Journal of Current Studies in SDGs
Homepage : https://journal.i-ros.org/index.php/JOCSIS
Email : jocsis@i-ros.org

e-ISSN 3089-7564
Vol.3, No.4, December 2027

Teachers' Understanding of STEM Education in Secondary Schools: A Systematic Literature Review and Bibliometric Mapping Towards SDG 4

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DOI : https://doi.org/10.63230/jocsis.3.4.322

Sections Info

Article history:
Submitted: March 10, 2026
Final Revised: July 06, 2026
Accepted: July 28, 2026
First Available Online: 30 August, 2026
Publication Date: December 27, 2027

Keywords:
Knowledge;
Secondary Education;
STEM Education;
STEM Pedagogical Content;
Teacher Competence;
Teacher Understanding.

ABSTRACT

Objective: *The study aims to map research on teachers' STEM understanding in secondary education, identify major themes and emerging trends, and examine research gaps related to teacher competence and STEM implementation across junior and senior secondary education.* ***Method:*** *A systematic literature review and bibliometric analysis were conducted on studies published between 2010 and 2025. Following the PRISMA framework, 884 records were initially identified, of which 144 studies met the inclusion criteria. The analysis covered keyword co-occurrence, thematic evolution, research density, geographical distribution, and qualitative synthesis of the selected studies.* ***Results****: The findings show that research has shifted from early attention to teachers' perceptions, attitudes, knowledge, and preparedness toward STEM pedagogical content knowledge, interdisciplinary competence, professional development, inquiry, engineering design, creativity, sustainability, and classroom implementation. STEM education, teacher training, professional development, and pedagogical content knowledge emerged as central themes. However, substantial gaps remain between teachers' STEM awareness, conceptual understanding, pedagogical readiness, and actual classroom implementation. Comparative studies between junior and senior secondary teachers also remain limited.* ***Novelty:*** *The study provides an integrated systematic and bibliometric mapping of teachers' STEM understanding across secondary education levels and highlights teacher competence as a potential bridge between quality education and sustainable development, particularly in relation to SDG 4, SDG 9, and SDG 13.*

INTRODUCTION

STEM education has emerged as an important approach for developing interdisciplinary knowledge, problem-solving skills, creativity, and the capacity to address complex real-world challenges (English, 2023; Pinar et al., 2025; Sokolova et al., 2025). The increasing prominence of STEM education, teaching, teacher professional development, pedagogical content knowledge, and STEM identity in the research landscape indicates that teachers play a central role in determining the quality of STEM implementation (Hamad et al., 2022; Khuyen et al., 2020; Lin et al., 2025; Wu et al., 2022). Existing research demonstrates that teachers' understanding of STEM extends beyond conceptual awareness to include pedagogical competence, interdisciplinary integration, curriculum understanding, self-efficacy, and readiness to translate STEM principles into classroom practices.

Research trends further indicate a shift from examining teachers' perceptions, attitudes, knowledge, and preparedness toward investigating their capacity to implement integrated STEM through inquiry, engineering design, creativity, problem-based learning, and authentic learning experiences. The temporal visualization shows that recent studies increasingly emphasize integrated STEM education, engineering design, sustainability, motivation, and curriculum integration, particularly within middle and high school contexts (Kegels et al., 2026; Kopbossyn et al., 2025; Liu & Liu, 2025; Saseendran & Thomas, 2025; Zhan et al., 2022; Zhan & Niu, 2023). This development

suggests that teachers' STEM understanding should be examined as a multidimensional construct involving conceptual knowledge, pedagogical content knowledge, interdisciplinary competence, and practical implementation (Chiriacescu et al., 2023; Hasim et al., 2022; Hu & Guo, 2021; Lin et al., 2022).

Empirical studies have identified persistent challenges in developing teachers' STEM competence (Aslam et al., 2023; Rehman et al., 2025; Shernoff et al., 2017). Secondary school teachers demonstrate varying levels of STEM pedagogical content knowledge, while STEM knowledge is not always fully integrated into teaching practices (Berry et al., 2025; Dong et al., 2020; Gardner et al., 2019; Nipyrakis et al., 2025). Teachers also encounter difficulties in designing integrated STEM learning sequences because of curriculum demands, pedagogical beliefs, limited professional development, time constraints, and insufficient instructional resources. Evidence from Indonesia similarly indicates that teachers generally hold positive attitudes toward STEM, whereas their STEM knowledge and practical implementation remain moderate. Differences in STEM understanding between junior and senior secondary teachers have also been reported, highlighting the importance of examining educational level as a potential contextual factor (Anning, 2024; Fang & Fan, 2023; Huang et al., 2024; Thibaut et al., 2018; X. Wu et al., 2024).

A systematic synthesis of the existing literature is therefore needed to clarify how teachers' STEM understanding has developed across educational levels and research contexts. The present review analyzes the literature on STEM understanding among junior and senior secondary teachers by examining its major themes, temporal development, geographical distribution, and dominant dimensions of teacher competence. The review also seeks to identify the extent to which previous studies have addressed conceptual knowledge, pedagogical content knowledge, self-efficacy, interdisciplinary competence, professional development, and classroom implementation. The resulting synthesis is expected to provide a clearer research foundation for understanding the current state of STEM teacher competence and identifying future directions for comparative research between Junior High School and Senior High School teachers.

Based on the objectives of the systematic review, the following research questions (RQs) are formulated:

RQ1. What are the main research themes and dimensions of teachers' understanding of STEM education at the junior and senior secondary school levels?

RQ2. How has research on teachers' understanding of STEM education evolved in terms of research trends, pedagogical approaches, and teacher competencies?

RQ3. What research gaps exist regarding differences in STEM understanding, pedagogical competence, and readiness between junior secondary and senior secondary teachers?

RESEARCH METHOD

The PRISMA flow diagram presents the systematic study selection process for research on teachers' understanding of STEM education at the junior and senior secondary school levels. A total of 884 records were identified from Scopus (n = 226), Cambridge Core (n = 20), and Springer (n = 638). After removing 16 duplicate records, 868 studies remained for screening. The screening process excluded 691 records that did not meet the predefined relevance criteria, resulting in 177 reports being sought for retrieval. All 177 reports were successfully retrieved and subsequently assessed for full-text eligibility (Figure 1).

