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Higher-Order Thinking Skills in Science Teacher Education: A Bibliometric Analysis Over the Last 11 Years

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ABSTRACT

Objective: *This study examines the research landscape of higher-order thinking skills (HOTS) in science teacher education within the framework of Education for Sustainable Development (ESD) from 2015 to 2025, addressing the limited integration of HOTS, science teacher education, and ESD in previous bibliometric studies.* ***Methods:*** *A bibliometric analysis was conducted using Scopus-indexed journal articles. After screening using PRISMA 2020, 108 articles were analyzed using Bibliometrix/Biblioshiny to examine publication trends, influential contributors, and thematic development.* ***Results:*** *HOTS research has grown substantially over the past decade, with the highest number of publications recorded in 2025. Indonesia emerged as a leading contributor, while the International Journal of Science Education (7 publications) and Sustainability (6 publications) were the most prolific journals. Thematic analysis identified four major thematic clusters, revealing a conceptual shift from individual cognitive skills toward inquiry-based learning, project-based learning, teacher education, sustainability, and generative artificial intelligence.* ***Novelty:*** *This study extends existing bibliometric research by integrating higher-order thinking skills, science teacher education, and Education for Sustainable Development within a single analytical framework, providing a more comprehensive understanding of the field's intellectual structure, thematic evolution, and future research directions.*

INTRODUCTION

In 2015, all 193 member states of the United Nations (UN) agreed on the 2030 Agenda for Sustainable Development, known as the SDGs. This agreement comprises 17 Sustainable Development Goals that address a range of challenges, including education, poverty and equality, health, environmental degradation, biodiversity, urbanization, energy and a sustainable economy (Zimon et al., 2023). Achieving the Sustainable Development Goals (SDGs), especially Sustainable Development Goal 4 (SDG 4) on quality education, requires an education system that prepares students to overcome increasingly complex scientific, environmental, and social challenges (Dube, 2026; Tytler et al., 2025). In this global agenda, science education occupies a strategic position because contemporary sustainability issues, such as climate change, biodiversity loss, renewable energy, and environmental health, demand citizens who can evaluate evidence, build well-reasoned arguments, solve authentic problems, and make informed decisions (Tijani & Adeduyigbe, 2026). As a result, science teacher education has become an important component of educational reform, as future science teachers are expected not only to have

strong disciplinary knowledge but also to cultivate higher-order thinking skills (HOTS) among their future students (Li & Zamri, 2025).

Therefore, preparing teachers with these competencies is essential to translate the vision of Education for Sustainable Development (ESD) into meaningful classroom practice (Shabrina et al., 2024). Higher-order thinking skills encompass a range of interconnected cognitive competencies, including critical thinking, scientific literacy, scientific argumentation, reflective reasoning, and problem-solving (Shutaleva, 2023). Rather than representing isolated abilities, these competencies enable individuals to analyze scientific information critically, evaluate competing claims using empirical evidence, and apply scientific knowledge to real-world situations (Ramadhan et al., 2026; Straser et al., 2026).

In science teacher education, HOTS is increasingly recognized as a fundamental professional competence because prospective teachers must be able to design inquiry-oriented teaching, facilitate evidence-based discussions, and guide students toward scientific reasoning (Mesci et al., 2025; Özer et al., 2026). Therefore, teacher preparation programs around the world are increasingly incorporating pedagogical approaches such as inquiry-based learning, project-based learning, argument-based inquiry, problem-based learning, and other student-centered instructional models that aim to strengthen these competencies while supporting the principles of Education for Sustainable Development (Bouckaert, 2023; Chee et al., 2025).

The growing emphasis on HOTS has been accompanied by a substantial increase in scientific attention over the past decade (Abbass et al., 2022). Research has examined various aspects of higher-order thinking in science teacher education, including the development of critical thinking, scientific literacy, argumentation, inquiry competence, pedagogical content knowledge, and sustainability-oriented teaching practices (Krell et al., 2023). The study covered a wide range of educational contexts, used different methodological approaches, and examined several instructional interventions. Such diversity reflects the expansion of the field's scope and a growing recognition that preparing future science teachers requires more than just transmitting scientific knowledge (Çetin & Somuncu, 2025).

However, this rapid expansion of the literature has also resulted in fragmented knowledge, with research themes, conceptual emphases, collaborative networks, and emerging directions scattered across a wide range of journals and disciplinary perspectives. Although some review studies have synthesized evidence related to individual constructs such as scientific literacy, critical thinking, inquiry-based learning, or Education for Sustainable Development, these studies generally focus on specific instructional approaches or educational outcomes rather than examining the broader intellectual structure of the research area (Cruz & Lagura, 2026; Kopbossyn et al., 2025; Tijani & Adeduyigbe, 2026).

In addition, previous bibliometric and review studies have provided valuable insights into individual domains; however, they have generally examined these domains separately, giving relatively limited attention to their integration within a single

analytical framework. As a result, important questions remain unanswered about how research in this field has evolved, which countries and institutions have driven scientific production, which journals and authors have exerted the greatest influence, and how thematic priorities have shifted over time in response to the growing emphasis on Education for Sustainable Development (Vysali, 2026). Without a comprehensive mapping of the knowledge landscape, identifying research gaps and future directions is becoming increasingly challenging for researchers, educators, and policymakers (Alberida et al., 2026).

Bibliometric analysis provides a systematic approach to addressing this challenge by quantitatively examining the intellectual, conceptual, and social structures of the research field (Mariani et al., 2023). Unlike conventional narratives or systematic reviews, bibliometric methods allow researchers to identify publication growth, influential contributors, patterns of collaboration, citation impact, and thematic relationships among research topics using large collections of scholarly publications (Donthu et al., 2021). Visualization techniques implemented through tools such as Bibliometrix/Biblioshiny further facilitate the exploration of research networks and thematic evolution, allowing researchers to understand not only what has been learned but also how the field has evolved and where future opportunities may arise. As research on HOTS develops in science teacher education, bibliometric mapping offers valuable insights into its developmental trajectory and its alignment with the broader Education for Sustainable Development goals.

