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Review

Global research trends on STEM integration in high school physics education: A bibliometric analysis (2015–2025)

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Abstract: The integration of science, technology, engineering, and mathematics (STEM) into physics education has become increasingly crucial for fostering twenty-first century competencies. However, comprehensive studies that map global research trends on the integration of STEM in high school physics education remain limited. This study conducted a bibliometric analysis of 96 Scopus-indexed publications from 2015 to 2025 using Bibliometrix and VOSviewer. The analysis covers publication trends, country and source productivity, citation patterns, and thematic development. The findings indicate a significant growth in publications since 2019, with the United States and Indonesia emerging as the most productive contributors. The *Journal of Physics: Conference Series* appears as the dominant publication source. Thematic and keyword mapping reveals research concentrations in project-based learning, critical thinking development, digital technology integration, and emerging topics such as computational thinking and virtual laboratories. Future research opportunities include the integration of artificial intelligence (AI), virtual reality (VR), and the Internet of Things (IoT) to enhance creativity, engagement, and higher-order thinking skills in STEM-integrated physics learning. Overall, this study provides an up-to-date overview of global research dynamics and identifies strategic directions for strengthening the integration of STEM in high school physics education.

Keywords: bibliometric analysis, high school, physics education, research trend, STEM

1. Introduction

Twenty-first century learning demands that students acquire a range of competencies to navigate global challenges. These essential skills include critical thinking, creativity, collaboration, and communication [1,2]. The rapid advancement of science and technology in the twenty-first century necessitates a shift in educational paradigms from theoretical to more applied and contextual approaches. In response to this need, science, technology, engineering, and mathematics (STEM) has emerged as a significant educational innovation [3–5]. Theoretically, STEM integration is defined as an effort to combine these four disciplines into a single discipline, where knowledge is built through a unified and integrated framework [6]. In this study, STEM integration is operationally treated as an interdisciplinary framework where explicit connections are made between physics content and other STEM disciplines to solve real-world problems. By positioning STEM in this manner, learning becomes more connected and relevant for students, as academic theory is directly linked to practical applications [7]. This approach emphasizes the strengthening of students' scientific conceptual understanding [8], while simultaneously integrating technology, engineering, and mathematics to create holistic, relevant learning experiences that are oriented toward solving real-world problems.

The STEM approach plays a crucial role in high school physics education. It enables students to comprehend abstract concepts through real-life applications [9]. Integrating STEM into physics learning provides opportunities for students to develop higher-order thinking skills and engage in creative problem-solving [5,10,11]. Moreover, the integration of STEM encourages students to actively explore, experiment, and innovate, thereby fostering more meaningful learning experiences [12,13]. Consequently, the STEM approach serves as an effective means to prepare young learners to be adaptive and ready to meet the demands of twenty-first century education.

Several previous studies have examined the integration of STEM in physics education from various perspectives. Flores-God ńez et al. [14] reported that integrating STEM into instruction can enhance students' interest in learning physics. Ardianti et al. [3] found that blended learning–based STEM instruction effectively improves students' critical thinking skills. Parno et al. [15] demonstrated that the Problem Based Learning (PBL)–STEM model fosters higher scientific literacy among high school students compared to conventional approaches. In addition, Sulaiman et al. [16] emphasized the significant impact of STEM–PBL on students' personal interest, sense-making abilities, and learning effort in physics. Despite these positive outcomes, a conceptual gap persists regarding the relationship between physics education and STEM frameworks. A key debate centers on how to reconcile the abstract and theoretical nature of physics with the applied, interdisciplinary requirements of STEM [7]. This gap often leads to fragmented learning, where students struggle to apply core physics principles within engineering or technological contexts. Addressing these conceptual challenges is essential for moving beyond simple classroom integration toward a systematic transformation of physics education. Despite its effectiveness, STEM research has largely focused on classroom integration and has not yet provided a comprehensive mapping of global research developments.

Several bibliometric studies have been conducted to examine STEM research trends in physics education. One such study is by Syaifuddin et al. [17], which mapped the development of research on the integration of STEM and project-based learning (PjBL) in physics education during the period 2013–2023. However, the scope of that study is still limited to one learning model and does not specifically focus on the high school level as a distinct domain. In fact, physics education at the high school level requires interdisciplinary strategies to bridge basic science with more complex advanced engineering concepts. This study addresses this limitation by selecting the period 2015–2025. This period is a decade that marks a major shift toward the integration of digital technology and a more systematic strengthening of twenty-first century skills in the global physics curriculum. The novelty of this study lies in its specific focus on the high school level, the broader scope of the STEM integration model, and the use of a more recent dataset up to 2025. The expanded timeframe to 2025 is important to enable the identification of emerging technological trends, such as artificial intelligence (AI) and augmented reality (AR), which are predicted to significantly change the physics learning landscape. Thus, this study is expected to present a more up-to-date and comprehensive roadmap compared to previous bibliometric analyses.

This study aims to analyze the development of scientific publications related to the integration of STEM in high school physics education during the period 2015–2025 using a bibliometric approach. The analysis was conducted to identify publication trends, country distribution, sources of publication, citation patterns, and major thematic developments over the last decade. Based on these objectives, this study seeks to address the following research questions (RQs):

1. RQ1: What are the publication trends regarding STEM integration in high school physics education during the period 2015–2025?
2. RQ2: How are the distribution and productivity of publications characterized across countries and publication sources (journals and conference proceedings)?
3. RQ3: What are the thematic patterns, dominant keywords, and developmental directions of STEM research in high school physics education based on bibliometric analysis?

The findings of this study are expected to provide a comprehensive overview of the global research landscape on STEM integration in high school physics education over the past decade. The results may serve as a reference for researchers, educators, and policymakers in designing more effective and innovative STEM-integrated physics education strategies aligned with twenty-first century learning needs. In addition, the mapping results help identify existing research gaps, offering an empirical foundation for future studies to explore underrepresented topics and expand the integration of STEM across diverse educational contexts.

2. Methods

2.1. Research method

This study employs a bibliometric analysis method. Bibliometric analysis is a methodological approach used to examine bibliographic data such as scientific publications, citations, and research patterns within a specific field [18,19]. This method enables researchers to explore and understand trends, patterns, and relationships based on bibliometric indicators, including annual publication counts, frequently used keywords, and the most productive countries.

