JPBIO (Jurnal Pendidikan Biologi)
Vol. 11, No. 1, April 2026, 113 – 128 //e-ISSN 2540-802X
http://jurnal.stkippersada.ac.id/jurnal/index.php/JBIO/index

Mapping the global research landscape of STEAM education: A bibliometric study of interdisciplinary learning approaches

Rifki Aldiansyah*, Paidi, Mualimin, Kintan Limiansi

Master of Biology Education, Faculty of Mathematics and Natural Sciences, Yogyakarta State University, Indonesia

*Corresponding author: rifkialdiansyah.2025@student.uny.ac.id

Article Info

Article History:
Received 11 February 2026
Revised 11 March 2026
Accepted 13 April 2026
Published 30 April 2026

Keywords:
STEAM education
Bibliometrics
Interdisciplinary learning

ABSTRACT

STEAM education has become an increasingly prominent focus in formal education, emphasizing the interdisciplinary integration of science, technology, engineering, arts, and mathematics. However, comprehensive studies mapping global research trends and thematic developments in STEAM remain limited. This study aims to analyze global STEAM research trends, identify influential contributors, and examine thematic evolution through bibliometric analysis. The research employed a Systematic Literature Review (SLR) combined with bibliometric analysis of 184 Scopus-indexed articles published between 2015 and October 2025. Data were analyzed using VOS viewer and Bibliometrix to explore publication patterns, collaboration networks, and thematic clusters. The findings indicate a significant growth in publications, particularly from 2022 to 2025, with the United States, China, and Spain as leading contributors. Lavicza, Z., and Johannes Kepler University Linz were identified as the most productive contributors. Thematic analysis revealed key clusters, including project-based learning, creativity, computational thinking, art integration, and maker-centered learning, reflecting a shift toward transdisciplinary approaches. These results highlight the evolving direction of STEAM education and suggest opportunities for future research in local implementation, technology integration, and authentic assessment.

Citation: Aldiansyah, R., Paidi, Mualimin, & Limiansi, K. (2026). Mapping the global research landscape of STEAM education: A bibliometric study of interdisciplinary learning approaches. *JPBIO (Jurnal Pendidikan Biologi), 11*(1), 113-128. DOI: https://doi.org/10.31932/jpbio.v11i1.6194

INTRODUCTION

STEAM education (Science, Technology, Engineering, Arts, and Mathematics) has become an important framework in the landscape of 21st-century education as it integrates scientific

understanding, technology, engineering, arts, and mathematics to enhance students' creativity, innovation, and problem-solving skills. The need for adaptive and creative human resources has encouraged many countries to adopt STEAM as a relevant learning approach to address global challenges such as the advancement of digital technology, sustainability issues, and the complexity of social problems. According to Yakman and Lee (2012), STEAM is designed to connect scientific concepts with artistic creativity, enabling students to construct knowledge holistically. This approach, as emphasized by Liao (2016), helps learners develop flexible and innovative ways of thinking when confronting real-world problems.

Research on STEAM has grown rapidly and gained widespread international attention. The increasing number of publications, citations, and curricular implementations indicates that STEAM has become a major focus in educational research (Perignat & Katz-Buonincontro, 2019). Various studies highlight that the integration of arts within STEAM strengthens creativity and design thinking (Henriksen, 2014) and facilitates project-based learning that promotes inquiry and collaboration (Beers, 2011). In practice, STEAM research has been conducted across different educational levels; however, most studies focus on secondary education, which is considered an ideal stage for developing interdisciplinary skills before students enter higher education or the workforce. Furthermore, STEAM implementation has been widely studied in East Asian countries, the United States, and Europe, which serve as global centers for STEAM development.

Although the number of STEAM studies continues to increase, most research still focuses on classroom implementation and curriculum model development within specific contexts. There remains limited research that systematically maps the development of STEAM studies from a bibliometric perspective, such as publication trends, patterns of collaboration among researchers and institutions, and the evolution of topics and thematic clusters over time. The lack of comprehensive mapping makes it difficult for researchers to understand the global dynamics of STEAM development, including which countries contribute most significantly, which authors are most influential, and which research themes are dominant or underexplored. In fact, bibliometric analysis is essential for assessing the direction of scientific development, identifying research gaps, and providing a foundation for future studies.