Therefore, this study conducted a bibliometric analysis of Scopus-indexed articles published between 2015 and 2025 to examine the evolution of research on higher-order thinking skills in science teacher education within the framework of Education for Sustainable Development. Previous studies have shown that the successful implementation of Education for Sustainable Development depends on teachers' ability to design learning experiences that foster students' higher-order thinking skills through science education. This indicates that HOTS, science teacher education, and ESD are conceptually interconnected rather than independent research domains. However, previous bibliometric and review studies have generally examined these domains separately. Consequently, comprehensive bibliometric mapping capturing their interrelationships remains limited. This study addresses this gap by integrating the three domains within a single bibliometric framework to provide a more comprehensive understanding of their intellectual structure, thematic evolution, and future research directions.

Based on these considerations, this study aims to provide a comprehensive bibliometric overview of research on higher-order thinking skills (HOTS) in science teacher education within the framework of Education for Sustainable Development (ESD). Specifically, the study examines the general characteristics of the publication dataset; publication trends; the most influential countries, institutions, journals, authors, and documents; the conceptual structure of the research field through keyword co-occurrence analysis; and the thematic evolution and emerging research trends. By

providing a comprehensive overview of the existing knowledge landscape, this study contributes to a deeper understanding of how higher-order thinking skills have been conceptualized and investigated in science teacher education, while offering evidence-based directions for future research, educational practice, and policy development that support Education for Sustainable Development. Accordingly, this study addresses the following research questions:

1. RQ1. What are the publication trends of HOTS research in science teacher education from 2015 to 2025?
2. RQ2. Which countries, institutions, journals, authors, and publications have made the greatest contributions to this field?
3. RQ3. What are the major conceptual structures and thematic relationships identified through keyword co-occurrence analysis?
4. RQ4. How have research themes evolved over time, and what future directions emerge for HOTS research within the framework of Education for Sustainable Development

RESEARCH METHODS

Research Design

This study uses a quantitative bibliometric approach to explore the development of research on higher-order thinking skills (HOTS) in science teacher education in the context of Education for Sustainable Development (ESD). Bibliometric analysis involving Bibliometrix/Biblioshiny was selected because it provides a systematic and objective approach to mapping research trends, intellectual structures, collaboration networks, and thematic evolution within a scientific field. Compared with traditional literature reviews, bibliometric analysis enables quantitative science mapping, making it suitable for identifying the development of HOTS research in science teacher education (Donthu et al., 2021). Figure 1 illustrates the overall research workflow adopted in this bibliometric study, from the identification of the research problem to data analysis and interpretation.

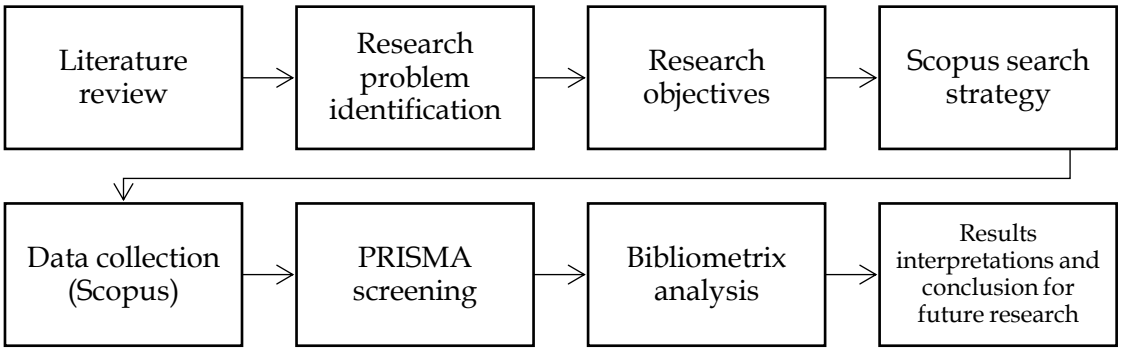

Figure 1. Research workflow.

Figure 1 presents the overall workflow adopted in this bibliometric study, providing a systematic overview of the research process before each methodological stage is described in detail in the following sections.

Data Source

Bibliographic data were collected from the Scopus database as of June 26, 2026, due to its broad coverage of peer-reviewed publications in education and related fields. The search was limited to journal articles published from 2015 to 2025 to reflect research advances on higher-order thinking skills in science teacher education over the past ten years. The search was performed using the following query:

TITLE-ABS-KEY("higher-order thinking" OR "scientific literacy" OR "critical thinking" OR "argumentation") AND ("science teacher education" OR "pre-service teacher" or "pre-service teacher") AND ("sustainable development" OR "ESD" OR "INQUIRY" OR "PROJECT-BASED")) AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND LIMIT-TO(DOCTYPE,"ar")

The search keywords were developed from the conceptual framework of this study and previous literature. Three keyword groups were used to represent the core constructs of higher-order thinking (e.g., higher-order thinking skills, critical thinking, scientific literacy, and argumentation), the educational context (science teacher education and pre-service teachers), and pedagogical approaches related to ESD (e.g., inquiry, project-based learning, and sustainable development). This combination was intended to capture relevant studies within the scope of the research comprehensively.

Instruments and Procedures

The bibliographic records obtained were exported in BibTeX format and analyzed using Bibliometrix/Biblioshiny (R). Biblioshiny is used to generate descriptive bibliometric indicators, including annual scientific output, country-level production, resource productivity, institutional contributions, citation metrics, thematic maps, and trend topic analyses (Donthu et al., 2021). The inclusion and exclusion results are shown in Table 1.

Table 1. Inclusion and exclusion criteria.