More broadly, bibliometric analysis serves as a key tool for evaluating various aspects of scientific publications. Its purpose is to map the intellectual, social, and conceptual structures of a discipline based on relationships among its components [19]. This method helps researchers understand literature in a field and track the development of research topics over time [20]. The insights gained provide an essential basis for identifying future research directions and opportunities.

2.2. Data collection

The metadata analyzed in this study was obtained from the Scopus database. Scopus was selected because it provides high-quality, credible, and reputable sources. To ensure that the retrieved publications aligned with the research focus, a set of search keywords was established. These keywords were intended to keep the search results specific and consistent with the topic. The search terms used in Scopus were *STEM Education*, *Physics Education*, and *High School*. These three keywords were chosen to ensure that the retrieved documents were relevant to studies on the integration of STEM in high school physics education. The Scopus search query used in this study is presented in Table 1.

Table 1. Data search queries.

Database	**Advanced query**
Scopus	TITLE-ABS-KEY (STEM Education AND physics education AND high school) AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE, “cp”) OR LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (LANGUAGE, “English”))

The total number of documents included in this study was obtained through a systematic selection process following the PRISMA guidelines, encompassing the stages of identification, screening, and inclusion [17,21,22]. A search conducted in the Scopus database on November 10, 2025, yielded 360 documents. The search was restricted to the years 2015–2025, limited to conference papers and journal articles, and filtered for publications written in English. Subsequent screening involved removing duplicates and assessing relevance based on the following criteria: application of STEM in education, focus on physics learning, and relevance to the high school context. This selection process resulted in a refined dataset that was specific and aligned with the research scope. The PRISMA flow diagram is presented in Figure 1.

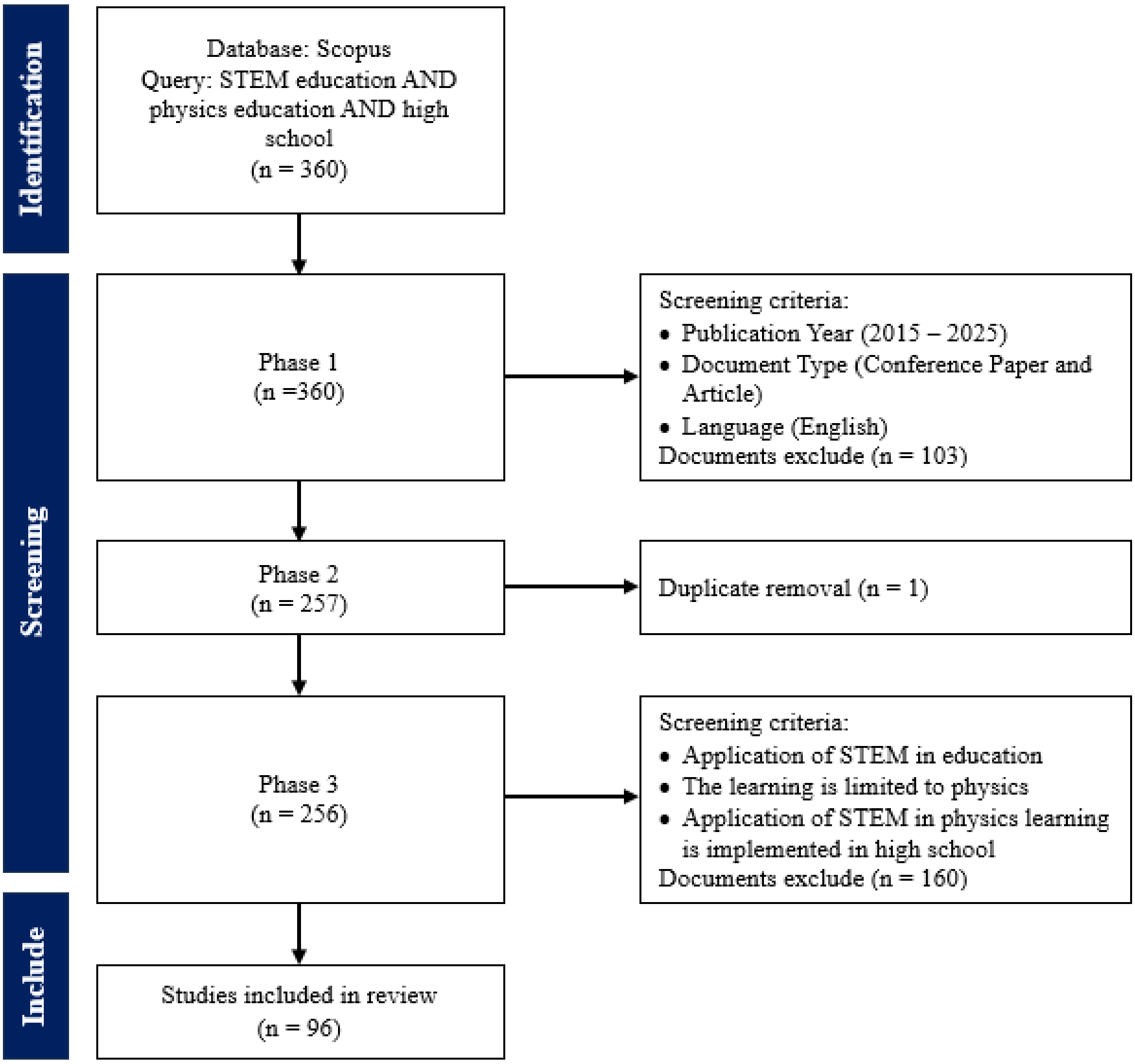

Figure 1. PRISMA flow diagram.

2.3. Data analysis

The data analysis was carried out systematically. The software used to examine the bibliometric data in this study was Bibliometrix and VOSviewer. Bibliometrix, which is implemented through RStudio, was employed to perform various bibliometric analyses, including assessments of author–country productivity and thematic mapping related to the research topic. The results of these analyses were visualized in multiple formats, such as country distribution maps and thematic maps.

In addition, the bibliometric analysis also utilized VOSviewer version 1.6.19. This software was used to perform keyword co-occurrence analysis. Using VOSviewer, data retrieved from the Scopus database were visualized in the form of bibliometric networks, illustrating the relationships among keywords so that research trends and influential topics could be interpreted more clearly. The combined use of VOSviewer and Bibliometrix provided a more comprehensive analytical outcome, as both tools complemented one another in terms of visualization capabilities and the robustness of bibliometric statistical analysis.