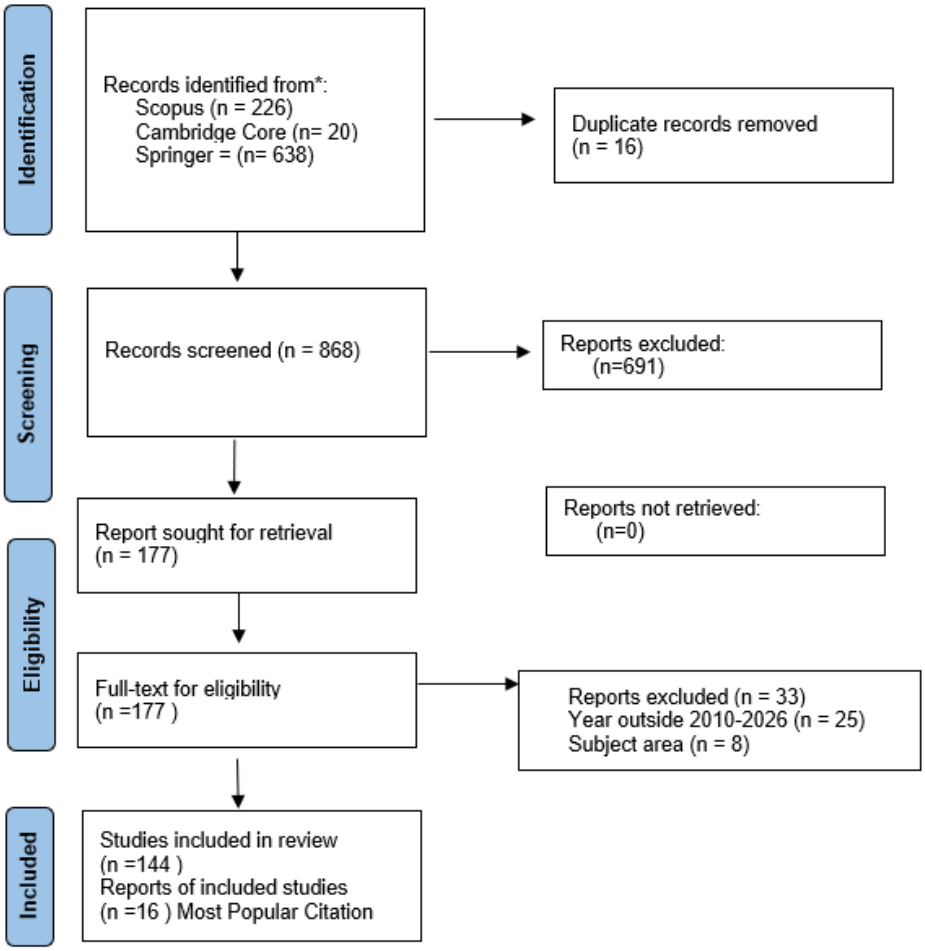

Figure 1. PRISMA flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies in the systematic literature review

The full-text assessment excluded 33 reports based on the established criteria, including publication outside the 2010–2026 period (n = 28) and inappropriate subject areas (n = 8). A total of 144 studies were therefore included in the systematic review, while 10 reports were identified as the most highly cited studies for further analysis. The final evidence base provides a focused representation of research concerning teachers' STEM understanding, particularly in relation to conceptual knowledge, perceptions, pedagogical competence, professional development, and STEM implementation among junior and senior secondary school teachers.

Table 1. Inclusion and exclusion criteria for study selection

Criterion	Inclusion	Exclusion
Publication year	2010–2026	Before 2010 or after 2026
Topic	STEM teacher understanding/competence	STEM unrelated to teachers
Educational level	Junior/senior secondary	Primary, university, informal education

Criterion	Inclusion	Exclusion
Publication type	Research articles/reviews	Editorials, proceedings if excluded
Language	English	Other languages
Availability	Full-text accessible	Full text unavailable

RESULTS AND DISCUSSION

Results

RQ1-Main research themes and dimensions

The dominance of STEM education and its strong links with teacher training, professional development, pedagogical content knowledge, perception, and STEM identity indicate that teachers' STEM competence is increasingly conceptualized as a multidimensional construct rather than as disciplinary knowledge alone. The network demonstrates that teachers' understanding of STEM is multidimensional, extending beyond conceptual knowledge toward pedagogical competence, interdisciplinary integration, curriculum understanding, and readiness to implement STEM-oriented instruction. The presence of middle school, high school, secondary schools, biology education, mathematics, physics, and engineering further indicates that STEM understanding is relevant across junior and senior secondary education and requires teachers to connect knowledge across disciplinary boundaries (Figure 2).

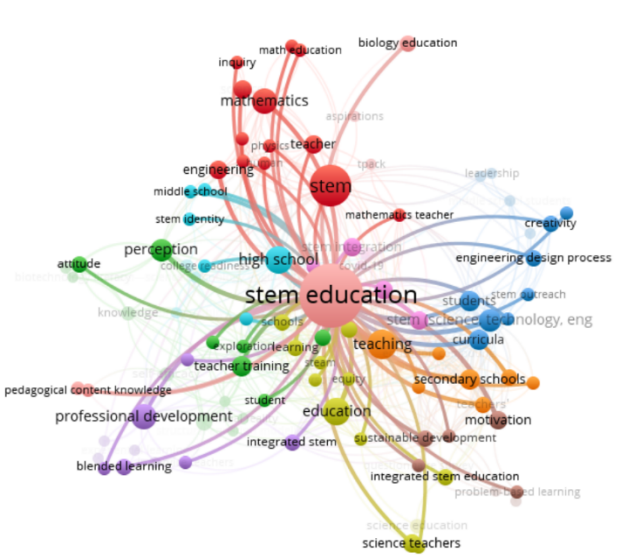

Figure 2. Keyword co-occurrence network illustrating the major research themes and conceptual relationships in studies of teachers' STEM understanding

The network also highlights engineering design process, creativity, inquiry, problem-based learning, exploration learning, and professional development as important pedagogical dimensions of STEM education. These themes suggest that teachers are expected to translate STEM concepts into student-centered learning through authentic problems, inquiry, design, creativity, and problem-solving. The connections among middle school, high school, and teacher-related themes provide a basis for examining differences in STEM understanding between junior and senior secondary teachers, particularly in terms of interdisciplinary knowledge, pedagogical content knowledge, curriculum integration, and classroom implementation. The visualization therefore supports a multidimensional perspective in which effective STEM education depends not only on teachers' conceptual understanding, but also on their pedagogical readiness and capacity to integrate science, technology, engineering, and mathematics into meaningful learning experiences.

The centrality of STEM education and its strong associations with teacher training, professional development, pedagogical content knowledge, perception, and STEM identity indicate that teachers' STEM competence is increasingly understood as a multidimensional construct. This suggests that effective STEM implementation depends not only on teachers' disciplinary knowledge but also on their ability to integrate pedagogical, interdisciplinary, and professional competencies into classroom practice.

The overlay visualization indicates a clear temporal evolution in research on STEM education between 2020 and 2025. STEM education remains the dominant and most central keyword, closely connected with teaching, teacher, high school, middle school, mathematics, engineering, and biology education. Earlier research, represented by blue and purple nodes, appears to emphasize perception, attitude, knowledge, teacher training, and professional development, suggesting that initial research attention focused on teachers' readiness, beliefs, and foundational understanding of STEM. The emergence of pedagogical content knowledge, STEM identity, and integrated STEM further indicates that teacher understanding has increasingly been viewed as a multidimensional construct rather than simple awareness of STEM concepts (Figure 3).

