

factors, including the implementation of national educational policies such as the *Merdeka Curriculum* in Indonesia, which has created an applicable context for the development of innovative models (Anwar & Gistituati, 2025), the increasing readiness of digital infrastructure reflected in high internet penetration rates (DataReportal, 2026; Kemp, 2026), and the consolidation of global research agendas focusing on the digital transformation of higher education despite ongoing implementation challenges (Maphoto & Moloi, 2025).

Thus, the fluctuations shown in the graph do not indicate instability; rather, they represent the responsive cycle and maturation of a research field that is becoming increasingly relevant in addressing the demands of the digital era.

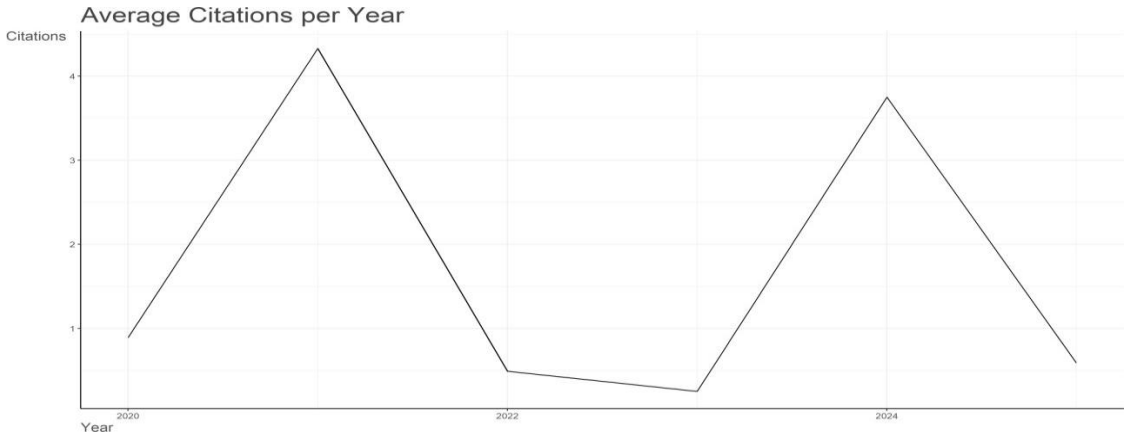


**Figure 6.** Citation Trend Graph for 2021

Figure 6 illustrates the pattern of average citations per year, showing a sharp increase in 2021, a decline during 2022–2023, a rise again in 2024, and another decrease in 2025. This pattern classically reflects the dynamics of the citation life cycle of scientific articles and the strong influence of the citation window or citation time span (Wang, 2018). The relatively low average citation count in 2020 is a common phenomenon, as newly published articles require time to be disseminated, read, and integrated into subsequent research before they begin to receive citations (Birkle et al., 2020).

The sharp increase reaching its peak in 2021 strongly indicates that publications from this period had significant academic impact and high relevance. This surge was likely driven by the emergency context of the COVID-19 pandemic, during which research on digital learning and teacher competence became highly central and urgent. Consequently, publications released during this period quickly became key references in responding to the global educational crisis (Maphoto & Moloi, 2025; Scherer et al., 2021).

The significant decline observed in 2022 and 2023, however, reflects the influence of time rather than a decrease in research quality. Articles published during these years were still relatively "young" and had not yet accumulated large numbers of citations, since the scientific publication cycle requires time for writing, peer review, and the publication of subsequent studies that may cite them (Thelwall & Wilson, 2014). The noticeable increase again in 2024 suggests that several publications from 2022–2023 had begun reaching their peak influence, indicating that this research topic remained relevant and increasingly adopted within broader research domains. Finally, the decline in 2025 can almost entirely be attributed to time limitations, as articles published during that year were still too recent to receive widespread citations in the scientific literature (Wang, 2018).