Criteria	Inclusions	Exceptions
Types of publications	Peer-reviewed journal articles	Conference papers, reviews, book chapters, editorials, notes
Year of publication	2015–2025	Before 2015 or after 2025
Language	English*	Other languages (if excluded)
Research topics	HOTS, scientific literacy, critical thinking, argumentation in science teacher education	Unrelated fields of education or non-science teacher education
Educational context	Science teacher education, pre-service science teacher	Public school students without the context of teacher education
Databases	Scopus	Other databases

The selection of documents follows the PRISMA 2020 framework to ensure transparency and reproducibility in the screening process. Of the 122 initial records found in the database search, 108 journal articles met the inclusion criteria and were included in the final bibliometric analysis. The PRISMA design is shown in Figure 2 below.

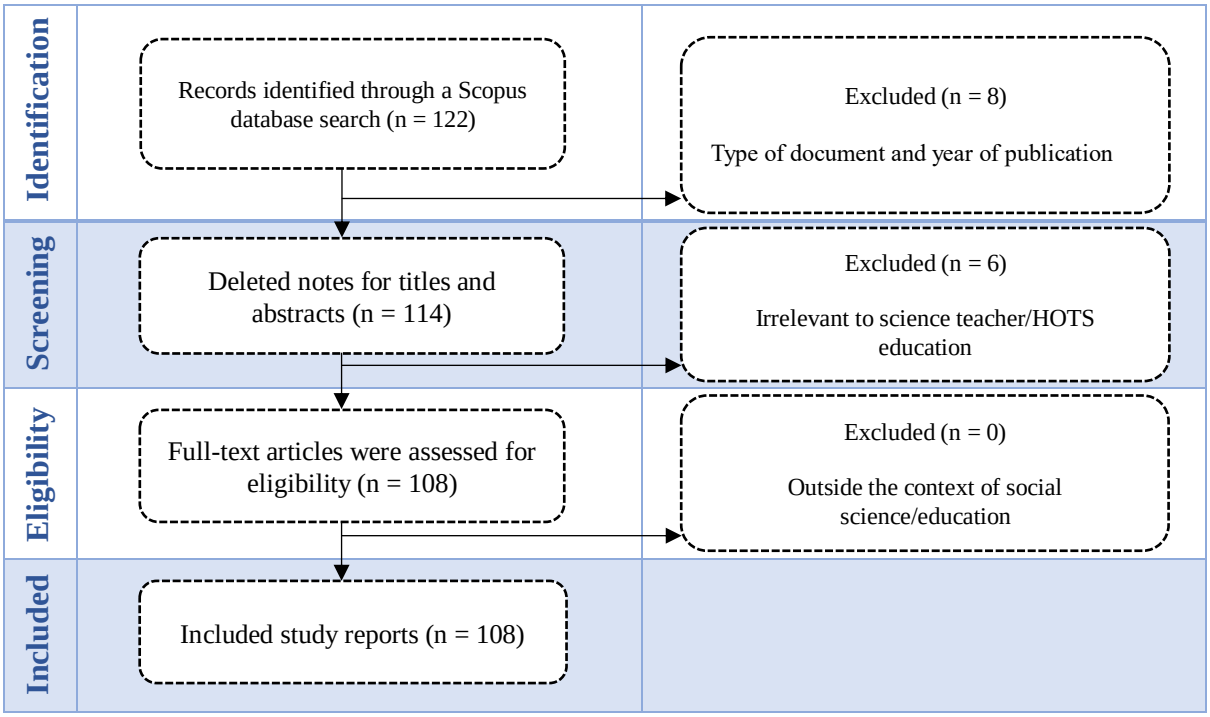

Figure 2. PRISMA flowchart.

Data Analysis

Bibliometric analysis consists of two complementary methods: performance analysis and science mapping. Performance analysis assesses patterns of annual publications, leading countries, institutions, journals, and highly cited papers, providing insights into the productivity and scientific impact of research on higher-order thinking skills in science teacher education.

Science mapping was used to investigate the intellectual and conceptual structure of the research field. Keyword co-occurrence analysis identified thematic clusters and conceptual relationships among research topics. The analysis was conducted using the Bibliometrix package (version 4.6.0) through the Biblioshiny interface. In addition, thematic mapping and trend topic analysis were performed to examine the evolution of research themes and identify emerging trends. To enhance the reliability of the findings, the bibliographic metadata were manually verified for completeness and consistency, and duplicate records were removed prior to analysis. The results were interpreted to answer the four research questions related to publication trends, key contributors, thematic structure, and the role of higher-order thinking skills within the framework of Education for Sustainable Development.

RESULTS AND DISCUSSION

Results

Main information

The bibliometric analysis includes 108 Scopus indexed journal articles published from 2015 to 2025. According to Table 2, these overall characteristics establish the basis for

further analysis of publication patterns, key contributors, and thematic trends. The international co-authorship rate of 16.67% indicates that research collaboration across countries has begun to develop, although most studies are still conducted within national research networks. Key information about the data can be seen in Table 2.

Table 2. Key information about data.

Description	Results
Time range	2015-2025
Sources (Journals, Books, etc.)	68
Documents	108
Annual Growth Rate (%)	16.49
Average Age of the Document	4.69
Average Citations per Document	12.06
References	3491
Keywords Plus (EN)	91
Keywords Author (DE)	357
Author	299
Sole Author Document Author	17
International Co-Writing (%)	16.67
Document Type	Articles (108)

Publication Trends

Figure 3 shows the annual scientific results on higher-order thinking skills in science teacher education from 2015 to 2025. Although there are some fluctuations, the overall trend is upward. Between 2015 and 2018, the study's output was relatively low, with annual publications ranging from 4 to 6 articles.