Based on these issues, this study aims to address the following questions: (1) What are the publication trends and developmental patterns of STEAM research over a given period? (2) Who are the key authors, institutions, and countries that exert the greatest influence in STEAM research? (3) How have the thematic clusters and research topics in STEAM evolved based on bibliometric analysis? This study offers novelty in the form of a comprehensive mapping of STEAM literature indexed in Scopus, which can serve as a strategic foundation for future STEAM research development and as a reference for subsequent researchers in formulating more targeted and relevant research directions.

RESEARCH METHODS

Research Design

This study employs a systematic literature review (SLR) design combined with bibliometric analysis to address research questions concerning the development, thematic directions, and patterns of scholarly contribution in STEAM education. This design was selected because SLR enables researchers to review the literature in a systematic, transparent, and replicable manner, thereby providing a comprehensive overview of the research topic (Kitchenham & Charters, 2007). This method is considered appropriate for the study's objectives as it allows for an in-depth analysis of published scientific evidence. Bibliometric analysis is incorporated to provide quantitative data on publication patterns and relationships among researchers, resulting in a more objective mapping of the field of study (Donthu et al., 2021).

Population and Samples

The study population includes all articles related to STEAM education and interdisciplinary learning published from 2015 to October 2025. Articles were selected through a screening process based on inclusion criteria, which comprised English-language articles, research or review articles, and publications that explicitly discuss STEAM education or interdisciplinary learning. Conference papers, editorials, and non-relevant documents were excluded from the analysis.

The research subjects consist of scientific documents indexed in the Scopus database, chosen for its broad coverage and credibility as a source of international publications (Falagas et al., 2008). The study population includes all articles related to STEAM education and interdisciplinary learning published from 2015 to October 2025. Articles were selected through a screening process based on inclusion criteria, which comprised English-language articles, research or review articles, and publications that explicitly discuss STEAM education or interdisciplinary learning. Conference papers, editorials, and non-relevant documents were excluded from the analysis. The selected time frame reflects the rapid development of STEAM over the past decade, as indicated by global publication trends (Yakman & Lee, 2012; Liao, 2016).

Instruments

Data collection was conducted by searching keywords in the Scopus database using the combined terms "STEAM education" and "interdisciplinary learning." The search process followed the PRISMA protocol to ensure transparency and a clear selection flow, starting from identification, screening, eligibility, and inclusion of articles (Page et al., 2021). From each selected article, metadata were extracted, including title, abstract, keywords, authors, affiliations, journal, and year of publication. This approach provides sufficient detail for other researchers to replicate the procedure by following the same steps.

Procedures

The procedure of this study was conducted systematically by integrating the Systematic Literature Review (SLR) approach with the PRISMA framework and bibliometric analysis. The process began with the identification stage, where articles were retrieved from the Scopus database within the publication period of 2015 to October 2025 using the primary keyword "STEAM education." This initial search yielded 3,270 articles.

In the screening stage, articles were filtered based on their titles, abstracts, and relevance to the keywords "STEAM" and "interdisciplinary education." This step aimed to ensure that only studies directly related to the research focus were retained, resulting in 445 articles. Subsequently, exclusion criteria were applied based on document type. Book chapters, books, review articles, conference proceedings, editorials, and notes were removed to maintain consistency and ensure that only empirical research articles were included for further analysis.

At the eligibility stage, 202 articles were considered suitable for full-text assessment. Additional filtering was conducted based on language, and only English-language publications were retained to ensure accessibility and standardization of analysis. Finally, in the inclusion stage, 184 articles met all criteria and were selected as the final dataset.

The selected articles were then subjected to two complementary analyses. Bibliometric analysis was performed using VOSviewer to map co-authorship networks, keyword co-occurrences, citation patterns, and thematic clusters. Simultaneously, content analysis was conducted as part of the SLR process through in-depth reading of each article to identify research focuses, contributions, and existing research gaps. This integrated procedure allowed for a comprehensive mapping of the development, trends, and thematic evolution of STEAM education research.