Overall, this graph confirms that citation impact is both dynamic and delayed. The citation peak in 2021 reflects not only publication quality but also a unique historical context that amplified the visibility and urgency of research in this field. This pattern highlights a fundamental principle in bibliometrics: evaluating the long-term impact of a research field or

publication requires a longer temporal perspective beyond a 5–6 year period, along with complementary analyses such as field-weighted citation impact metrics that account for disciplinary differences in citation practices (Waltman, 2016).

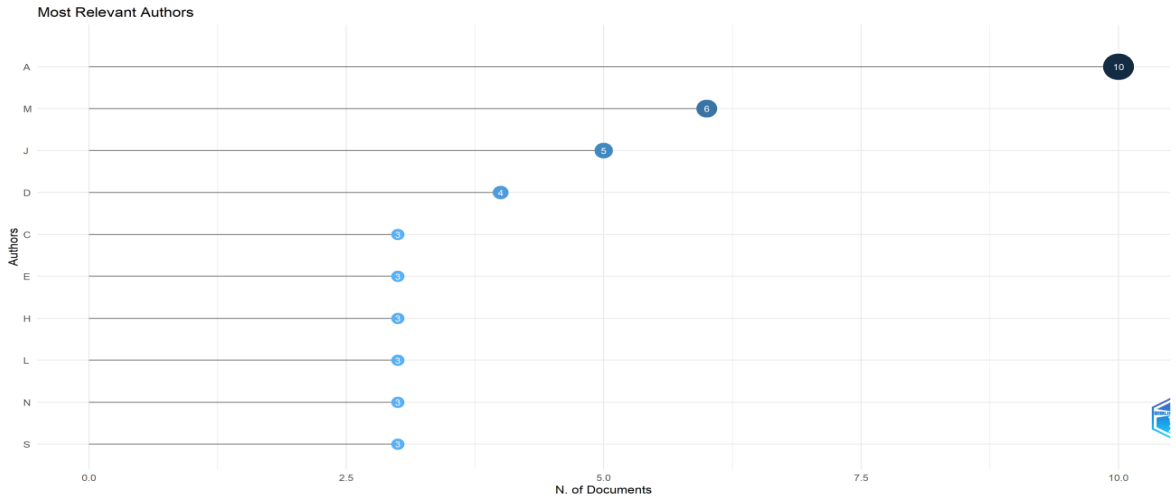


**Figure 7.** Author Contribution Distribution

The author productivity distribution presented in Figure 7, where Author A dominates with 10 documents, followed by Author M with 6 documents and Author J with 5 documents, and subsequently followed by a group of authors with smaller contributions, represents a classic manifestation of Lotka's Law in bibliometrics. This law states that a small proportion of authors contribute the majority of publications within a research field, resulting in a highly unequal productivity structure (Lotka, 1926; Egghe, 2005). The dominance of several core authors, such as Author A, indicates that they have played a central role as intellectual leaders and primary drivers in shaping the research discourse on digital competence among pre-service science teachers and digital-based learning models (Zuccala, 2006). Their consistent and significant contributions have likely helped define conceptual frameworks, identify methodological trends, and establish a coherent discourse community surrounding this topic (Crane, 1972).

Meanwhile, the presence of authors with moderate contributions (4 documents) and lower contributions (3 documents) reflects the dynamics of collaboration and knowledge diffusion within the field. These authors may function as active collaborators within research networks led by the core authors or as independent researchers contributing diverse perspectives and contextual applications (de Solla Price, 1963). Although uneven, this productivity pattern is actually beneficial for an emerging research field. The concentration of expertise among a few key researchers can accelerate intellectual progress and maintain conceptual coherence, while broader participation from other authors ensures that the field remains dynamic, open to new approaches, and not confined to a single dominant paradigm (Merton, 1968). In the context of highly applied research areas such as teacher education, contributions from authors with varying levels of productivity are particularly important for testing and adapting core concepts across diverse cultural and institutional settings.