RQ2-Research evolution and trends

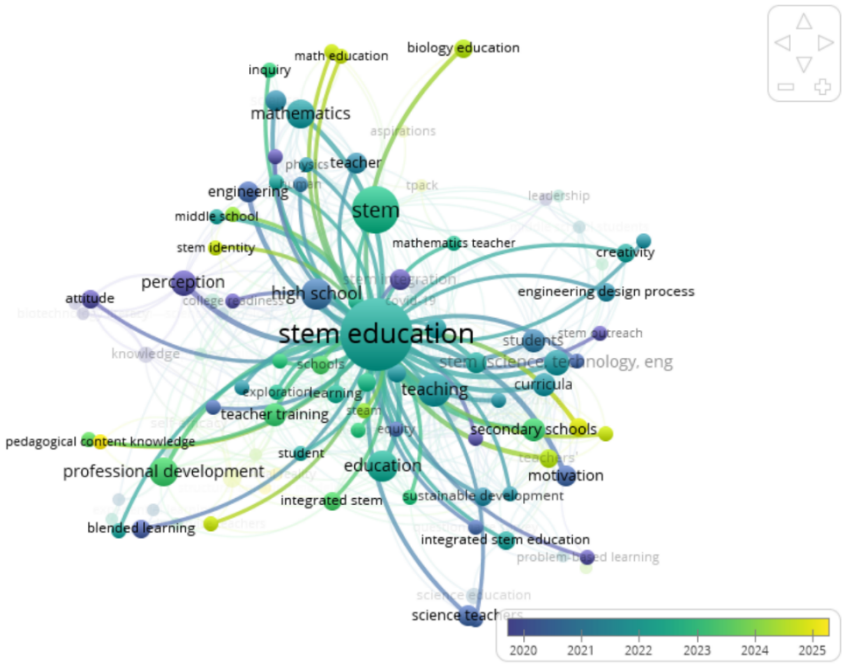

Figure 3. Overlay visualization showing the temporal evolution of research themes in teachers' STEM education research from 2020 to 2025

Recent research, represented by green and yellow nodes, increasingly emphasizes creativity, engineering design process, inquiry, integrated STEM education, sustainable development, motivation, and curricula. The strong connections of these themes with middle school and high school demonstrate growing attention to how teachers translate STEM knowledge into interdisciplinary classroom practices at both secondary education levels. The temporal pattern suggests a shift from examining teachers' perceptions and preparedness toward investigating their pedagogical capacity to integrate disciplines, facilitate inquiry and engineering design, develop creativity, and connect STEM learning with authentic and sustainability-oriented problems. This evolution provides a strong basis for examining differences in STEM understanding between junior and senior secondary teachers, particularly regarding conceptual knowledge, pedagogical content

knowledge, interdisciplinary integration, and practical implementation of STEM learning.

The density visualization demonstrates that STEM education represents the most concentrated and dominant research theme, followed by closely related concepts such as teaching, students, high school, secondary schools, teacher training, and professional development. High-density areas around these terms indicate substantial scholarly attention to teachers' roles and instructional practices in STEM learning. The presence of perception, attitude, knowledge, self-efficacy, pedagogical content knowledge, and STEM identity highlights that teachers' understanding of STEM encompasses cognitive, affective, and pedagogical dimensions. These dimensions are particularly relevant for examining both junior and senior secondary teachers because effective STEM implementation requires teachers to understand not only STEM concepts but also how interdisciplinary knowledge can be translated into classroom instruction (Figure 4).

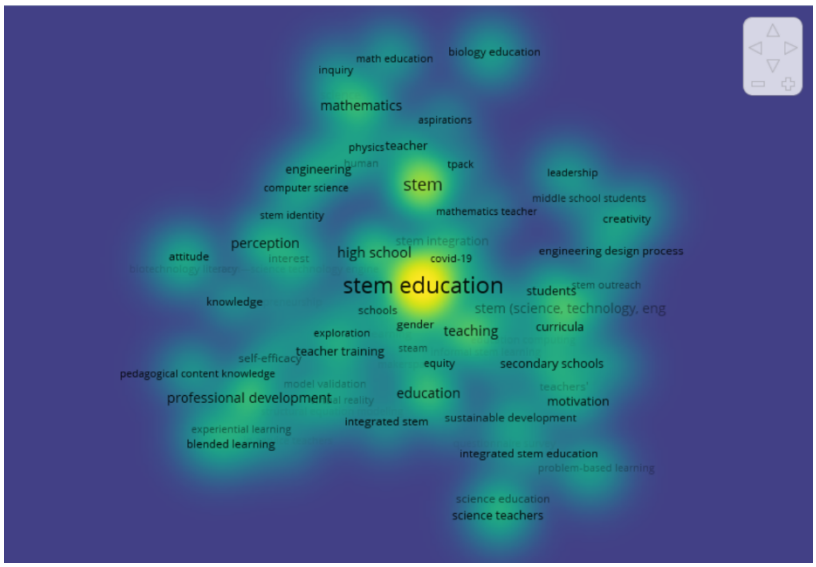

Figure 4. Density distribution of research themes highlighting the centrality of STEM education, teaching, teacher training, professional development, and pedagogical content knowledge

The visualization also identifies engineering design process, creativity, inquiry, problem-based learning, integrated STEM, and sustainable development as important surrounding themes. Such patterns suggest an increasing research emphasis on teachers' capacity to implement STEM through inquiry-based, problem-oriented, interdisciplinary, and authentic learning experiences. The relatively strong density around middle school and high school supports the relevance of comparing STEM understanding across junior and senior secondary education. Differences may emerge in teachers' disciplinary backgrounds, pedagogical content knowledge, self-efficacy, and ability to integrate science, technology, engineering, and mathematics. The density map therefore reinforces the need to conceptualize teachers' STEM understanding as a comprehensive construct involving conceptual knowledge, pedagogical competence, interdisciplinary integration, and practical readiness to design and facilitate STEM learning.

The temporal evolution suggests a shift from understanding STEM as an educational innovation that requires teacher awareness and preparedness toward a more practice-oriented conception emphasizing integration, engineering design, inquiry, creativity, and sustainability. This transition indicates that the research field is moving from the question

of whether teachers are ready for STEM toward the more complex question of how teachers can enact integrated STEM pedagogy effectively in authentic educational contexts.

The geographical distribution indicates that STEM teacher research remains concentrated in a limited number of countries, suggesting an uneven global evidence base. The relatively strong contribution from Indonesia is noteworthy, but cross-national comparative studies remain limited. This geographic concentration highlights the need for research that examines how STEM teacher competence is shaped by differences in curriculum, teacher preparation systems, educational policy, and sociocultural contexts (Figure 5).