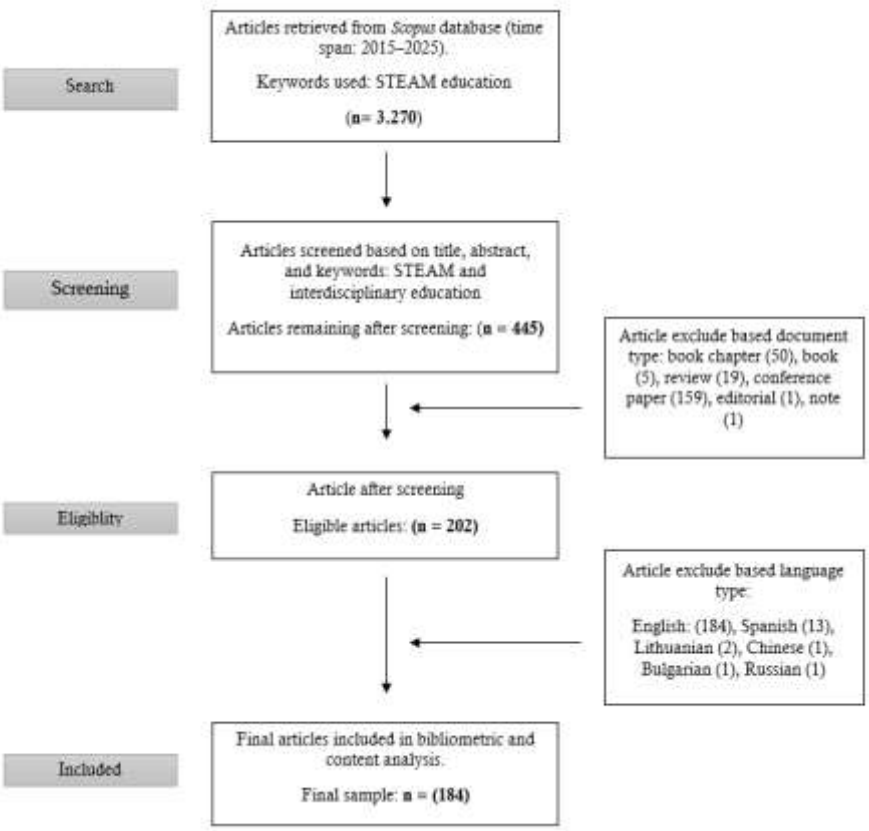

Figure 1. Systematic Literature Review Using the PRISMA Method.

Data Analysis

The collected data were analyzed using bibliometric techniques through VOSviewer software, which is widely used to map relationships among authors, keyword co-occurrences, and citation networks (van Eck & Waltman, 2010). This analysis helps identify thematic clusters, the evolution of key terms, and prominent research directions in the field of STEAM. Meanwhile, the SLR analysis was conducted through an in-depth reading of the articles to identify research focuses, contributions, and emerging research gaps. This combined approach provides a more comprehensive understanding of the developmental patterns and future directions of STEAM education research.

The systematic literature review (SLR) process followed the PRISMA framework, which consists of four main stages: identification, screening, eligibility, and inclusion. The search was conducted using the Scopus database, covering publications from 2015 to October 2025. The initial search using the keyword "STEAM education" yielded 3,270 articles. During the screening stage, articles were filtered based on their titles, abstracts, and relevance to the keywords "STEAM" and "interdisciplinary education," resulting in 445 articles.

Subsequently, exclusion criteria were applied based on document type, removing book chapters (50), books (5), review articles (19), conference proceedings (159), editorials (1), and notes (1). At the eligibility stage, 202 articles were identified as suitable for full-text assessment. Further screening was conducted based on language, retaining only English-language articles. At the inclusion stage, a total of 184 articles were selected for bibliometric and content analysis. These selected articles constituted the final dataset for mapping and interpretation using VOS viewer and SciSpace AI.

Based on this process, the study addresses several research questions: RQ1, what are the publication trends and research patterns related to STEAM and interdisciplinary education from 2015 to 2025; RQ2, how is the distribution of scientific publications related to STEAM and interdisciplinary education; and RQ3, what thematic clusters and emerging topics can be identified through bibliometric mapping of STEAM-related studies.