This structure also carries practical implications for new researchers entering the field. Identifying core authors such as A, M, and J constitutes a strategic first step in conducting an in-depth literature review, as their publications are likely to serve as foundational theoretical references and central points of citation (Small, 1973). Furthermore, analyzing co-authorship networks involving these authors can reveal collaboration patterns, knowledge flows, and potential opportunities for future research partnerships (Newman, 2004). Therefore, the author distribution pattern illustrated in Figure 7 not only reflects the current state of the field but also provides an intellectual roadmap for navigating and strategically developing future research directions.

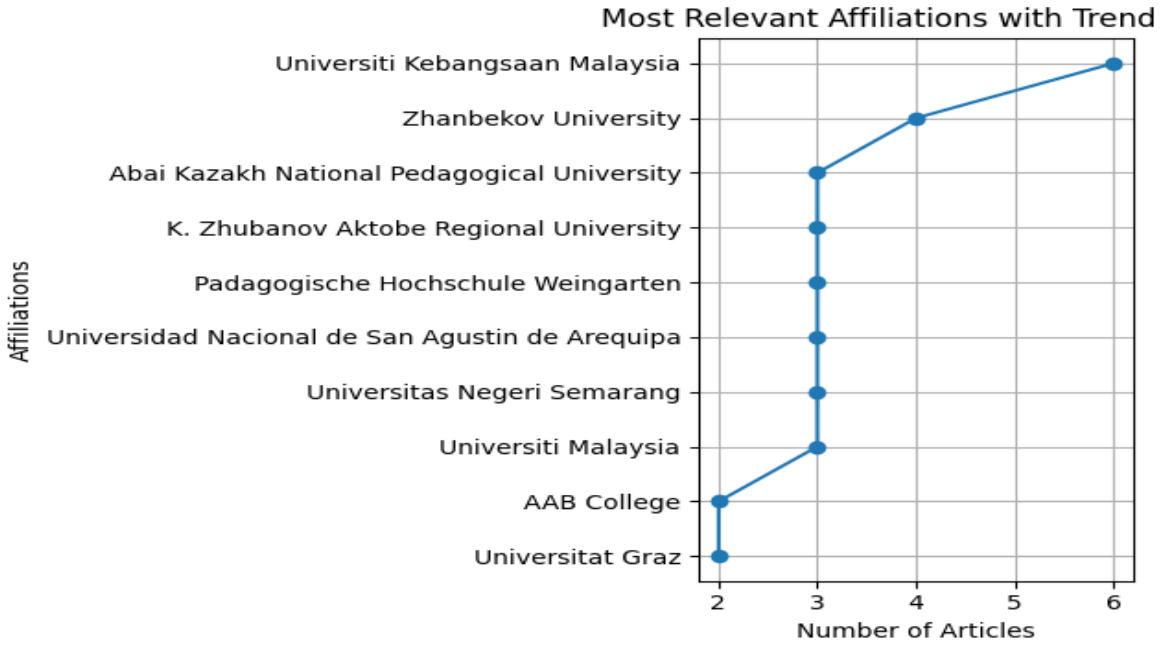


**Figure 8.** Cross-Country Author Contributions

The institutional affiliation analysis presented in Figure 8 shows that author contributions are dominated by Universiti Kebangsaan Malaysia (UKM) with six publications, followed by several universities from Kazakhstan, Germany, Peru, Indonesia, and other institutions from Malaysia. This distribution reveals an interesting geographical and strategic landscape in research on the digital competence of pre-service science teachers. The dominance of UKM as a "core contributing institution" aligns with findings that countries such as Malaysia demonstrate high research productivity in this field, often driven by proactive national policies promoting the integration of Information and Communication Technology (ICT) in education, as well as strong commitments to publishing research in international journals (Maphoto & Moloi, 2025; Huang et al., 2022).