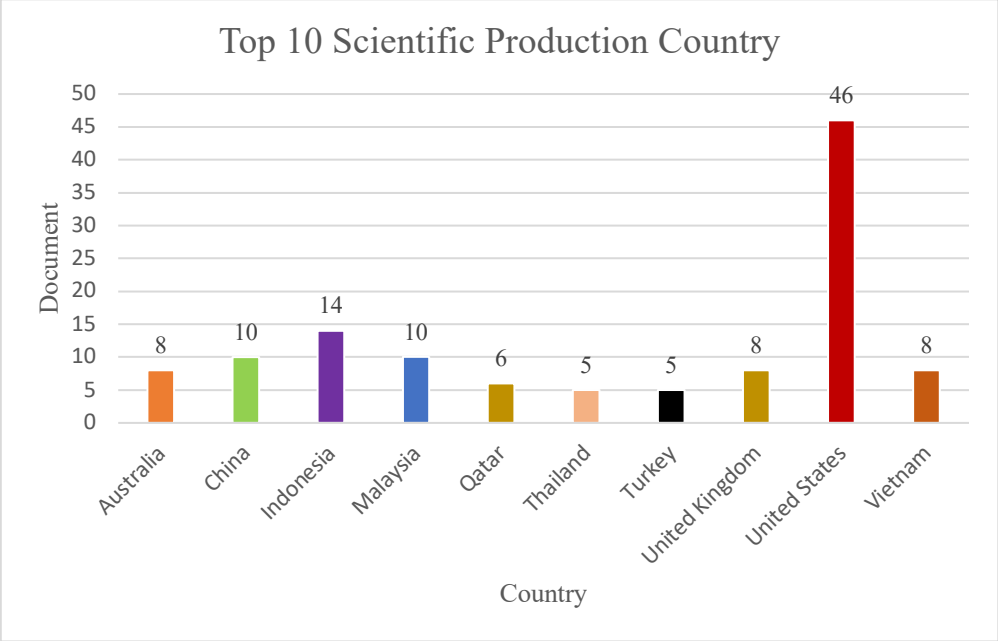

Figure 5. Geographical distribution of scientific production on teachers' understanding of STEM education across the top contributing countries

The relatively high contribution from Indonesia is particularly relevant to research examining STEM understanding among junior and senior secondary teachers. The distribution suggests that STEM education has become an internationally established research domain, while country-specific investigations remain important for understanding contextual differences in teachers' knowledge, perceptions, pedagogical competence, and readiness to implement STEM learning. Indonesia's position among the leading contributing countries provides a strong research context for investigating how teachers at the Junior High School and Senior High School levels understand interdisciplinary STEM concepts and translate them into classroom practices. The geographical distribution also indicates an opportunity for comparative research to identify differences in STEM teacher competence across educational systems and national contexts.

RQ3-Research gaps and differences between Junior High School and Senior High School teachers

The existing literature demonstrates a growing body of research examining teachers' understanding, perceptions, self-efficacy, pedagogical content knowledge, and implementation of STEM education at the secondary school level. Previous studies have addressed various aspects of STEM teacher competence, including STEM pedagogical

content knowledge, interdisciplinary competence, teacher identity, instructional self-efficacy, professional development, curriculum integration, and the design of STEM learning sequences.

The reviewed studies also indicate that positive attitudes toward STEM do not necessarily correspond to adequate knowledge and classroom implementation. Indonesian studies, for example, report positive teacher attitudes alongside moderate levels of STEM knowledge and application, while other studies identify differences in STEM understanding between junior and senior secondary teachers. The following table synthesizes the main findings of previous studies and identifies unresolved issues that provide a basis for further investigation of teachers' STEM understanding, particularly the comparative dimensions of junior and senior secondary education (Table 2).

Table 2. Comparative synthesis of previous studies on teachers' STEM understanding, competence, and implementation, with identified gaps across secondary education contexts

No	Author & Year	Article Title	Source/ Journal	Database	Method	Focus and Key Finding	Year
1	(San Gilbert Ramos et al., 2026)	Teachers' Perceptions on the Integration of STEM Projects in Secondary Education	Canadian Journal of Science, Mathematics and Technology Education	Springer	Mixed methods (survey + semi-structured interviews, n=31)	Teachers have a positive attitude toward STEM but are hindered by a lack of interdisciplinary training and technological resources.	2026
2	(Margot & Kettler, 2019)	Teachers' Perception of STEM Integration and Education: A Systematic Literature Review	International Journal of STEM Education	Springer	SLR (25 article, 2000–2016)	Teachers consider STEM important, but they face pedagogical, curricular, and structural barriers, as well as a lack of institutional support.	2019
3	(Rahman et al., 2022)	Secondary School Teachers' Perceptions of STEM Pedagogical Content Knowledge (STEMPCK)	Journal on Mathematics Education	Scopus	Quantitative online survey (n=66 junior high and high school teachers in Malaysia)	Teachers' understanding of STEMPCK varies; their STEM content knowledge has not yet been fully integrated into their teaching practices.	2022
4	(Wang & Sang, 2024)	Interdisciplinary Competence of Primary and Secondary School Teachers: A Systematic Literature Review	Cogent Education (Taylor & Francis)	Scopus	SLR, predominantly qualitative and mixed-methods	Teachers' interdisciplinary competencies include subject-matter knowledge, pedagogical skills, and collaboration; the number of publications has increased	2024

No	Author & Year	Article Title	Source/ Journal	Database	Method	Focus and Key Finding	Year
						significantly since 2019.	
5	(Grimalt-Álvaro et al., 2025)	How Do Secondary-School Teachers Design STEM Teaching–Learning Sequences? A Mixed Methods Study for Identifying Design Profiles	International Journal of Science and Mathematics Education	Springer	Mixed methods, analisis artefak Teaching-Learning Sequences	Teachers face the complexity of designing STEM activities due to curriculum requirements and their personal pedagogical beliefs.	2024
6	(Teshale et al., 2024)	Exploring Ethiopian Secondary School Science Teachers' Conceptions about the Nature of Scientific Knowledge (NOSK)	Education Sciences (MDPI)	Scopus	Qualitative, open-ended questionnaire (n=48 teachers)	Teachers hold "naive" conceptions regarding 4 of the 7 aspects of the nature of scientific knowledge; only 2 aspects are adequately understood.	2024
7	(Holincheck & Galanti, 2023)	Applying a Model of Integrated STEM Teacher Identity to Understand Change in Teachers' STEM Self-Efficacy and Career Awareness	School Science and Mathematics	Scopus	Sequential mixed methods (n = 23 graduate-level teachers)	Teachers' self-perception as "STEM teachers" develops through direct experience with STEM integration in the classroom.	2023
8	(Sellami et al., 2024)	Unveiling Teachers' Instructional Self-Efficacy in Science, Mathematics, and Technology: Personal and Contextual Influences	Canadian Journal of Science, Mathematics and Technology Education	Springer	Exploratory quantitative study (n=322 junior high and high school teachers, Qatar)	Teachers' self-efficacy regarding STEM is quite high, but varies significantly by gender, grade level, and academic qualifications.	2025
9	(Kelley et al., 2020)	Increasing High School Teachers' Self-Efficacy for Integrated STEM Instruction through a Collaborative Community of Practice	International Journal of STEM Education	Springer	Quasi-experimental (pretest-posttest, the TRAILS program)	Collaborative training based on a community of practice enhances high school teachers' self-efficacy in integrated STEM instruction.	2020
10	(Mao et al., 2024)	Investigating How Subject Teachers Transition to Integrated STEM Education: A Hybrid Qualitative Study on Primary and	Humanities and Social Sciences Communications (Nature)	Scopus	Hybrid qualitative (Grounded Theory + Epistemic Network Analysis, n=10)	Teachers' transition toward an understanding of integrated STEM occurs in three stages: imitation, exploration, and innovation.	2024