3. Results

3.1. Research trends on STEM integration in high school physics education from 2015 to 2025

The research trend can be assessed through the yearly growth in the number of published studies. Conducting a trend analysis is essential to ensure that the development of scientific knowledge, particularly in the field of education, continues to progress and does not stagnate. To examine research trends related to the integration of STEM in high school physics education, publication data indexed in the Scopus database over the past decade (2015–2025) were analyzed. Overall, a total of 96 articles were identified as relevant to the topic of this study. The annual distribution of publications on STEM in high school physics education is presented in Figure 2.

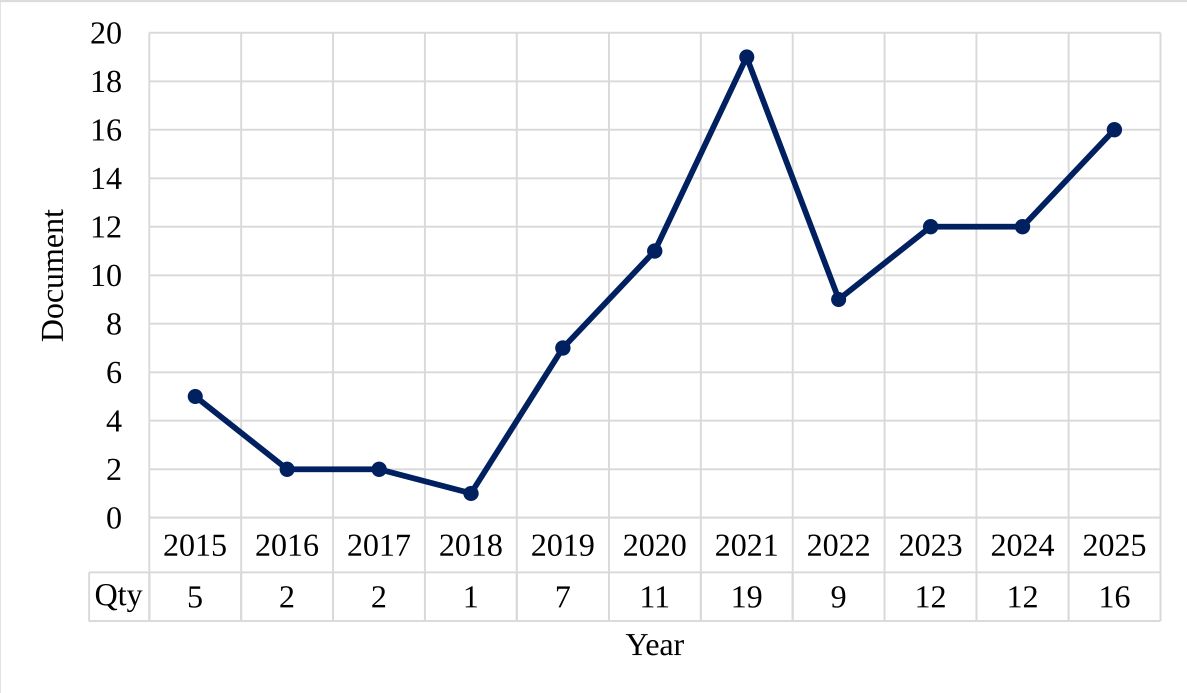

Figure 2. Annual scientific production on STEM in high school physics education (2015–2025).

Figure 2 illustrates the publication trends on the integration of STEM in high school physics education. The number of publications in this topic fluctuates but shows a notable upward trend throughout 2015–2025. Between 2015 and 2018, the publication volume remained low (1–5 articles), indicating that the topic had not yet become a major focus of research. A sharp increase occurred in 2019–2020, reflecting growing interest in integrating STEM into physics instruction. The peak was reached in 2021 with 19 publications. This significant increase in the number of publications is thought to be related to the high demand for digital learning innovations and virtual laboratory environments during the COVID-19 pandemic. Although the number of publications declined slightly in 2022, it increased again and stabilized during 2023–2025, ranging from 12 to 16 publications per year. This pattern suggests that research on STEM integration in physics learning in high schools continues to grow consistently and remains a central concern in efforts to enhance the quality of education in the twenty-first century.

3.2. Distribution and productivity of research publications on STEM in high school physics education

The distribution of publications provides an overview of the geographical spread and productivity of research on the integration of STEM in high school physics education, based on contributing countries, publication sources, and their scholarly impact as reflected in citation counts. This analysis aims to identify the regions and scientific forums that are most active in advancing this research area, while also examining the extent of the academic influence generated by each publication.

Table 2. Top 10 most productive countries based on publications and citations.

Country	Number of documents	Citation	
		Total citations	Citations per article
United States	22	47	2.14
Indonesia	16	14	0.88
Italy	8	18	2.25
Malaysia	6	48	8.00
Czech Republic	5	20	4.00
Germany	5	5	1.00
Thailand	4	55	13.75
Vietnam	4	48	12.00
Spain	4	20	5.00
China	3	9	3.00

The results presented in Table 2 indicate that STEM in high school physics education has become a prominent focus of research at the international level. The United States ranks first with 22 documents, 47 citations, and an average of 2.14 citations per article, reaffirming its position as a leading center for research in science and technology education. Indonesia follows in second place with 16 publications and 14 citations, reflecting a growing interest in the integration of STEM in high school physics instruction, although its citation impact remains relatively modest. Italy occupies the third position with 8 publications and 18 citations. Meanwhile, Malaysia and Vietnam, with 6 and 4 documents, respectively, demonstrate strong influence, each achieving high citation averages of 8.00 and 12.00 citations per article. Thailand also stands out with 4 publications and an average of 13.75 citations per article, making it one of the countries with the highest publication quality. Other countries, such as the Czech Republic, Germany, Spain, and China, contribute fewer publications, yet continue to play an important role in expanding the diversity of global research in this field.