Significant contributions from universities in Kazakhstan, such as Zhanibekov University and Abai Kazakh National Pedagogical University, reflect the increasing involvement of Central Asian countries in the global educational research agenda. This trend is likely supported by educational modernization programs and increased investment in research funding. The presence of institutions from Germany, Peru, and Indonesia, including Pädagogische Hochschule Weingarten, Universidad Nacional de San Agustín de Arequipa, and Universitas Negeri Semarang, demonstrates that the issue of teachers' digital competence is universal in nature. However, local contexts, challenges, and approaches differ considerably, requiring contextualized studies from diverse regions around the world (Voogt et al., 2013).

This structure, characterized by several core institutions alongside numerous supporting institutions, forms what may be described as an "implied collaboration network." Although the data only indicate affiliations, the concentration of publications within certain universities often signals the existence of strong research groups, adequate supporting facilities, and potentially productive international collaboration networks (Newman, 2004). The diversity of institutional affiliations—ranging from pedagogical universities and comprehensive research universities to regional institutions—suggests that this topic is being examined from multiple institutional perspectives. Some institutions focus primarily on pedagogical development, others emphasize technological aspects, while some address region-specific educational needs.

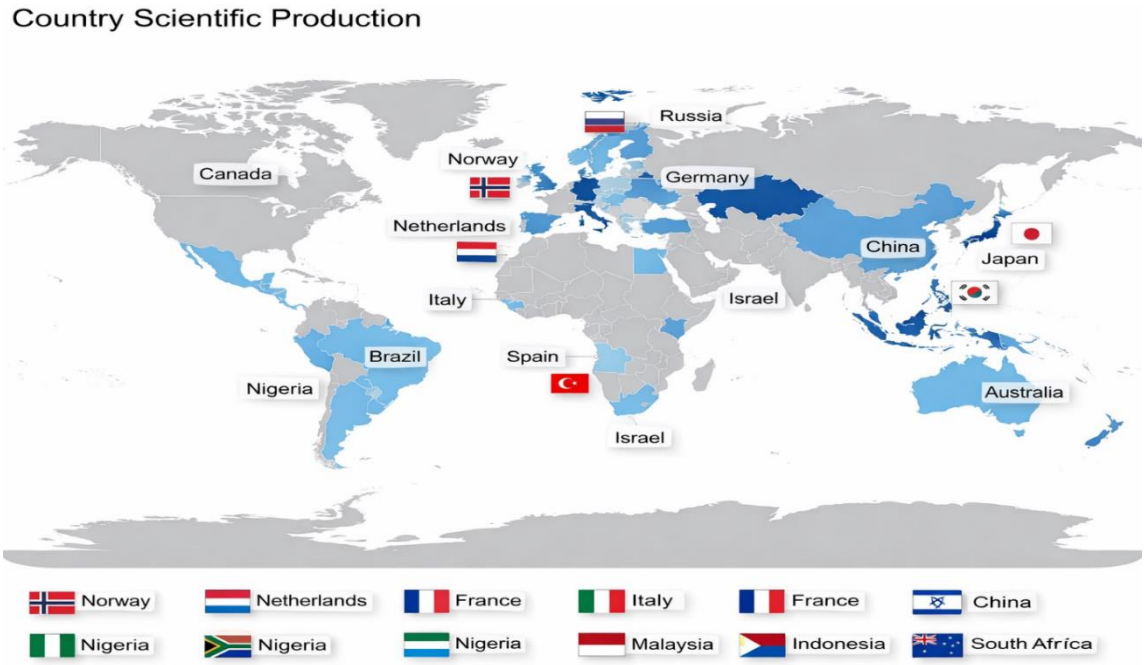


**Figure 9.** Geographic Visualization of Research Distribution Related to Digital Competence

In this context, Indonesia's position within the medium-intensity category accurately reflects the broader dynamics of the international research landscape. Comparative reports indicate a significant global shift, where the rapid growth of countries such as China and India has contributed to the relative decline in publication shares of traditional research powers, thereby creating opportunities for scientifically ambitious countries like Indonesia to strengthen their research presence (UK Department for Science, Innovation & Technology, 2025).