RESULTS

The findings of this study are based on 184 articles indexed in the Scopus database related to STEAM education and interdisciplinary learning. These data were obtained through the systematic search process described earlier, covering ten years from 2015 to 2025. Based on the "Documents by Year" graph, the number of publications began to show an upward trend starting in 2015. Initially, the number of published documents was very low; however, it began to increase in 2016 and experienced fluctuations until 2018. After this period, a consistent growth trend is evident from 2019 to 2025. The most significant increase is observed in 2024, with the peak occurring in 2025, reaching more than 60 documents. This pattern indicates that since 2015, research interest and productivity on this topic have grown rapidly, particularly over the last five years.

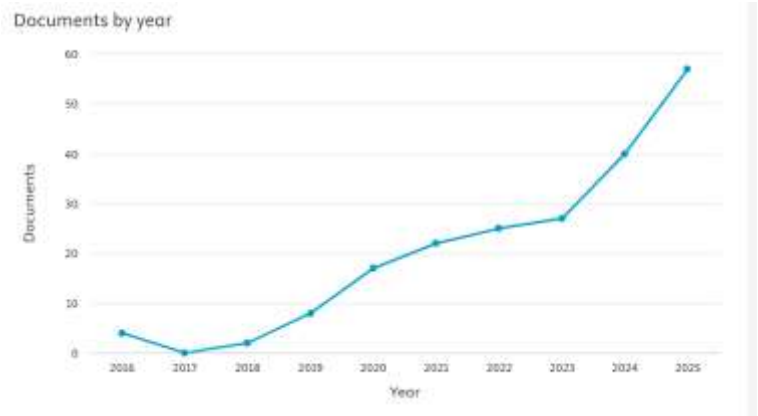

Figure 2. Scopus Database: Documents by Year

Based on data obtained from the Scopus database, the first articles addressing the topic of STEAM and interdisciplinary education appeared in 2016. In that year, four articles were identified as relevant to this theme. These early studies highlighted the implementation of STEAM approaches in student-centered learning, teacher education, the integration of arts into science and technology education, and interdisciplinary collaboration. Clapp and Jimenez (2016) investigated the implementation of STEAM in the context of maker-centered learning, emphasizing creation- and creativity-based learning. Jho, Hong, and Song (2016) analyzed STEM/STEAM teacher education in Korea through case studies of two schools from a community of practice perspective. Sochacka, Guyotte, and Walther (2016) explored STEAM education through a collaborative autoethnographic approach to understand interdisciplinary learning experiences between science and the arts. Meanwhile, Liao (2016) discussed a paradigm shift from interdisciplinary to transdisciplinary approaches through the integration of arts in STEAM education, emphasizing deeper cross-disciplinary collaboration. These four studies laid an important foundation for the academic discourse on STEAM education. The year 2016 marked the early emergence of arts integration into science and technology education, highlighting not only cognitive aspects but also creative, reflective, and collaborative values in the teaching and learning process.

By 2025, attention to STEAM and interdisciplinary education had increased substantially. According to Scopus data, 57 articles were published in that year alone. Among them, Çelik and Dutta (2025) examined STEAM learning through linocut printmaking, Viseu, Gonçalves, and

Martins (2025) investigated the interconnectedness of STEAM areas in the study of functions, and Christopher and Pinias (2025) reviewed the balance between theory and practice in STEAM education. This increase indicates that STEAM research is now increasingly focused on cross-disciplinary collaboration and the strengthening of creativity in learning processes.

From 2016 to November 2025, research on STEAM education has shown significant development, as reflected in both the increasing number of publications and the deepening of thematic exploration. Trends in titles and topics during this period reveal a shift in focus from discipline-based STEAM integration toward transdisciplinary approaches that emphasize arts integration, cross-field collaboration, creativity, design, and reflective thinking in learning. Early studies generally focused on the development of STEAM learning models, whereas later publications placed greater emphasis on real-world applications, pedagogical innovation, and the strengthening of technological literacy.

After examining the early emergence and development of STEAM and interdisciplinary education, the next analysis is directed toward the distribution of research as an answer to the second research question. Research distribution was analyzed by categorizing articles based on countries, institutions, authors, and publication sources, with particular attention to the top ten contributing countries. This analysis was also compared with patterns observed in previous bibliometric studies on STEM education, which tend to show broader thematic coverage and greater variation in educational contexts, particularly because STEM research has encompassed K–12 education, higher education, and professional teacher development programs. This comparison helps to identify the position of STEAM as a relatively newer approach that is rapidly developing, as the integration of arts is considered to enrich creativity and problem-solving processes in learning.