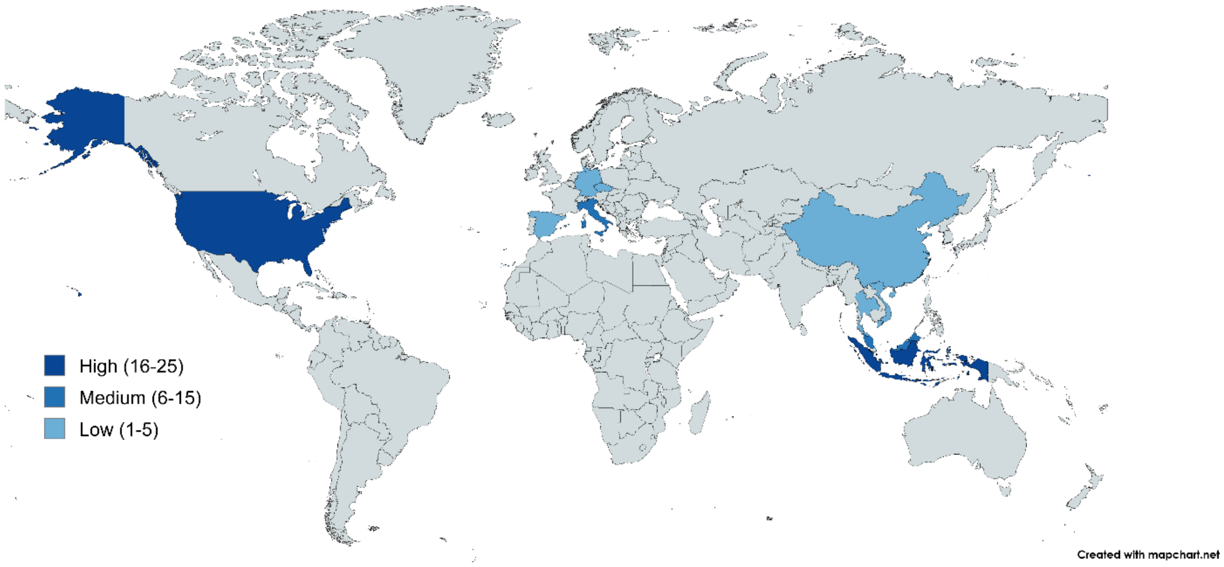

Figure 3. Map of scientific production by country (created with mapchart.net).

Figure 3 illustrates that research on STEM integration in high school physics education has spread across multiple continents. The United States shows the highest contribution and serves as the primary research hub in the Americas. In Asia, research activity is particularly prominent in Indonesia, Malaysia, Thailand, Vietnam, and China, reflecting the growing attention toward STEM integration in physics education within the region. In Europe, substantial contributions are observed from Italy, the Czech Republic, Germany, and Spain, highlighting the important role of educational and research institutions in these countries. This distribution demonstrates that STEM-integrated physics education at the high school level has gained global attention. Countries across Asia, Europe, and the Americas are actively engaged in advancing science education that is increasingly integrated with technological innovation.

Table 3. Most productive journals and proceedings with impact metrics.

Source	Type	Number of documents	Scopus quartile	SJR
Journal of Physics: Conference Series	Proceeding	14	-	0.187
AIP Conference Proceedings	Proceeding	7	-	0.153
Physics Education	Journal	7	Q2	0.523
Education Sciences	Journal	4	Q1	0.730
Frontiers in Education	Journal	4	Q2	0.650

Table 3 indicates that the *Journal of Physics: Conference Series* is the most productive source, contributing 14 documents, followed by *AIP Conference Proceedings* with 7 documents. Both serve as primary venues for disseminating early-stage research on physics-based STEM learning innovations. In the journal category, *Physics Education* ranks highest with 7 publications and is classified as a Q2 journal (SJR 0.523). This journal plays an important role in advancing the physics education literature relevant to STEM-integrated instructional approaches. *Education Sciences* (Q1; SJR 0.730) and *Frontiers in Education* (Q2; SJR 0.650) each published four documents and are recognized as reputable journals with a strong emphasis on interdisciplinary instructional innovations. Overall, the data illustrate that research on STEM in high school physics education is disseminated across a wide range of reputable scientific outlets, including both proceedings and peer-reviewed journals. This distribution reflects growing global recognition of the importance of this topic in advancing educational development.

Table 4. Most influential articles by number of citations.

No.	Authors	Title	Citations	Main topic
1	Holly et al. [23]	Designing virtual reality (VR) experiences: expectations for teaching and learning in VR	101	The design of learning experiences and user expectations in VR-based instruction for high school physics and STEM education
2	Ardianti et al. [3]	The impact of the use of a STEM education approach on blended learning to improve students' critical thinking skills	37	The integration of a STEM-based blended learning model to enhance high school students' critical thinking skills in physics instruction
3	Parno et al. [15]	A comparison of high school students' scientific literacy competencies domain in physics with different methods: PBL–STEM education, PBL, and conventional learning	31	A comparison of the effectiveness of PBL–STEM, PBL, and conventional instruction in improving high school students' scientific literacy on physics topics related to optical instruments
4	Silva et al. [24]	Technological structure for technology integration in the classroom, inspired by the maker culture	24	Development of a digital technology–integration model in physics and STEM instruction to enhance high school students' STEM competencies
5	Khalil et al. [4]	STEM-based curriculum and creative thinking in high school students	23	The influence of integrating a STEM-based curriculum on the development of high school students' creative thinking skills in physics learning

The citation analysis presented in Table 4 indicates that research on the integration of STEM in high school physics education has largely focused on innovative themes aligned with the demands of twenty-first century learning. The most highly cited article is authored by Holly et al. [23], "Designing VR Experiences: Expectations for Teaching and Learning in VR", which has accumulated 101 citations. The article examined the integration of virtual reality (VR) in educational contexts. Ardianti et al. [3], with 37 citations, highlighted the effectiveness of STEM-based blended learning in enhancing students' critical thinking skills. Meanwhile, Parno et al. [15], cited 31 times, demonstrated the superiority of the PBL–STEM model in improving students' scientific literacy. In addition, Silva et al. [24] and Khalil et al. [4] emphasized the importance of digital technology integration and STEM-based curricula in fostering students' creativity and twenty-first century competencies. Collectively, these studies illustrate a research trajectory that prioritizes technological innovation, active learning approaches, and the development of higher-order thinking skills within STEM-integrated physics education.