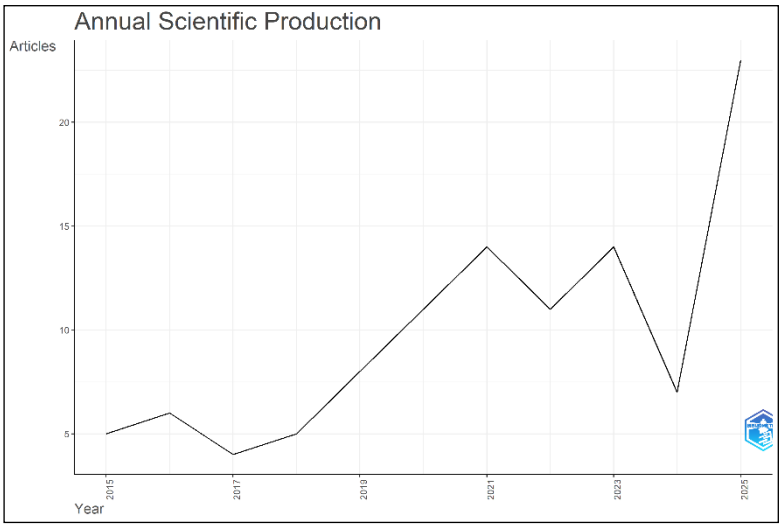

Figure 3. Annual scientific production.

Starting in 2019, there was a steady increase that peaked at 14 publications in 2021. Although there was a slight decline in 2022 and a more pronounced decline in 2024, 2025 saw a significant surge with 23 publications, the highest annual result during the period. This overall increase reflects growing academic interest in higher-order thinking skills in

science teacher education, especially amid modern educational reforms that emphasize critical thinking, scientific literacy, inquiry-based learning, and sustainability.

Most Productive Countries, Resources, and Institutions

The geographical distribution of research on higher-order thinking skills in science teacher education shows contributions from different regions around the world (Figure 4).

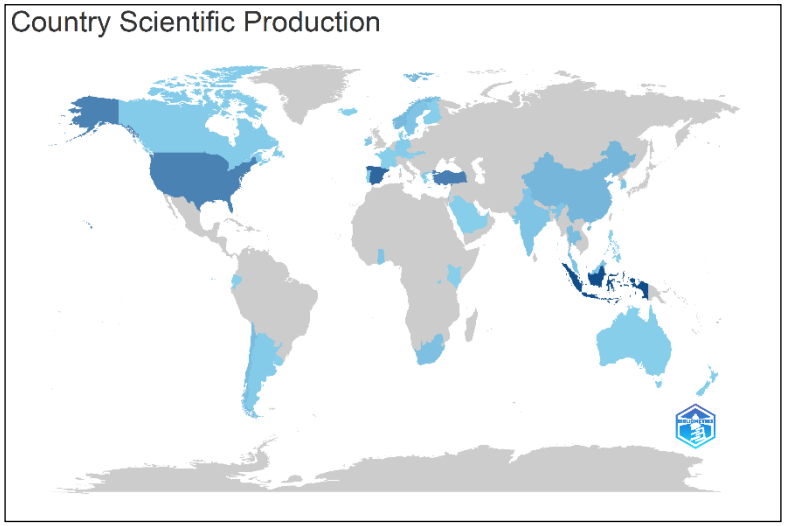

Figure 4. Country scientific production.

Indonesia leads the way in the research results, followed by the United States, Spain, Turkey, and several other countries in Asia and Europe. This pattern reflects a growing global focus on improving science teacher education to meet modern educational challenges and ESD goals, expanding interest beyond traditional research fortresses. The main source of the publication is shown in Figure 5.

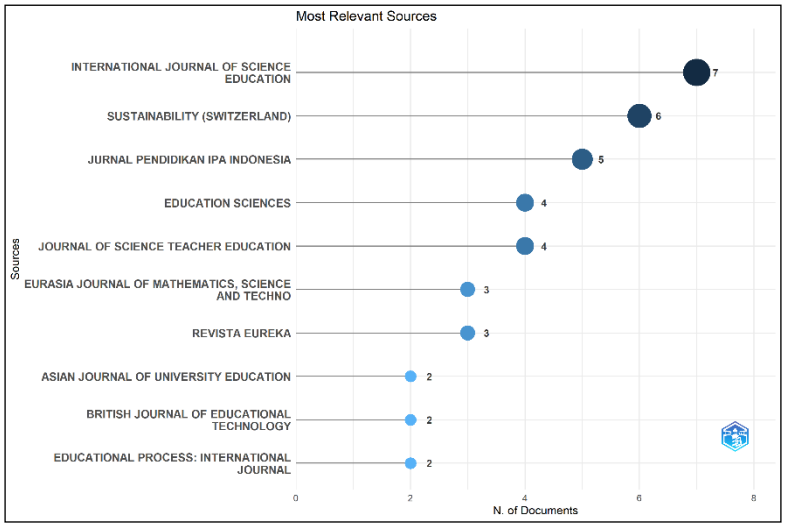

Figure 5. The most relevant sources.

The International Journal of Science Education led with seven articles, followed by Sustainability with six, and the Indonesian Journal of Science Education with five. Other

notable journals include Educational Science and the Journal of Science Teacher Education, each with four publications. The excellence of these journals underscores the interdisciplinary nature of this field, which includes science education, teacher training, educational innovation, and sustainability. Institutional productivity is detailed in Figure 6.