No	Author & Year	Article Title	Source/ Journal	Database	Method	Focus and Key Finding	Year
		Middle School Teachers					
11	(Dare et al., 2018)	Understanding Science Teachers' Implementations of Integrated STEM Curricular Units through a Phenomenological Multiple Case Study	International Journal of STEM Education (PMC)	Springer	A phenomenological case study (n=9 junior high school science teachers)	Teachers' levels of STEM integration vary (low to high); their understanding is influenced by their initial experience implementing STEM units.	2019
12	(Parmin et al., 2020)	Science Teachers' Views on STEM Attitude, STEM Knowledge, and STEM Application at Junior High Schools	Artikel nasional terindeks (survei 4 provinsi Indonesia)	Scopus	Quantitative survey (n=93 junior high school science teachers, 4 provinces)	Teachers have a positive attitude toward STEM, but their knowledge and application of STEM practices remain at a moderate level.	2022
13	(Febriani et al., 2025)	Barriers to the Implementation of STEM Education: Indonesian Junior High School Science Teachers' Understanding and Readiness	ERIC / jurnal pendidikan IPA nasional	ERIC (Scopus Indexed)	Qualitative, interviews (n=40 teachers)	Teachers understand STEM as the integration of problem-solving, but they mistakenly assume that the four disciplines must be given equal weight.	2024
14	(Permanasari et al., 2021)	STEM Education in Indonesia: Science Teachers' and Students' Perspectives	Journal of Innovation in Educational and Cultural Research	Scopus	Qualitative descriptive study, teacher and student questionnaires	Teachers' perceptions of STEM are quite positive, but there is still a gap in understanding between junior high school and high school teachers.	2021
15	(Rahman et al., 2022)	Secondary School Teachers' Perceptions of STEM Pedagogical Content Knowledge (Perbandingan Regional)	Journal on Mathematics Education	Cambridge Core	Descriptive quantitative survey	Teachers with more teaching experience demonstrate a more mature understanding of STEMPCK than novice teachers.	2022
16	(Yildiz Durak et al., 2023)	Examining the Predictors of TPACK for Integrated STEM: Science Teaching Self-Efficacy, Computational Thinking, and Design Thinking	Education and Information Technologies	Springer	Structural Equation Modeling (SEM), Survey of Science and Mathematics Teachers	Self-efficacy in teaching science, computational thinking, and design thinking are strong predictors of teachers' TPACK understanding	2023

No	Author & Year	Article Title	Source/ Journal	Database	Method	Focus and Key Finding	Year
						of integrated STEM.	

The synthesis of previous studies reveals several important gaps in the literature on teachers' understanding of STEM education. First, existing research tends to examine individual dimensions of teacher competence separately, such as perception, self-efficacy, STEM pedagogical content knowledge, professional development, or instructional practice. Evidence shows that teachers may have positive attitudes toward STEM while still demonstrating moderate STEM knowledge and difficulties in implementing integrated STEM instruction. Such findings indicate a conceptual gap in treating teachers' STEM understanding as an integrated construct that combines conceptual knowledge, pedagogical content knowledge, interdisciplinary integration, self-efficacy, and practical implementation.

Second, the literature provides limited systematic comparison between junior secondary and senior secondary teachers. Several studies have investigated secondary school teachers or focused specifically on either junior or senior secondary contexts, while evidence from Indonesia indicates that differences in STEM understanding between SMP and SMA teachers may exist. The available evidence, however, does not sufficiently explain how educational level may relate to teachers' conceptual understanding, interdisciplinary competence, pedagogical readiness, and capacity to implement integrated STEM learning. This gap is particularly important because teachers at different secondary levels may encounter different disciplinary structures, curricular demands, and instructional contexts.

Third, previous research increasingly emphasizes the implementation-oriented dimensions of STEM, including inquiry, engineering design, creativity, problem-based learning, and integrated STEM. Research on teachers' understanding therefore needs to move beyond measuring whether teachers recognize the importance of STEM toward examining whether they can translate STEM principles into coherent interdisciplinary learning experiences. Studies have also demonstrated that professional development and collaborative learning can improve teachers' STEM self-efficacy and pedagogical competence, indicating that teacher understanding is potentially shaped by professional experience and learning opportunities.

Table 3. Alignment of multidimensional STEM teacher competence with educational practices and relevant sustainable development goals

STEM Teacher Competence	Pedagogical Practice	Expected Student Outcome	SDG Alignment
Conceptual knowledge	Concept-based STEM learning	Scientific literacy	SDG 4
STEM-PCK	Integrated STEM instruction	Deeper STEM understanding	SDG 4
Interdisciplinary competence	Interdisciplinary projects	Systems thinking	SDG 4, SDG 13
Engineering competence	Engineering design	Innovation and problem solving	SDG 9
Technological competence	Technology-enhanced STEM	Digital/technological literacy	SDG 9
Inquiry competence	Inquiry-based learning	Evidence-based reasoning	SDG 4

STEM Teacher Competence	Pedagogical Practice	Expected Student Outcome	SDG Alignment
Sustainability competence	Sustainability-oriented STEM	Sustainability literacy	SDG 13
Creativity/self-efficacy	Problem-based learning	Creative problem solving	SDG 9
Curriculum integration	Authentic STEM projects	Application of knowledge	SDG 4, SDG 9, SDG 13

The main research gap can therefore be formulated as the limited availability of a comprehensive and comparative understanding of STEM teacher competence across junior and senior secondary education. Previous studies provide valuable evidence regarding individual components of STEM competence, but the relationships among conceptual understanding, pedagogical content knowledge, self-efficacy, interdisciplinary integration, and classroom implementation remain insufficiently synthesized. The present study addresses this gap by systematically mapping the literature and identifying how these dimensions have been investigated across SMP and SMA contexts. Such a synthesis can provide a stronger empirical foundation for developing context-sensitive STEM teacher professional development and for determining the specific competencies that require strengthening at different secondary education levels.