3.3. Thematic map analysis of STEM integration in high school physics education

The thematic analysis was conducted to identify and map the main themes emerging from studies on the integration of STEM in high school physics education. Through the thematic map, the relationships and interconnections among the themes that constitute the core focus of research in this field can be observed. The results of this analysis provide a comprehensive overview of the direction and emphasis of STEM-integrated physics education research, which is visualized in the thematic map presented in Figure 4.

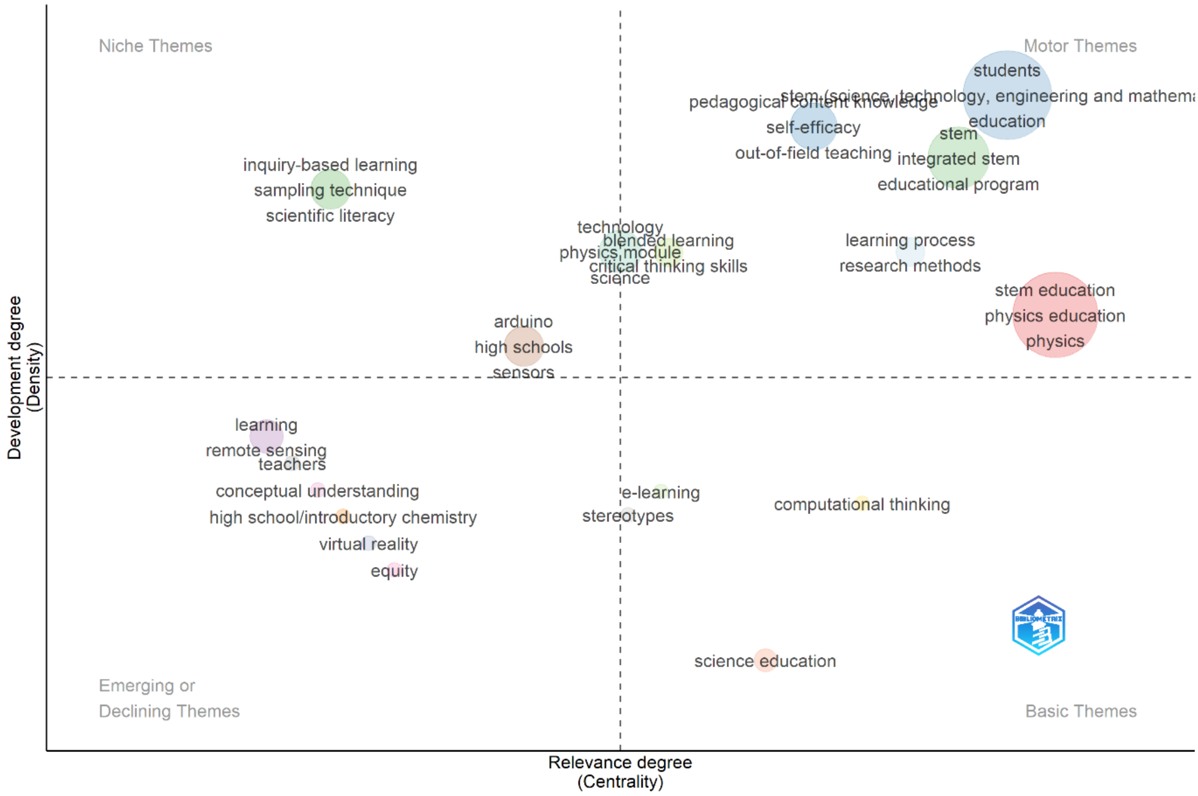

Figure 4. Thematic map of STEM in high school physics education.

The thematic map in Figure 4 provides a strategic look into how STEM research in high school physics is evolving. The motor themes, such as *STEM* and *learning process*, show that the field has moved past just talking about theory. Instead, the focus is now on how students actually learn and how these methods are applied in the classroom. This suggests that STEM is no longer just a trend but a central part of how modern physics is taught.

On the other hand, finding *inquiry-based learning* and *scientific literacy* in the niche themes quadrant is quite revealing. It suggests that while these are important goals, they are often treated as specialized topics rather than being woven into the broader STEM curriculum. Meanwhile, the rise of emerging themes like *virtual reality* and *equity* reflects a new direction for the field. It shows that researchers are starting to prioritize immersive technology and social fairness, aiming for a more inclusive and modern approach to physics education. Lastly, *computational thinking* as a basic theme confirms that bridging physics with computer science is now seen as an essential foundation for preparing students for the future.

3.4. Analysis of keyword patterns in STEM research on high school physics education

Keyword analysis was conducted to identify the key terms and concepts most frequently appearing in publications related to the integration of STEM in high school physics education. Through this analysis, the main research field, the interconnections among topics, and the developmental directions of this field can be clearly observed. The frequency and co-occurrence patterns of keywords reflect the dominant research trends as well as emerging topics that are beginning to gain scholarly attention.