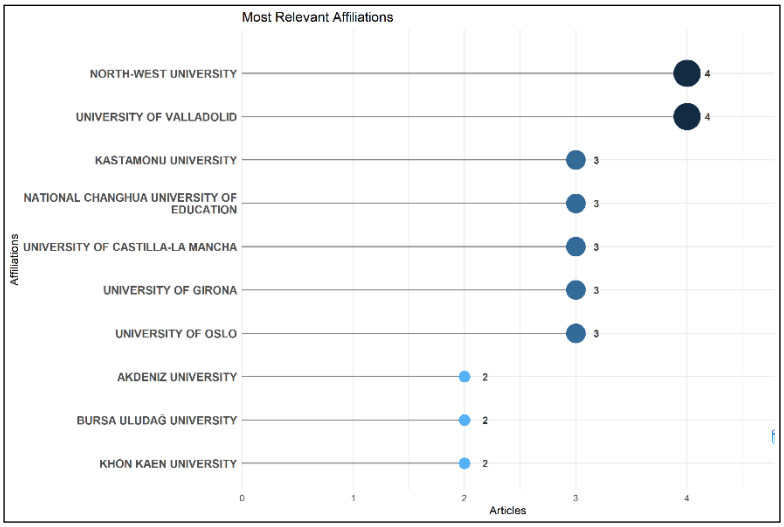

Figure 6. The most relevant affiliations.

The University of the North West and the University of Valladolid each contributed four publications, while institutions such as the University of Kastamonu, the National Education University of Changhua, the University of Castilla-La Mancha, the University of Girona, and the University of Oslo produced three each. The spread of publications in several universities around the world shows that research in higher-order thinking skills is characterized by broad international collaboration rather than dominance by a few institutions. Figure 7 shows the most globally cited publications on higher-order thinking skills in science teacher education from 2015 to 2025.

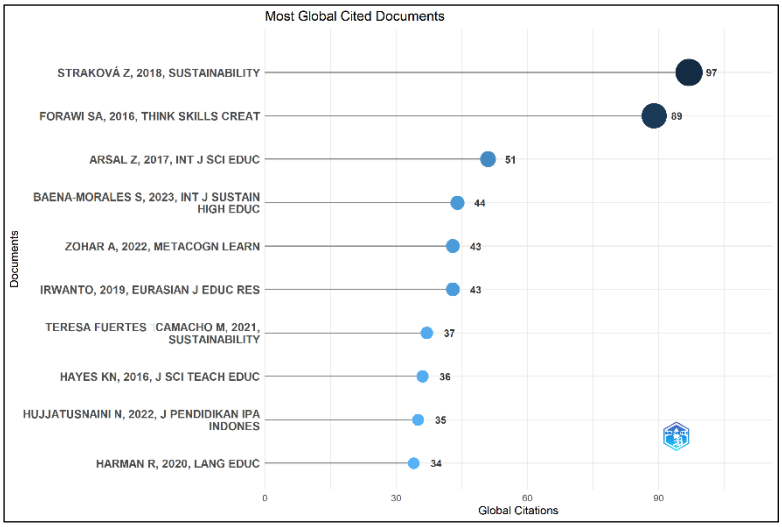

Figure 7. Most globally cited documents.

The most-cited paper, written by Straková (2018) in Sustainability, received 97 citations worldwide, followed by Forawi's (2016) article in Thinking Skills and Creativity, which received 89 citations. Other well-known, widely cited works include those of Arsal (2017), Baena-Morales (2023), Zohar (2022), and Irwanto (2019), all of which have made significant contributions to research in this field. The citation distribution indicates that a relatively small number of highly cited publications have played a central role in shaping subsequent research directions in HOTS and science teacher education.

The citation pattern reveals that major publications have focused on fostering higher-order thinking skills through innovative teaching methods, including critical thinking, metacognitive learning, scientific literacy, sustainability education, and science teacher training. These influential studies have laid important theoretical and pedagogical foundations that continue to guide ongoing research. Its impact is evident not only in citation metrics but also in the development of related research themes, as highlighted by the co-emergence of keywords and an upcoming thematic analysis.

Research Theme

A conceptual framework of research on higher-order thinking skills in science teacher education was analyzed using keywords. As illustrated in Figure 8, the network is divided into four thematic groups, which represent the main research areas in the field. The size of the node indicates how often the keyword appears, while the link indicates the strength of appearing with it.

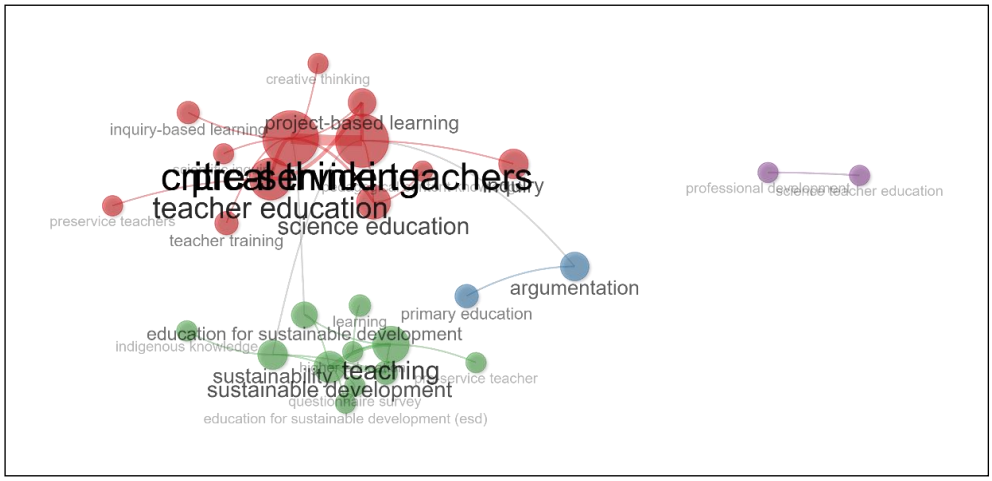

Figure 8. Keyword co-occurrence network.

The largest cluster (red) revolves around science teacher education and is closely related to pre-service teachers, teacher education, project-based learning, inquiry-based learning, critical thinking, and science education. It highlights a major focus on instructional methods that promote higher-order thinking skills in future science teachers. The green cluster centers on teaching, professional development, curriculum development, pedagogical content knowledge, and educational innovation, reflecting a growing emphasis on teacher skills and instructional strategies that support the integration of higher-order thinking into science education.