The distribution of scientific publications indicates that the United States ranks first with 39 documents. The high number of publications from this country can be associated with strong educational policies that emphasize integrative STEM and STEAM programs at the K–12 level, as well as substantial research investment in learning innovation. China ranks second with 22 documents, driven by the rapid development of science and technology education research integrated with creativity enhancement through the arts. Spain follows with 17 documents, while Taiwan has produced 15 documents. Portugal ranks fifth with 12 documents, followed by Austria with 10 documents.

Other countries that also demonstrate significant development in STEAM publications include Indonesia, Finland, Brazil, and Malaysia, each contributing between 8 and 9 documents. These findings indicate that STEAM research is not only advancing in developed countries but is also increasingly growing in Southeast Asia and Latin America (see Figure 3).

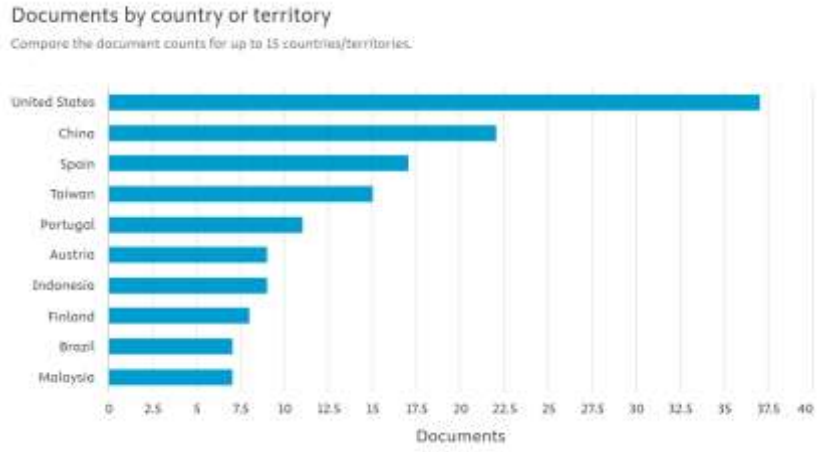

Figure 3. Scopus Database: Number of Articles by Country or Territory (Top 10 Countries)

These findings indicate that research on STEAM education has received widespread attention, particularly in countries with advanced educational and innovation ecosystems such as the United States, China, and several European nations. The dominance of the United States highlights its central role in developing interdisciplinary STEAM approaches integrated with technology and creativity. Meanwhile, the significant contributions from China and Spain reflect an increasing focus on STEAM-based curriculum and pedagogical innovation in Asia and Europe. The involvement of other countries such as Taiwan, Portugal, and Indonesia demonstrates that STEAM research has developed globally, although it remains concentrated in regions with strong research capacity and international collaboration.

Furthermore, based on Figure 4, the distribution of publications across institutions contributing to STEAM education research can be observed. The graph shows that Johannes Kepler University Linz ranks first with the highest number of publications, totaling 8 documents. This indicates that the university is among the most active and influential institutions in advancing STEAM research. Other institutions, such as Universidade do Minho, Beijing Normal University, and Universidade de Aveiro, each contribute around 4 publications, demonstrating significant involvement from European and Asian universities in the development and implementation of STEAM concepts. Meanwhile, institutions such as Kennesaw State University, National Taiwan Normal University, and Universitas Negeri Jakarta show consistent contributions with 3 publications each.