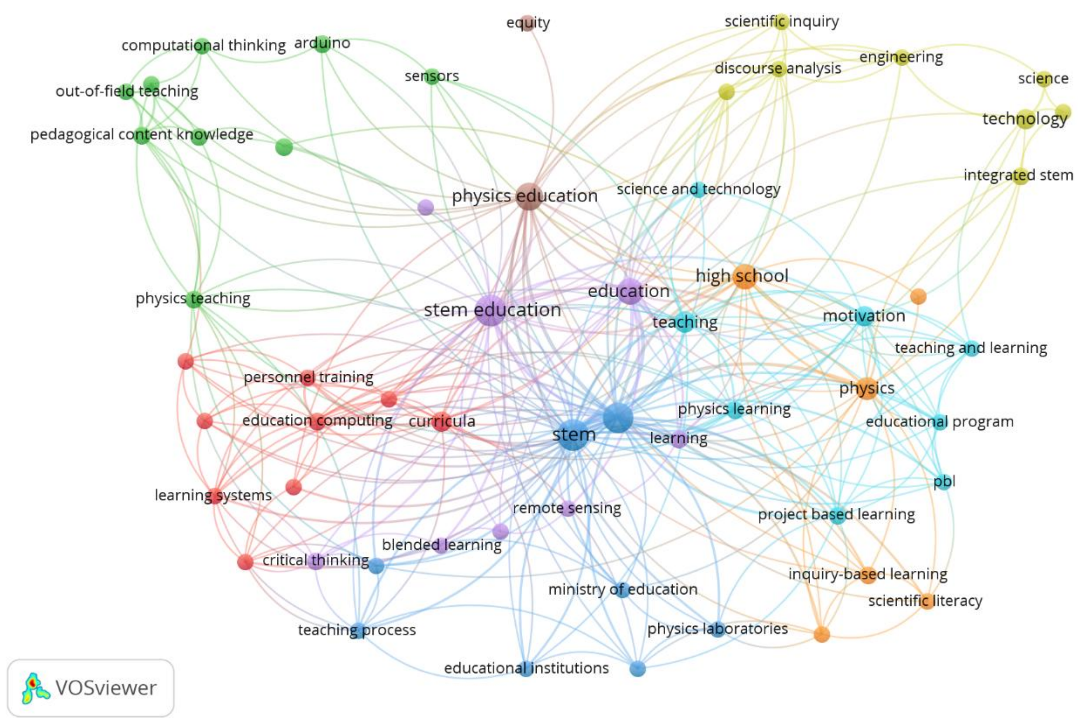

Figure 5. Keyword network visualization.

The keyword network in Figure 5 reveals the interconnected nature of the STEM landscape in high school physics. Beyond the eight distinct clusters, the map shows a clear convergence between technical tools and pedagogical frameworks. For example, the synergy between the red and purple clusters indicates that digital innovations, such as virtual reality and e-learning, are no longer mere “add-ons” but are being deeply integrated into teacher training and curriculum design to support twenty-first century competencies.

Impressively, the bridge between the light and blue clusters indicates that project-based learning (PjBL) has become a primary vehicle for fostering higher-order cognitive skills such as critical thinking and problem-solving. This shift highlights the transition from passive content delivery to active, hands-on physics education. Furthermore, the emergence of the brown cluster is an important finding focusing on equity and access. It signals that the field is moving in a more socially responsible direction, recognizing that the benefits of STEM-integrated physics must be accessible to a broader and more diverse student population. Overall, this network underscores that the future of physics education lies at the intersection of innovative technologies, student-centered pedagogy, and social inclusivity.

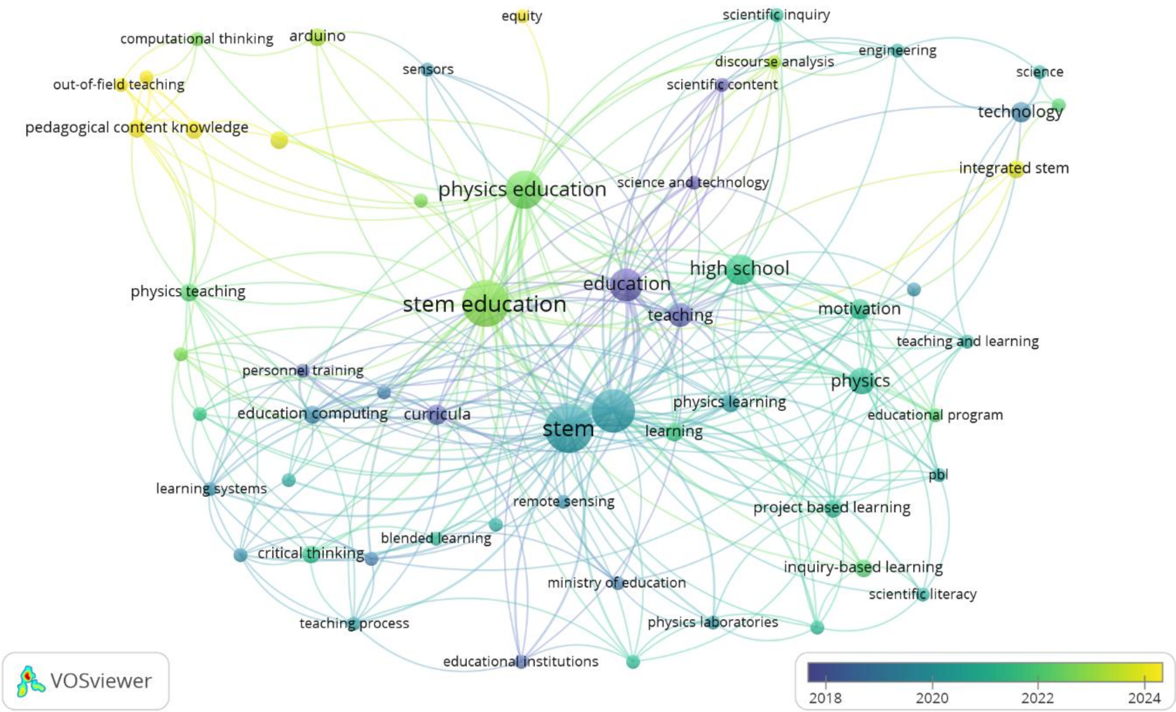

Figure 6. Visualization of the keyword distribution overlay by publication year.

Figure 6 illustrates the evolution of research themes related to the integration of STEM in high school physics education. The color transitions clearly show that the research focus has shifted from simply building a conceptual foundation to implementing more practical and cutting-edge technologies. In the initial period (2018–2019), keywords such as STEM, learning, and curriculum dominated, indicating that researchers were still focused on integrating STEM approaches into the physics curriculum. Entering 2020–2022, the trend began to shift toward more specific classroom approaches, with a strong emphasis on conceptual understanding and strengthening critical thinking. This indicates that STEM is no longer just a concept but is beginning to be tested for its effectiveness in the teaching and learning process. Finally, the latest trends (2022–2024), marked in yellow, such as computational thinking and Arduino, demonstrate that the integration of digital technology is now a new norm in physics education. This evolution illustrates that future research will no longer focus solely on basic STEM concepts; instead, the application of advanced technologies such as AI, VR, and AR can help students understand physics effectively. This change emphasizes that physics education is moving toward a more adaptive digital era, where digital literacy and computational thinking skills are mandatory competencies for students.

4. Discussion

4.1. What are the publication trends related to the integration of STEM in high school physics education during the 2015–2025 period?