Arguments related to science education and teaching dominate the blue cluster. Although smaller, this group shows a growing interest in evidence-based reasoning and scientific discourse as essential elements of higher-order thinking. The purple cluster encompasses professional learning and science education. However, it is somewhat isolated from other groups, suggesting that professional learning remains a niche topic not yet fully integrated into the broader discussion of higher-order thinking skills in science teacher education.

Overall, the keyword network revealed that the research was largely centered on teacher education, student-focused pedagogy, and innovative teaching. The strong relationship between inquiry-based learning, project-based learning, critical thinking, and science teacher education suggests these themes form the core foundation for developing higher-order thinking skills. While the co-occurrence of keywords illustrates the current conceptual structure, thematic mapping and trend analysis provide insight into how these research themes have evolved.

Thematic development of research on higher-order thinking skills in science teacher education was analyzed using thematic mapping and trend analysis. As shown in Figure 9, the thematic map divides topics into four quadrants based on their centrality and density, representing motor themes, specific themes, base themes, and emerging or decreasing themes.

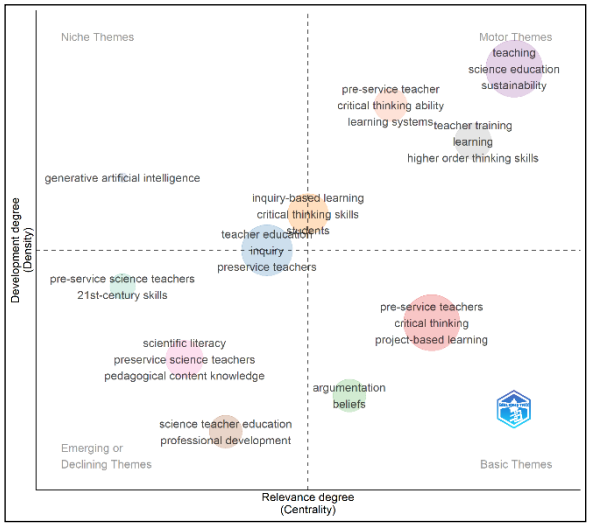

Figure 9. Thematic maps.

Motor themes (top right quadrant) include teaching, science education, sustainability, teacher training, higher-order thinking skills, and learning. These themes have high centrality and density, suggesting they are well developed and central to the field's knowledge structure. Their strong connections show recent research focuses on integrating higher-order thinking skills into science teacher education to promote Education for Sustainable Development practices. Basic themes (bottom-right quadrant), such as pre-tenured teachers, critical thinking, and project-based learning, are highly relevant but have lower density, suggesting they require further theoretical and empirical work.

Similarly, argumentation emerged as a fundamental topic, reflecting the growing interest in evidence-based reasoning in higher-order thinking. Niche themes (top left quadrant) include generative artificial intelligence, a niche area with strong internal development but limited broader connections. In contrast, emerging or decreasing themes (bottom-left quadrant), such as scientific literacy, pedagogical content knowledge, and professional development, showed lower centrality and density, indicating a reduced focus of research compared to the dominant theme. The temporal analysis (Figure 10) is consistent with these findings. From 2018 to 2020, the research concentrated on the arguments and education of science teachers.

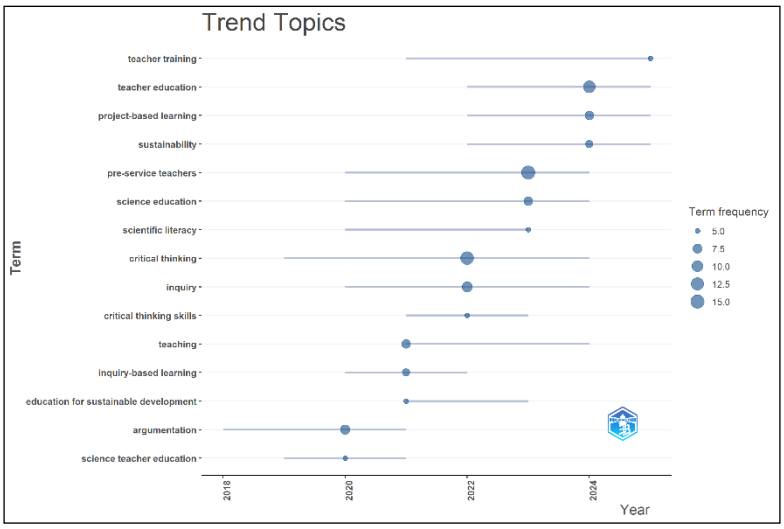

Figure 10. Trending topics.

Starting in 2021, the focus shifted to inquiry-based learning, teaching, and Education for Sustainable Development, followed by increased attention to critical thinking, scientific literacy, and science education in 2022–2023. More recent studies increasingly emphasize project-based learning, teacher education, teacher training, and sustainability, reflecting a shift toward instructional strategies that prepare future science teachers to foster higher-order thinking and support sustainable education goals.

Overall, this thematic and temporal pattern shows a progression from an isolated higher-order thinking concept to an integrated approach that combines pedagogical innovation, teacher preparation, and sustainability. This suggests future research is likely to focus on interdisciplinary strategies that link higher-order thinking skills with the broader goals of Education for Sustainable Development and SDG 4.

Discussion

Why is HOTS research thriving?

Figure 2 illustrates a steady increase in scientific publications focusing on higher-order thinking skills (HOTS) in science teacher education from 2015 to 2025, peaking in 2025. This upward trend reflects HOTS becoming a significant and sustainable research area in the field. By 2025, research relating to HOTS had seen a massive increase. This rise in research on HOTS demonstrates alignment with the demands of 21st-century education.

21st-century education emphasizes that skills, knowledge, and attitudes are essential for citizens to navigate the digital, sustainable, and social worlds ethically and humanistically (González-Pérez & Ramírez-Montoya, 2022).