A major opportunity for enhancing Indonesia's research capacity lies in two key strategies reflected in global research patterns. First, deepening and expanding international collaboration is essential, as demonstrated by the United Kingdom, which has maintained its competitive position through an international collaboration rate exceeding 60%—one of the highest in the world—to enhance the visibility and impact of its research outputs (UK Department for Science, Innovation & Technology, 2025). Second, focusing on research quality and impact through metrics such as Field-Weighted Citation Impact (FWCI) has become a critical differentiator amid increasing competition in publication volume. For Indonesia, investing in in-depth and original research, while prioritizing publication in high-reputation journals, will be a more effective strategy for strengthening its scientific profile in the long term.

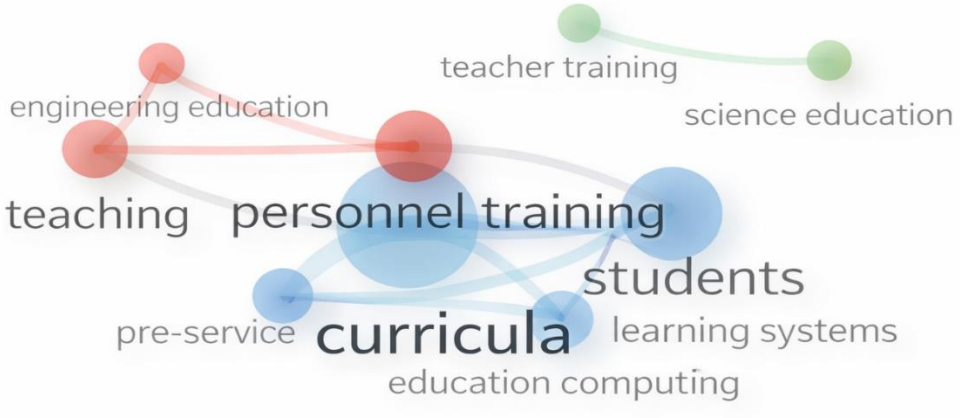


**Figure 10.** Research Network Based on Digital Competence Keywords

Figure 10 illustrates a keyword-based exploration of digital competence research, revealing that educational research networks are primarily centered on curriculum development and teacher competency enhancement, with strong connections to learning systems and student needs (Lay et al., 2026; Biko, 2025). Central elements such as "curricula," "teaching," "personnel training," and "students" form an interconnected and mutually reinforcing relationship. Curriculum innovations, including the integration of STEM/STEAM approaches and scientific learning models, have proven effective in enhancing 21st-century skills such as critical thinking and curiosity among elementary school students (Syarief Abdullah, 2025; Rahmadhani, 2025).

However, the successful implementation of these innovative curricula largely depends on the quality of teacher training and teacher readiness, which are reflected in the "personnel training" theme (Surya et al., 2025). Furthermore, the integration of digital technology into learning—such as video-based media, simulations, and interactive platforms—has become a crucial enabler supporting the three major aspects of curriculum, teaching, and teacher training. These technologies contribute to creating more effective learning experiences and improving students' conceptual understanding (Biko, 2025; Saputra et al., 2024).

Overall, this visualization comprehensively reflects the direction and concentration of research themes in the field of education, which are oriented toward improving student learning outcomes through the interconnected pillars of curriculum, teachers, and educational technology.