Based on the bibliometric analysis of 96 Scopus-indexed publications, the research trends on the integration of STEM in high school physics education show a substantial increase throughout the 2015–2025 period. During the early years (2015–2018), the number of publications remained relatively low, ranging from 1 to 5 documents per year, indicating that this topic had not yet become a major focus in physics education research. However, from 2019 to 2021, a sharp rise in publication output occurred, reaching its highest point in 2021 with a total of 19 documents. This upward trend is plausibly associated with the growing emphasis on technology-enhanced learning innovations during the COVID-19 pandemic. While a direct causal link requires further empirical validation, the period observed (2019–2021) coincides with a global shift toward digital approaches, virtual laboratories, and blended learning, as highlighted in several studies [3,23]. This shift is further supported by evidence that school lockdowns acted as a critical global incident, forcing educators to rapidly adopt digital technologies and virtual teaching environments to maintain instructional continuity [25]. After 2021, the number of publications stabilized at around 12–16 documents per year through 2025, suggesting that scholarly interest in this topic remained consistent and continued to develop.

The steady trend after 2021 indicates that STEM has shifted from an urgent need to a formal standard in physics teaching. This transition was driven by large-scale educational reforms, such as the implementation of the Next Generation Science Standards (NGSS) in the United States, which institutionalized engineering practices in the science curriculum [26]. Similarly, high productivity in Indonesia aligns with the national implementation of the Independent Curriculum (Kurikulum Merdeka), which mandates interdisciplinary projects and STEM-based learning to address local educational gaps. Unlike general STEM studies, a specific focus on physics requires a unique balance between mastery of abstract concepts and practical application, a challenge increasingly addressed through digital integration models proposed in recent literature [24].

Furthermore, the evolution of keywords from 2015 to 2025 indicates a maturing research landscape. The shift from basic curriculum design to advanced themes such as computational thinking and virtual reality [4,23] reflects the broader digital transformation in science education. These developments indicate that researchers are now prioritizing how technology can enhance scientific literacy and motivation [13,14]. By linking these thematic trends to the digital demands of Industry 4.0, the data confirms that the future of physics education lies in creating adaptive environments that prepare students for competitive global challenges.

4.2. How are the publications distributed, and what is the productivity of research output by country and publication sources (journals and conference proceedings)?

The analysis shows substantial global growth in STEM-integrated research in physics education. The United States emerged as the leading contributor, followed by Indonesia. Other Asian countries, such as Malaysia, Thailand, and Vietnam, also demonstrated strong productivity, reflecting a shift in the center of science education innovation from the West to Asia [27–29]. In Southeast Asia, particularly Indonesia and Malaysia, this trend highlights the emergence of new research powerhouses increasingly active in global collaboration [30]. This trend enriches the pedagogical perspective in international literature.

The United States' high productivity can be attributed to long-term federal investment in STEM through strategic alignment with the NGSS [26], which provides a robust framework for physics-engineering integration. Conversely, Indonesia's position as the second-most productive country is a direct result of major educational reforms and prioritizing teacher professional development in STEM-based research as part of a national effort to improve the quality of human resources [31]. This demonstrates that while the US leads in basic research, Asian countries are rapidly accelerating empirical implementation to address local educational gaps and industry needs.

The global distribution of publications demonstrates that research on STEM integration in high school physics education spans multiple continents, with the United States and European countries such as Italy, the Czech Republic, and Germany continuing to play major roles in advancing this approach. Meanwhile, Asian countries are actively expanding STEM integration to align with local educational needs, including the integration of digital technologies and contextual learning. This cross-continental distribution reflects the strong global emphasis on the urgency of STEM education in responding to the Fourth Industrial Revolution and the demands of the twenty-first century [9,13]. These findings underscore that STEM integration has become a fundamental component of global science education reform.

In terms of publication sources, the *Journal of Physics: Conference Series* is the most productive outlet, contributing 14 documents, followed by *AIP Conference Proceedings* with 7 documents. Both proceedings serve as major venues for disseminating early-stage innovations in physics-based STEM instruction. Within journal publications, *Physics Education* (Q2; SJR 0.523) is the most prominent source with 7 documents, while *Education Sciences* (Q1; SJR 0.730) and *Frontiers in Education* (Q2; SJR 0.650) also demonstrate strong contributions to the dissemination of interdisciplinary STEM research. The involvement of these reputable journals reflects growing international recognition of the relevance of STEM-integrated physics education research within the global academic landscape [14]. This trend indicates that research in this field has advanced not only in quantity but also in terms of scientific rigor and methodological quality.

The dominance of conference proceedings suggests that the field is still in a high-velocity innovation phase, where researchers prioritize the rapid deployment of new experimental models. However, the consistent presence of Q1 and Q2 journals demonstrates the successful transition from these early-stage ideas to high-quality, peer-reviewed evidence. This balance between proceedings and journals reflects a healthy research ecosystem that values both rapid prototyping and theoretical validation [29].

In addition to productivity, citation levels also reflect the scholarly influence of publications in this field. The most highly cited article was authored by Holly et al. [23], "Designing VR Experiences: Expectations for Teaching and Learning in VR", which highlights the use of virtual reality in STEM-based physics instruction. Other influential publications, such as those by Ardianti et al. [3] and Parno et al. [15], also received substantial citations due to their integration of STEM with blended learning and problem-based learning (PBL) to enhance students' critical thinking skills and scientific literacy. This pattern indicates that studies combining STEM with technological and pedagogical innovation tend to achieve greater citation impact, aligning with the ongoing educational shift toward digital and project-based learning [4,24]. These findings underscore that the integration of advanced technologies and modern instructional approaches constitutes a strategic factor in producing relevant, high-impact research.

Overall, these findings indicate that research on the integration of STEM in high school physics education has expanded substantially and has gained strong recognition from the international scholarly community. The increasing contributions from Asian countries, along with the growing number of publications in reputable journals and conference proceedings, reflect a significant acceleration in research development in this field. This dynamic underscores that STEM is not merely a pedagogical approach but a global strategic framework for strengthening scientific literacy, creativity, and twenty-first century competencies among young learners.

4.3. How do the thematic patterns, dominant keywords, and the developmental directions of research on STEM integration in high school physics education emerge based on the bibliometric analysis?