Discussion

The increasing prominence of integrated STEM, engineering design, inquiry, creativity, and sustainability-oriented learning suggests that STEM teacher competence has broader implications for sustainable development (Ogunniyi & Iwuanyanwu, 2024; Stouthart et al., 2025; Yao & Abd Halim, 2026). The findings indicate that teacher competence extends beyond conceptual knowledge to include pedagogical, interdisciplinary, and professional capacities that enable teachers to translate STEM principles into authentic learning experiences. Conceptual knowledge provides the disciplinary foundation, pedagogical competence facilitates meaningful instructional practices, interdisciplinary competence supports STEM integration, and professional development strengthens teachers' capacity to implement these approaches in diverse classroom contexts (Nguyen et al., 2020; Stouthart et al., 2023).

These dimensions provide a conceptual pathway linking STEM teacher competence with SDG 4 (Quality Education) through improved teaching quality and learner competencies, SDG 9 (Industry, Innovation and Infrastructure) through innovation-oriented and engineering-based learning, and SDG 13 (Climate Action) through sustainability-oriented STEM practices. From this perspective, strengthening teachers' multidimensional STEM competence may contribute to educational environments that foster critical thinking, creativity, problem-solving, innovation, and sustainability literacy. However, these relationships should be interpreted as educational implications rather than direct causal contributions to SDG achievement, as the present review did not empirically measure SDG outcomes (Al-Barakat et al., 2026; Msambwa et al., 2024; Tarlochan et al., 2025). The findings therefore support a shift from viewing STEM teacher competence as an isolated professional attribute toward understanding it as a strategic educational capacity for preparing learners to address complex scientific, technological, and environmental challenges.

CONCLUSION

Fundamental Finding: This systematic literature review and bibliometric analysis demonstrate that STEM teacher competence is a multidimensional construct extending beyond conceptual knowledge to include pedagogical competence, interdisciplinary integration, professional development, self-efficacy, and classroom implementation. The evidence base also indicates a shift in research emphasis from teachers' perceptions, attitudes, knowledge, and preparedness toward more practice-oriented dimensions, including integrated STEM, inquiry, engineering design, creativity, sustainability, and authentic learning. Despite generally positive perceptions of STEM, a persistent gap remains between teachers' awareness and knowledge of STEM and their capacity to translate these competencies into effective classroom practice. Moreover, systematic comparative evidence between junior and senior secondary teachers remains limited. **Implication:** These findings suggest that improving STEM education requires a shift from viewing teacher competence as an individual attribute toward understanding it as a multidimensional and context-dependent professional capacity. Professional development should therefore move beyond short-term awareness-building toward sustained programs that strengthen STEM pedagogical content knowledge, interdisciplinary integration, inquiry, engineering design, problem solving, and sustainability-oriented teaching. From a sustainable development perspective, these findings have implications for SDG 4 (Quality Education) through improved STEM teaching, SDG 9 (Industry, Innovation and Infrastructure) through innovation- and engineering-oriented learning, and SDG 13 (Climate Action) through sustainability-oriented STEM education. **Limitation:** Several limitations should be acknowledged. First, the review was restricted to the selected scholarly databases, publication period, English-language studies, and accessible full-text publications; therefore, relevant evidence outside these boundaries may have been excluded. Second, bibliometric analysis primarily identifies patterns, relationships, and trends in the literature and does not establish causal relationships between teacher competence and educational outcomes. Third, the available literature provides limited systematic comparisons between junior and senior secondary teachers. Consequently, the findings should be interpreted as a synthesis of the existing evidence base rather than a comprehensive representation of all STEM teacher competence research. **Future Research:** Future research should develop and empirically validate a multidimensional framework of STEM teacher competence that integrates conceptual knowledge, STEM pedagogical content knowledge, interdisciplinary competence, self-efficacy, professional development, and actual classroom implementation. Comparative studies between junior and senior secondary teachers are particularly needed to examine how educational level, disciplinary background, teaching experience, and professional development shape STEM implementation. Mixed-method and longitudinal research could further investigate the relationship between teachers' perceived competence and their observed classroom practices. Future studies should also examine how sustainability-oriented STEM teacher competence can support learning outcomes related to innovation, environmental literacy, and climate-related problem solving, thereby providing stronger empirical connections between STEM education and the Sustainable Development Goals.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to the Institute for Research and Community Service (LPPM), Universitas Negeri Surabaya (UNESA) for providing

financial support for this research. The authors also gratefully acknowledge the institutional support that contributed to the completion of this study.

AUTHOR CONTRIBUTIONS

Pramita Yakub contributed to conceptualization, formulation of the research questions, development of the research framework, methodology, and overall study design; Rinie Pratiwi Puspitawati contributed to literature searching, study screening, data curation, bibliometric analysis, and data visualization; Rooselyna Ekawati contributed to investigation, literature synthesis, interpretation of the findings, and development of the discussion, including the implications for STEM teacher competence and the Sustainable Development Goals; Muhammad Zahrudin Afnan contributed to validation, manuscript review and editing, project administration, and coordination of the submission process. All authors reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no financial, personal, or professional conflicts of interest that could have influenced the research, analysis, interpretation of the findings, or preparation of this manuscript.

ETHICAL COMPLIANCE STATEMENT

This study complies with applicable principles of research and publication ethics. The authors confirm that the manuscript represents original academic work, has been prepared with academic integrity, and is free from plagiarism, fabrication, falsification, and other forms of research or publication misconduct.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors acknowledge the use of ChatGPT (OpenAI) as an AI-assisted tool during the preparation of this manuscript, primarily for language refinement, grammar checking, restructuring of sentences, and improvement of academic writing clarity. AI-generated suggestions were critically evaluated, verified, and substantially reviewed by the authors. The authors remain fully responsible for the accuracy, originality, interpretation of the evidence, and scholarly integrity of the manuscript. The use of AI tools did not replace the authors' intellectual contribution, scholarly judgment, or responsibility for the final content.

REFERENCES

Al-Barakat, A., AlAli, R., Al-Hosan, A. M., Alghamdi, M. S., Abdullatif, A., & Zaher, A. (2026). Enhancing children's environmental cognition, affect, and behavior through project-based STEM learning toward the SDGs. *Frontiers in Psychology, 17*(7),1-23. https://doi.org/10.3389/fpsyg.2026.1880850

Anning, A. S. (2024). Investigating STEM teachers' personal and sociocultural particularities in the Ghanaian context. *International Journal of Educational Research, 125*(3),1-13. https://doi.org/10.1016/j.ijer.2024.102341

Aslam, S., Alghamdi, A. A., Abid, N., & Kumar, T. (2023). Challenges in implementing STEM education: Insights from novice STEM teachers in developing countries. *Sustainability, 15*(19), 1-17. https://doi.org/10.3390/su151914455

Berry, A., Carpendale, J., & Mulhall, P. (2025). Understanding secondary inservice teachers' perceptions and practices of implementing integrated STEM education. *Education Sciences, 15*(2), 1-20. https://doi.org/10.3390/educsci15020255