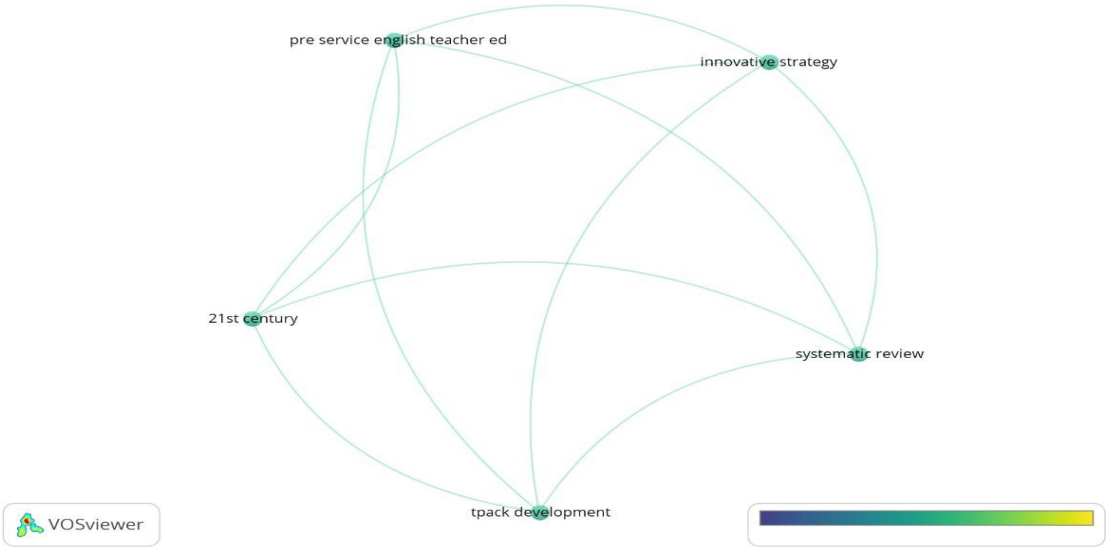


**Figure 11.** Keyword Network Visualization Using VOSviewer

Figure 11 presents a visual network generated through VOSviewer, which serves as a highly useful graphical representation for identifying thematic relationships and research concentrations within a particular field. The visualization displays keyword nodes and their interconnections based on co-occurrence patterns within scientific publications. The map in this study indicates that current research trends are strongly focused on the development of Technological Pedagogical Content Knowledge (TPACK), innovative teaching strategies, and pre-service teacher education, all of which are closely connected to the context of 21st-century skills and systematic review approaches.

This close relationship is not coincidental. Previous studies emphasize that 21st-century teachers require mastery of TPACK in order to effectively integrate technology into their teaching practices (Gómez Niño et al., 2025). The development of TPACK, as a complex professional competency, requires innovative strategies implemented in both pre-service and in-service teacher education programs. Various instructional approaches, including Problem-Based Learning (PBL), Project-Based Learning, and flipped classroom models, have been examined as effective strategies for developing these competencies while simultaneously

equipping future teachers with essential 21st-century skills (Shobiroh et al., 2025; Rehman et al., 2024).

These research trends do not emerge randomly but are increasingly analyzed and synthesized through systematic review methodologies. This methodological approach is widely used to map the research landscape, consolidate fragmented findings, and identify existing knowledge gaps (Shobiroh et al., 2025). The strong emphasis on systematic reviews indicates that this field has reached a certain level of maturity, where researchers are attempting to make sense of the growing volume of publications and establish a robust evidence base for future educational policy and teacher education practices.

***Significance of the Findings and Global Research Positioning***

This bibliometric analysis reveals a clear pattern: research on the digital competence of pre-service science teachers remains largely dominated by institutions and researchers from developed countries, particularly in Europe and East Asia, while contributions from developing countries such as Indonesia remain at a moderate level. A recent international systematic review covering the period 2014–2024 confirmed that the current literature still suffers from limitations in geographical and contextual representation, as most studies focus primarily on specific countries or regions (Wang, 2026).

This finding represents more than a descriptive observation; it highlights the strategic positioning of the present study. By explicitly identifying and focusing on this imbalance, the study shifts the narrative from merely "following global trends" toward "responding to underrepresented local needs within international discourse." Consequently, this article functions not merely as a review report, but as an academic manifesto advocating for contextual research perspectives from the Global South, an approach increasingly valued by high-impact Q1 journals concerned with inclusivity and equitable knowledge production.