In addition, there is growing recognition that future science teachers need skills beyond conceptual knowledge (Skakov et al., 2026). Modern science education emphasizes critical thinking, scientific literacy, argumentation, and problem-solving as essential for addressing complex scientific and social challenges (Aripin et al., 2025; Irwandi et al., 2026; Tytler et al., 2025). As a result, teacher education programs have shifted from simply delivering content to preparing preservice teachers to foster higher-order learning in real classroom settings. This growth is also in line with the global rise in Education for Sustainable Development (ESD) and the adoption of Sustainable Development Goal 4 (SDG 4), which emphasizes equipping learners with the skills and values for sustainable development (Peters et al., 2024). Within this framework, HOTS is seen as essential to enable learners to analyze complex issues, assess evidence, and make informed decisions about sustainability (Filho et al., 2024; Verawati & Sukaisih, 2021). As ESD has been embedded in policies and curricula worldwide, research on teaching strategies that promote HOTS has evolved accordingly (Purnamasari et al., 2026).

Another factor is the rapid emergence of student-centered teaching methods. Keyword and thematic analyses highlight the relationship between HOTS research and approaches such as inquiry-based and project-based learning. This method engages students in exploring real problems, constructing evidence-based explanations, and developing scientific reasoning, making it ideal for fostering HOTS in science teacher education. The adoption of this pedagogy has increased the diversity of research and opportunities in HOTS (Dogan et al., 2026; Erawati & Hariani, 2026). This increasing trend of publication carries important implications. Instead of seeing HOTS as a stand-alone cognitive skill, recent research increasingly integrates it into teacher professional competence and Education for Sustainable Development (Verawati & Sukaisih, 2021). This shift suggests that future research must go beyond assessing students' thinking skills to explore how teacher preparation, instructional design, and curriculum innovation can systematically nurture higher-order thinking to support the broader goals of Education for Sustainable Development (Peretz, 2025).

Why do Indonesia and some countries dominate?

Figure 3-5 shows that research on higher-order thinking skills (HOTS) in science teacher education is globally dispersed, with important contributions from Indonesia, the United States, Spain, and Turkey. This trend is also evident across a wide range of journals and research institutions, with internationally and regionally recognized science education journals playing a key role in disseminating research findings.

Indonesia's important role likely stemmed from national education reforms that emphasized HOTS. Over the past decade, curriculum reforms, teacher professional development, and national assessment policies have increasingly promoted critical thinking, scientific literacy, inquiry, and problem-solving in science education (Samsuri

et al., 2025). This shift in policy has encouraged extensive research activities, especially among universities that publish in national and global journals (Basuki et al., 2022; Hidayah et al., 2022; Rizaldi et al., 2020).

Similarly, strong research results from the United States, Spain, and Turkey may reflect their well-established traditions in teacher education and training research. Universities in these countries consistently explore inquiry-based learning, project-based learning, scientific literacy, and teacher professional development—areas closely related to the development of HOTS. Their ongoing research productivity highlights the institutions' ongoing commitment to improving science teacher education through evidence-based pedagogical innovation (Antonio et al., 2022; Özer et al., 2026; Sengül, 2026).

Leading journals such as the International Journal of Science Education, Sustainability, and the Journal of Science Teacher Education illustrate the interdisciplinary nature of HOTS research. Beyond science education, this field now intersects with sustainability education, educational technology, teacher professional development, and curriculum innovation. This diverse landscape of publications reflects a growing understanding that fostering higher-order thinking requires integrated pedagogical and institutional strategies (Bond et al., 2020). The spread of productive institutions across multiple universities, rather than concentrated in a single center, suggests that HOTS research has evolved through a variety of institutional initiatives and collaborative efforts. Enhancing international collaboration among these institutions can expand knowledge sharing, enable cross-cultural studies, and accelerate the development of innovative methods for preparing future science teachers to address global sustainability challenges.

How does conceptual focus shift?

The keywords co-emergence networks and thematic analysis (Figures 8-10) show that the research focus on higher-order thinking skills (HOTS) has evolved significantly over the past decade. Previous work concentrated primarily on individual cognitive skills such as critical thinking, scientific literacy, and argumentation. More recent studies have shifted towards instilling these skills in broader pedagogical frameworks such as inquiry-based learning, project-based learning, teacher education, and sustainability. This shift suggests that HOTS is now seen more as a product of holistic instructional design than a stand-alone cognitive ability (Azzaroiha et al., 2025; Thahir et al., 2021). This uneven thematic development reflects changing educational priorities and global policy agendas. Inquiry-based learning, project-based learning, and sustainability expanded rapidly because they align closely with competency-based curricula, the implementation of SDG 4, and the increasing emphasis on learner-centered science education. At the same time, the emergence of generative artificial intelligence reflects recent technological advances that have stimulated new directions for developing higher-order thinking skills in teacher education. These findings suggest that conceptual changes in HOTS research have been driven not only by advances in educational theory but also by broader educational reforms and technological innovation.

Science teachers' views significantly influence their sustainability-related teaching practices (Stouthart et al., 2025). The growing emphasis on sustainability and teacher training as central themes highlights the growing impact of ESD on science teacher education. Current research places greater emphasis on equipping future teachers to create a learning environment that fosters higher-order thinking and addresses real-world scientific and social problems, rather than focusing solely on students' thinking skills (Bramastia et al., 2025; Jensen et al., 2025).

Another emerging theme is generative artificial intelligence, which, while still specialized, shows growing interest in AI-powered learning environments for developing HOTS. This trend shows a promising path for research as AI becomes more integrated into teacher education and science learning (Al-Shabandar et al., 2024; Ka et al., 2023). Overall, the conceptual developments identified in this study suggest that HOTS research is progressing towards an interdisciplinary approach that integrates pedagogy, teacher preparation, sustainability, and advancements in educational technology. Future research should aim to develop instructional models that integrate these elements to better prepare science teachers for the complex challenges of twenty-first-century education.