Chiriacescu, F. S., Chiriacescu, B., Grecu, A. E., Miron, C., Panisoara, I. O., & Lazar, I. M. (2023). Secondary teachers' competencies and attitude: A mediated multigroup model based on usefulness and enjoyment to examine the differences between key dimensions of STEM teaching practice. *PLOS ONE, 18*(1), 1-32. https://doi.org/10.1371/journal.pone.0279986

Dare, E. A., Ellis, J. A., & Roehrig, G. H. (2018). Understanding science teachers' implementations of integrated STEM curricular units through a phenomenological multiple case study. *International Journal of STEM Education, 5*(1), 1-19. https://doi.org/10.1186/s40594-018-0101-z

Dong, Y., Wang, J., Yang, Y., & Kurup, P. M. (2020). Understanding intrinsic challenges to STEM instructional practices for Chinese teachers based on their beliefs and knowledge base. *International Journal of STEM Education, 7*(1), 1-12. https://doi.org/10.1186/s40594-020-00245-0

English, L. D. (2023). Ways of thinking in STEM-based problem solving. *ZDM–Mathematics Education, 55*(7), 1-12. https://doi.org/10.1007/s11858-023-01474-7

Fang, S.-C., & Fan, S.-C. (2023). Exploring teachers' conceptions and implementations of STEM integration at the junior secondary level in Taiwan: An interview study. *International Journal of Science and Mathematics Education, 21*(7), 2095–2121. https://doi.org/10.1007/s10763-022-10335-w

Febriani, W. N., Natadiwijaya, I. F., Gunawan, C. W., & Putri, U. (2025). Barriers to the implementation of STEM education at the middle school level. *In M. S. Ozturk, M. Unal, & M. L. Ciddi (Eds.)*, Proceedings of ICEMST 2025—International Conference on Education in Mathematics, Science and Technology.

Gardner, K., Glassmeyer, D., & Worthy, R. (2019). Impacts of STEM professional development on teachers' knowledge, self-efficacy, and practice. *Frontiers in Education, 4*(4), 26. https://doi.org/10.3389/feduc.2019.00026

Grimalt-Álvaro, C., López-Simó, V., & Tena, È. (2025). How do secondary-school teachers design STEM teaching–learning sequences? A mixed methods study for identifying design profiles. *International Journal of Science and Mathematics Education, 23*(1), 235–260. https://doi.org/10.1007/s10763-024-10457-3

Hamad, S., Tairab, H., Wardat, Y., Rabbani, L., AlArabi, K., Yousif, M., Abu-Al-Aish, A., & Stoica, G. (2022). Understanding science teachers' implementations of integrated STEM: Teacher perceptions and practice. *Sustainability, 14*(6), 1-19. https://doi.org/10.3390/su14063594

Holincheck, N. M., & Galanti, T. M. (2023). Applying a model of integrated STEM teacher identity to understand change in elementary teachers' STEM self-efficacy and career awareness. *School Science and Mathematics, 123*(6), 234–248. https://doi.org/10.1111/ssm.12610

Hu, W., & Guo, X. (2021). Toward the development of key competencies: A conceptual framework for the STEM curriculum design and a case study. *Frontiers in Education, 6*(10),1-12. https://doi.org/10.3389/feduc.2021.684265

Huang, X., Erduran, S., Luo, K., Zhang, P., & Zheng, M. (2024). Investigating in-service teachers' STEM literacy: The role of subject background and gender. *Research in Science & Technological Education, 42*(3), 867–887. https://doi.org/10.1080/02635143.2022.2153243

Kegels, C., Struyf, A., & Thomas, V. (2026). Motivating youth for STEM: A narrative literature review of motivational STEM interventions. *Education Sciences, 16*(2), 1-28. https://doi.org/10.3390/educsci16020290

Kelley, T. R., Knowles, J. G., Holland, J. D., & Han, J. (2020). Increasing high school teachers' self-efficacy for integrated STEM instruction through a collaborative community of practice. *International Journal of STEM Education, 7*(1), 1-13. https://doi.org/10.1186/s40594-020-00211-w

Kopbossyn, A., Laiskhanov, S., Aksoy, B., Tokbergenova, A., Nametkulov, M., & Kozybakova, A. (2025). Integrated STEM for sustainability in school and early teacher education: A systematic review (2019–2025). *Frontiers in Education, 10*(10), 1-13. https://doi.org/10.3389/feduc.2025.1697058

Lin, K.-Y., Ku, C.-J., Wei, H.-T., Yu, K.-C., & Williams, P. J. (2025). Processes, challenges, and teacher roles in developing and implementing collaborative STEM curricula: Case studies of two Taiwanese schools. *International Journal of STEM Education, 12*(1), 1-19. https://doi.org/10.1186/s40594-025-00545-3

Lin, P.-Y., Chai, C. S., Di, W., & Wang, X. (2022). Modeling Chinese teachers' efficacies for the teaching of integrated STEM with interdisciplinary communication and epistemic fluency. *Frontiers in Psychology, 13*(6), 1-12. https://doi.org/10.3389/fpsyg.2022.908421

Liu, Y., & Liu, Y. (2025). Advancing STEM education for sustainability: The impact of graphical knowledge visualization and user experience on continuance intention in mixed-reality environments. *Sustainability, 17*(9), 1-27. https://doi.org/10.3390/su17093869

Mao, G., Zhang, Q., Ma, T., Li, F., & Lan, M. (2024). Investigating how subject teachers transition to integrated STEM education: A hybrid qualitative study on primary and middle school teachers. *Humanities and Social Sciences Communications, 11*(1), 1-11. https://doi.org/10.1057/s41599-024-03565-6

Margot, K. C., & Kettler, T. (2019). Teachers' perception of STEM integration and education: A systematic literature review. *International Journal of STEM Education, 6*(1), 1-16. https://doi.org/10.1186/s40594-018-0151-2

Mohamad Hasim, S., Rosli, R., Halim, L., Capraro, M. M., & Capraro, R. M. (2022). STEM professional development activities and their impact on teacher knowledge and instructional practices. *Mathematics, 10*(7), 1-20. https://doi.org/10.3390/math10071109

Msambwa, M. M., Daniel, K., Lianyu, C., & Fute, A. (2024). A systematic review of the factors affecting girls' participation in science, technology, engineering, and mathematics subjects. *Computer Applications in Engineering Education, 32*(2), 1-17. https://doi.org/10.1002/cae.22707

Nguyen, T. P., Nguyen, T. H., & Tran, T. K. (2020). STEM education in secondary schools: Teachers' perspective towards sustainable development. *Sustainability, 12*(21), 1-16. https://doi.org/10.3390/su12218865

Nipyrakis, A., Stavrou, D., & Avraamidou, L. (2025). Examining S-T-E-M teachers' design of integrated STEM lesson plans. *International Journal of Science and Mathematics Education, 23*(2), 537–560. https://doi.org/10.1007/s10763-024-10474-2