***Identification of Specific and Actionable Research Gaps***

Beyond the geographical analysis, this study successfully identifies substantive gaps within the existing literature. The findings indicate that current research remains fragmented, often separating investigations of digital learning models from studies on the development of digital competence among pre-service teachers. Most existing literature focuses primarily on student learning outcomes or general instructional design.

A recent in-depth literature review on the role of digital literacy in gamified integrated science learning demonstrated that foundational digital literacy continues to dominate current discussions, while the development of integrated digital learning models specifically designed to foster pedagogical-digital competence among future teachers remains insufficiently explored (Sundahry, 2025). Therefore, the research gap addressed by this article is highly concrete: the need for an integrated digital learning framework specifically designed to develop the digital competence of pre-service science teachers holistically and evaluated based on their mastery as future educational change agents. The identification of this evidence-based and highly specific gap substantially strengthens the theoretical contribution of the manuscript, demonstrating that the study is not a repetition of previous research but rather a necessary conceptual advancement within the field.

***Relevance to Global Agendas and the Future of Education***

The discussion within this manuscript connects the findings to global agendas such as the United Nations Sustainable Development Goals (SDGs) and the demands of the Industrial Revolution 4.0 and Society 5.0. Recent studies on digital competence for sustainable education confirm that teachers' digital mastery plays a critical role in achieving SDG 4, which aims to ensure inclusive, equitable, and quality education for all (Wang, 2026).

The emphasis on developing teachers' digital competence as a foundation for quality, inclusive, and sustainable science education positions this research within the broader discourse

of global educational transformation. Rather than merely analyzing past trends, the article uses bibliometric evidence to project future research directions, making the study both relevant and forward-looking. Alignment with global priorities significantly enhances the potential academic impact of the research.

### *Practical Implications and Future Potential*

The discussion in this manuscript leads to several clear and urgent practical implications. By confirming the limited availability of structured and evidence-based digital learning models, this study provides a strong foundation for encouraging researchers and practitioners—particularly in developing countries—to develop and evaluate contextual digital learning models for science teacher education.

Furthermore, the analysis of factors influencing teachers' ability to integrate technology, such as continuous professional development and institutional support, provides valuable entry points for designing effective educational interventions (Indrianingsi, Sihotang, & Simbolon, 2025). These implications possess broad relevance because they directly address real educational needs in classrooms and teacher education institutions. As such, this manuscript functions as an academic roadmap capable of inspiring collaborative international research programs, an aspect that is highly attractive to reputable international journals.

## CONCLUSION

This bibliometric study provides a systematic overview of research trends on digital competence in pre-service science teacher education based on Scopus-indexed publications from 2020 to 2025. The findings indicate that research in this field has developed dynamically, with fluctuating but generally increasing publication trends, particularly in response to the acceleration of digital learning after the pandemic. The bibliometric mapping shows that scholarly contributions are still dominated by several countries, institutions, and thematic clusters, especially those related to TPACK, teacher training, digital learning, pedagogical innovation, science education, and 21st-century competencies. However, the analysis also reveals an important gap: existing studies have not sufficiently integrated digital learning model development with the systematic strengthening of pre-service science teachers' digital competence. This gap is particularly relevant for developing countries, including Indonesia, where contextual and sustainable digital learning frameworks are needed to support science teacher education. Therefore, future studies should move beyond descriptive mapping by developing, testing, and evaluating integrative digital learning models that combine science content, digital pedagogy, technological innovation, and teacher professional development. Although this study is limited to Scopus-indexed documents and a relatively small corpus of 30 publications, it offers an evidence-based research roadmap for advancing digital competence studies and strengthening the preparation of future science teachers in increasingly digital educational environments.

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