Implications for Science and ESD Teacher Education

This bibliometric analysis shows that higher-order thinking skills (HOTS) have shifted from being seen primarily as cognitive abilities to being an important part of professional preparation for science teachers. The bibliometric analysis in Figure 9, in the 'Motor Themes' (key themes) quadrant, shows keywords including 'higher-order thinking skills, critical thinking ability, learning systems, teaching, sustainability'; these keywords indicate that science teacher education serves as a means of equipping trainee teachers with pedagogical competences that enable them to design HOTS-based learning activities capable of supporting high-quality learning. Increasing research focus, broader global participation, and shifting thematic trends suggest that teacher education programs should not only improve teachers' subject knowledge in the future but also strengthen their capacity to promote critical thinking, scientific literacy, argumentation, and evidence-based decision-making. These skills are essential for preparing learners to tackle complex scientific and sustainability challenges (Hanifah et al., 2025; Schuster et al., 2026; Sriatun et al., 2025).

These findings also reveal an increased alignment between HOTS research and Education for Sustainable Development (ESD) goals. The prominence of themes such as sustainability, teacher training, inquiry-based learning, and project-based learning suggests that effective science teacher education requires a pedagogy that combines higher-order thinking with real-world problem-solving (Tijani & Adeduyigbe, 2026). The improvement of teachers' skills through training can be fostered by institutional involvement. Institutions play a vital role in integrating practical and contextual training to ensure that educators can apply concepts creatively in real-world contexts (Susantini et al., 2025). Instead of treating sustainability as a separate issue, teacher preparation

should embed ESD principles in an inquiry-driven, evidence-based learning experience that encourages future teachers to foster responsible scientific reasoning and sustainable decision-making (Bhoi et al., 2025; Koçulu, 2025). In the world of education, implementing sustainable learning requires institutional support, enhanced teacher competencies, and technology integration. These three aspects are key to realizing an inclusive education system aligned with the objectives of SDG 4, a key element of sustainable development (Sugiyanto et al., 2026).

Based on the theories presented, this study demonstrates that science teachers, who play a vital role in the learning process, must possess the skills to deliver science lessons that develop students' higher-order thinking skills (HOTS). The delivery of high-quality teaching by teachers demonstrates support for one of the Sustainable Development Goals (SDGs), namely SDG 4 (quality education), which ensures that all pupils have equal access to education and learning. Consequently, science teachers are expected to possess the necessary competence to deliver lessons that develop pupils' higher-order thinking skills (HOTS). The enhancement of these skills among science teachers or trainee science teachers can be supported through specific training or education programs to enable them to deliver high-quality teaching.

This study provides a focused direction for future research by highlighting the need for empirical studies that build upon the emerging themes identified in this bibliometric analysis. Future studies should design and evaluate instructional approaches that integrate higher-order thinking skills, Education for Sustainable Development, inquiry-based learning, project-based learning, and emerging technologies, such as generative artificial intelligence, into science teacher education. Comparative research across different educational contexts and countries is also needed to examine the applicability and effectiveness of these integrated approaches in preparing future science teachers for sustainable education.

CONCLUSION

Fundamental Findings: This bibliometric study shows that research on higher-order thinking skills (HOTS) in science teacher education has grown substantially during 2015–2025. These findings identify increasing publication trends, key contributions from several countries and journals, and conceptual shifts towards inquiry-based learning, project-based learning, sustainability, and teacher education within the framework of Education for Sustainable Development (ESD). **Implications:** These findings highlight the importance of integrating HOTS with ESD-oriented pedagogy in science teacher education. The identified research landscape can serve as a reference for researchers, curriculum developers, and teacher educators in designing future instructional innovations. **Limitations:** This study analyzed only Scopus-indexed journal articles published between 2015 and 2025. As a result, publications from databases and other document types are not included. **Future Research:** Future empirical studies should build upon the emerging themes identified in this bibliometric analysis by designing and evaluating instructional approaches that integrate higher-order thinking skills,

Education for Sustainable Development, inquiry-based learning, project-based learning, and emerging technologies, such as generative artificial intelligence, into science teacher education. Comparative studies across different educational contexts and countries are also needed to validate the applicability and effectiveness of these integrated approaches.

AUTHOR'S CONTRIBUTION

Rif'atul Himmah contributed to the conceptualization, research design, methodology, data collection, bibliometric analysis, data visualization, manuscript drafting, and manuscript revision. **Elsa Monica** contributed to the conceptual framework, literature review, data interpretation, and manuscript editing. **Moch Faizul Huda** contributed to the validation of the research design, interpretation of the findings, critical review of the manuscript, and research supervision. **Steven Taniwan** contributed to the interpretation of the findings, critical review of the manuscript, and improvement of the scientific quality of the manuscript. **Salma Hasna Hamiydah** was interpretation of the findings, critical review of the manuscript. **Muhammad Rey Dafa Ahmadi** was critical review and manuscript revision. All authors reviewed and approved the final version of the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no financial, professional, or personal conflicts of interest that could affect the research, analysis, or publication of this research.

ETHICAL COMPLIANCE STATEMENT

This research is in accordance with research and publication ethics. The authors confirm that the manuscript is original, has not been published elsewhere, and is free from plagiarism, fabrication, forgery, and other forms of academic violation.

A WRITTEN STATEMENT ABOUT THE USE OF AI OR DIGITAL TOOLS

The authors used ChatGPT (OpenAI) and Claude.ai to support language refinement, script organization, and editing during the preparation of this article. Bibliometrix and Biblioshiny are used for bibliometric analysis and data visualization. All AI-assisted results are critically reviewed, verified, and revised by the authors. The authors are solely responsible for the accuracy, interpretation, and integrity of the final manuscript.

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