Ogunniyi, M., & Iwuanyanwu, P. N. (2024). Analysis of teachers' perspectives towards the use of IKS to improve STEM education for sustainable development. *African Journal of Research in Mathematics, Science and Technology Education, 28*(3), 319–329. https://doi.org/10.1080/18117295.2024.2352980

Parmin, P., Saregar, A., Deta, U. A., & El Islami, R. A. Z. (2020). Indonesian science teachers' views on attitude, knowledge, and application of STEM. *Journal for the Education of Gifted Young Scientists, 8*(1), 17–31. https://doi.org/10.17478/jegys.647070

Permanasari, A., Rubini, B., & Nugroho, O. F. (2021). STEM education in Indonesia: Science teachers' and students' perspectives. *Journal of Innovation in Educational and Cultural Research, 2*(1), 7–16. https://doi.org/10.46843/jiecr.v2i1.24

Pinar, F. I. L., Panergayo, A. A. E., Sagcal, R. R., Acut, D. P., Roleda, L. S., & Prudente, M. S. (2025). Fostering scientific creativity in science education through scientific problem-solving approaches and STEM contexts: A meta-analysis. *Disciplinary and Interdisciplinary Science Education Research, 7*(1), 1-17. https://doi.org/10.1186/s43031-025-00137-9

Rahman, N. A., Rosli, R., Rambely, A. S., Siregar, N. C., Capraro, M. M., & Capraro, R. M. (2022). Secondary school teachers' perceptions of STEM pedagogical content knowledge. *Journal on Mathematics Education, 13*(1), 119–134. https://doi.org/10.22342/jme.v13i1.pp119-134

Rehman, N., Huang, X., Mahmood, A., Zafeer, H. M. I., & Mohammad, N. K. (2025). Emerging trends and effective strategies in STEM teacher professional development: A systematic review. *Humanities and Social Sciences Communications, 12*(1), 1-24. https://doi.org/10.1057/s41599-024-04272-y

San Gilbert Ramos, Y. Y., Perera Rodríguez, V. H., & Murillo Estepa, P. (2026). Teachers' perceptions on the integration of STEM projects in secondary education. *Canadian Journal of Science, Mathematics and Technology Education, 26*(4), 1-18. https://doi.org/10.1007/s42330-026-00481-6

Saseendran, A., & Thomas, M. V. (2025). Design thinking in science and integrated STEM/STEAM education: Trends, challenges, and future directions from a systematic review. *STEM Education, 5*(6), 1058–1101. https://doi.org/10.3934/steme.2025046

Sellami, A., Santhosh, M. E., Michaleczek, I., Alazaizeh, M., & Madad, J. (2024). Unveiling teachers' instructional self-efficacy in science, mathematics, and technology: Personal and contextual influences. *Canadian Journal of Science, Mathematics and Technology Education, 24*(3), 418–438. https://doi.org/10.1007/s42330-025-00359-z

Shernoff, D. J., Sinha, S., Bressler, D. M., & Ginsburg, L. (2017). Assessing teacher education and professional development needs for the implementation of integrated approaches to STEM education. *International Journal of STEM Education, 4*(1), 1-16. https://doi.org/10.1186/s40594-017-0068-1

Sokolova, E. V., Blaginin, V. A., & Shatrova, A. Y. (2025). Evolution and current trends in STEM education: A retrospective and bibliometric analysis. *Journal of Hypermedia & Technology-Enhanced Learning, 3*(1), 90–107. https://doi.org/10.58536/j-hytel.169

Stouthart, T., Bayram, D., & van der Veen, J. (2023). Capturing pedagogical design capacity of STEM teacher candidates: Education for sustainable development through socioscientific issues. *Sustainability, 15*(14), 1-26. https://doi.org/10.3390/su151411055

Stouthart, T., Bayram, D., & van der Veen, J. (2025). Science teachers' views on student competences in education for sustainable development. *Journal of Research in Science Teaching, 62*(6), 1617–1653. https://doi.org/10.1002/tea.22021

Tarlochan, F., Alduais, A., Chaaban, Y., & Du, X. (2025). Integrating sustainability into STEM education and career development: A scientometric and narrative review.

International Journal of STEM Education, 12(1), 1-22. https://doi.org/10.1186/s40594-025-00582-y

Teshale, T. D., Negasi, R. D., & Getahun, D. A. (2024). Exploring Ethiopian secondary school science teachers' conceptions about the nature of scientific knowledge (NOSK). *Education Sciences, 14*(6), 1-17. https://doi.org/10.3390/educsci14060559

Thi To Khuyen, N., Van Bien, N., Lin, P.-L., Lin, J., & Chang, C.-Y. (2020). Measuring teachers' perceptions to sustain STEM education development. *Sustainability, 12*(4), 1-15. https://doi.org/10.3390/su12041531

Thibaut, L., Knipprath, H., Dehaene, W., & Depaepe, F. (2018). How school context and personal factors relate to teachers' attitudes toward teaching integrated STEM. *International Journal of Technology and Design Education, 28*(3), 631–651. https://doi.org/10.1007/s10798-017-9416-1

Wang, H., & Sang, L. (2024). Interdisciplinary competence of primary and secondary school teachers: A systematic literature review. *Cogent Education, 11*(1), 1-16. https://doi.org/10.1080/2331186X.2024.2378277

Wu, P., Yang, L., Hu, X., Li, B., Liu, Q., Wang, Y., & Huang, J. (2022). How K12 teachers' readiness influences their intention to implement STEM education: Exploratory study based on decomposed theory of planned behavior. *Applied Sciences, 12*(23), 1-22. https://doi.org/10.3390/app122311989

Wu, X., Yang, Y., Zhou, X., Xia, Y., & Liao, H. (2024). A meta-analysis of interdisciplinary teaching abilities among elementary and secondary school STEM teachers. *International Journal of STEM Education, 11*(1), 1-20. https://doi.org/10.1186/s40594-024-00500-8

Yao, N., & Abd Halim, N. D. (2026). Enhancing STEM teachers' technology integration competencies to support education for sustainable development. *Sustainability, 18*(5), 1-20. https://doi.org/10.3390/su18052520

Yildiz Durak, H., Atman Uslu, N., Canbazoğlu Bilici, S., & Güler, B. (2023). Examining the predictors of TPACK for integrated STEM: Science teaching self-efficacy, computational thinking, and design thinking. *Education and Information Technologies, 28*(7), 7927–7954. https://doi.org/10.1007/s10639-022-11505-7

Zhan, Z., & Niu, S. (2023). Subject integration and theme evolution of STEM education in K-12 and higher education research. *Humanities and Social Sciences Communications, 10*(1), 1-13. https://doi.org/10.1057/s41599-023-02303-8

Zhan, Z., Shen, W., Xu, Z., Niu, S., & You, G. (2022). A bibliometric analysis of the global landscape on STEM education (2004–2021): Towards global distribution, subject integration, and research trends. *Asia Pacific Journal of Innovation and Entrepreneurship, 16*(2), 1-33. https://doi.org/10.1108/APJIE-08-2022-0090

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