The thematic analysis indicates that research on the integration of STEM in high school physics education has evolved toward increasingly diverse and integrative directions. The thematic map shows that STEM education serves as the central theme connected to various subtopics such as education, learning, teaching, and high school. These connections suggest that the primary focus of current studies remains within the pedagogical domain, specifically how STEM approaches can be integrated to enhance the effectiveness of physics learning at the high school level. This finding aligns with the perspectives of Purwaningsih et al. [10] and Asrizal et al. [13], who emphasized that integrating STEM plays a crucial role in fostering students' critical thinking, creativity, and collaboration skills as core competencies of the twenty-first century.

This pedagogical focus has recently matured into a more complex framework known as technological pedagogical content knowledge (TPACK). The analysis reveals that learning systems, critical thinking, computational thinking, and pedagogical content knowledge constitute prominent themes within the thematic clusters. These themes indicate a shift in research focus from merely developing instructional models toward strengthening higher-order thinking skills and students' cognitive potential. Several studies, such as those by Ardianti et al. [3] and Parno et al. [15], demonstrate that STEM approaches integrated with PBL and blended learning can enhance students' critical thinking skills and scientific literacy. This transition suggests that STEM is no longer viewed as an isolated curriculum add-on but as a fundamental vehicle for cognitive transformation, where the physical laws of nature are explored through the lens of engineering and mathematical modeling.

The thematic evolution analysis also reveals a significant shift in research directions over the past decade. During the early period of 2015–2018, studies were primarily centered on introducing the concept of STEM and developing science- and technology-based curricula. However, from 2019 to 2025, the themes diversified toward the integration of digital technologies and the strengthening of twenty-first century competencies. Emerging topics such as virtual reality, engineering design, blended learning, and computational thinking began to appear, expanding the context of STEM integration in physics education. This development indicates a transition from theory-oriented instruction to experiential and technology-enhanced learning [23,24]. This shift is not just a technological trend, but also a response to global educational reforms that are pushing physics education into an immersive and data-driven environment.

The keyword analysis further reinforces these findings, indicating that STEM education is the most dominant term with strong associations to other key concepts such as physics education, critical thinking, teacher education, technology, and scientific inquiry. These connections illustrate that recent research has increasingly focused on strengthening the role of STEM in physics education as a means to develop scientific reasoning, problem-solving skills, and technology-driven innovation. In addition, the emergence of keywords such as Arduino, sensors, and virtual laboratories highlights the growing integration of technological tools to support experimental and contextual learning in physics classrooms [4,14]. This trend affirms that contemporary physics education places greater emphasis on cultivating twenty-first century competencies through technology-enhanced learning experiences, effectively bridging the gap between niche themes like scientific literacy and motor themes like digital innovation.

In addition to mapping the current research directions, the findings also reveal several emerging opportunities that can further strengthen the integration of STEM in high school physics education. Computational thinking has begun to appear but remains underdeveloped within the context of physics learning, creating room for the design of STEM models that effectively support students' computational reasoning and problem-solving skills. The integration of advanced technologies such as artificial intelligence (AI), augmented reality (AR), and the Internet of Things (IoT) has likewise received limited attention, even though these technologies hold substantial potential for enriching experimentation, simulation, and experiential learning. Furthermore, the emerging focus on educational equity within these clusters suggests a new mandate for researchers: ensuring that high-tech STEM innovations are accessible to diverse student populations, thereby fulfilling the social promise of STEM education. Overall, future research is expected to advance toward pedagogical innovation and deeper technological integration aimed at enhancing students' creativity, engagement, and higher-order thinking skills.

5. Conclusions

5.1. Summary

This study provides a comprehensive mapping of global research trends on the integration of STEM in high school physics education during the period 2015–2025. The findings indicate a consistent increase in publications since 2019, with the United States and Indonesia emerging as the primary contributors, and reputable journals and conference proceedings serving as the dominant publication venues. The thematic analysis reveals a strong research focus on project-based learning, the enhancement of critical thinking skills, the integration of digital technologies, and the emergence of new themes such as computational thinking and virtual laboratories. These insights contribute significantly to understanding the current directions and dynamics of research related to STEM integration in physics education.

5.2. Implications and future directions

The findings of this study confirm that STEM integration has become a key pillar of modern physics education, necessitating fundamental changes in curriculum design. Schools and educational institutions need to shift from a siloed teaching model to an integrated, interdisciplinary approach. This is achieved by incorporating engineering design processes and the use of technology directly into physics materials, making learning more authentic and meaningful for students.

Furthermore, there are significant implications for professional teacher development. Training programs are needed that not only enhance pedagogical skills but also the specific competencies required for STEM integration. The focus of development should be on collaborative teaching models, enabling physics teachers to collaborate with technology and mathematics educators to design and manage effectively integrated learning projects in the classroom.

Regarding future research directions, incorporating additional databases and exploring underrepresented topics, such as the integration of artificial intelligence (AI), augmented reality (AR), virtual reality (VR), and the Internet of Things (IoT), in physics learning is recommended. Future research should also focus on developing STEM integration models that can strengthen students' computational thinking and digital literacy to address the challenges of rapid technological development.

5.3. Limitations

This study has limitations related to data coverage and search strategy. The analysis was based solely on the Scopus database, thus potentially introducing database bias into the findings. Relevant articles indexed in other databases, such as Web of Science, Google Scholar, or Dimensions, were not included in this study. These databases could provide additional perspectives on broader global research trends.

Furthermore, the search strategy employed was rather specific, focusing only on the terms *STEM education*, *physics education*, and *high school*. Using these keywords risks missing important studies that use other terms with similar meanings, such as *secondary school*, *upper secondary*, or *K–12 physics*. This limited keyword variety should be considered when interpreting the literature mapping results, and future research is recommended to expand the search string to minimize keyword bias.

Author contributions

Hafiz Almahfuz Agusti: Research conceptualization, methodological design, data collection, data analysis, data curation, and manuscript writing; Heru Kuswanto: Supervision, methodological validation, and review and evaluation of data analysis; Devinda Putri Maharani: Data screening, data visualization, and manuscript review and editing; Amanatus Sa'diyyah: Manuscript editing, reference checking and format consistency verification, and English language proofreading.

Use of Generative-AI tools declaration

The authors declare that they did not use Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare that they have no conflict of interest regarding the research, authorship, or publication of this article.

Ethics declaration

This study does not involve human participants, animals, or sensitive personal data. Therefore, ethical approval was not required. All procedures conducted in this research comply with standard academic and publication ethics.

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