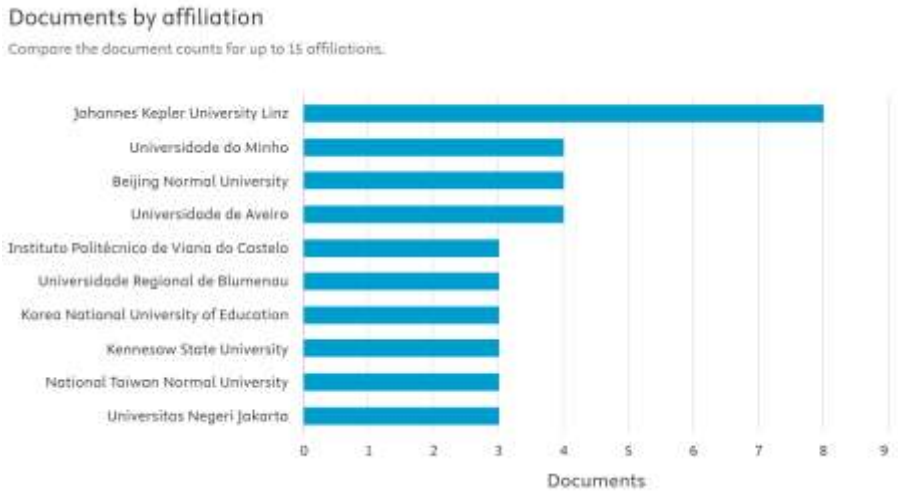

Figure 4. Scopus Database: Network country visualization

Overall, this distribution illustrates that STEAM education research is globally collaborative, with active participation from various countries and continents. The dominance of European institutions indicates strong attention to the development of STEAM approaches in that region, while the presence of Asian institutions such as Beijing Normal University, Korea National University of Education, and Universitas Negeri Jakarta demonstrates the expanding implementation and research of STEAM across Asia.

Third, the trend in publications related to STEAM education shows a significant increase in recent years, particularly during the 2022–2024 period. The journal Sustainability (Switzerland) recorded the highest surge in publications in 2022 with four relevant articles, reflecting growing attention to the integration of sustainability principles within STEAM approaches. Subsequently, the journal Education Sciences reached its peak contribution in 2024 with six documents, indicating that the focus on pedagogical innovation and interdisciplinary integration has become increasingly prominent in global academic discourse. This pattern suggests that STEAM research

has evolved into an established field that continues to attract interdisciplinary interest, with a shift in focus from early conceptualization toward practical implementation in modern educational contexts.

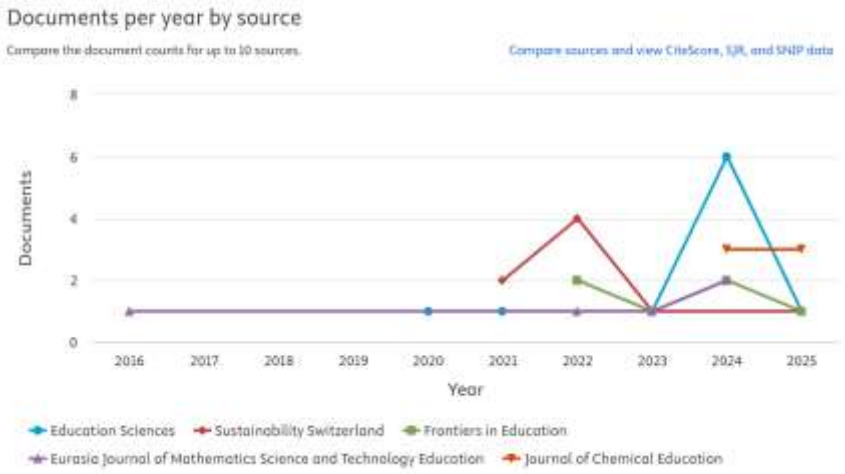

Figure 5. Scopus Database: Documents per Year by Source

Figure 5 shows that publications on STEAM education have continued to increase and have attracted broad attention from various international journals. The upward trend in the number of articles during the 2022–2024 period indicates that STEAM has become increasingly relevant to the demands of 21st-century education, particularly in promoting collaborative and integrated learning across science, technology, engineering, arts, and mathematics. This development also reflects a global shift toward educational approaches that emphasize solving complex problems, aligned with the Sustainable Development Goals (SDGs), which require critical thinking, creativity, and interdisciplinary collaboration. Thus, STEAM research has not only grown conceptually but has also moved toward more practical and responsive implementation to address global challenges.

Fourth, the distribution of publications by contributing authors in the field of STEAM education shows that Lavicza, Z. is the most prolific author, with 6 documents. This highlights his consistency and influence in advancing STEAM studies. Other authors, such as Barbosa, A., Borges, E. M., Mardiah, A., Rahmawati, Y., Saimon, M., and Sequeira, C. A., also make significant contributions with 3 documents each. Meanwhile, Vale, I., Alsina, Á., and Aros, M. contribute approximately 2 documents each. This distribution demonstrates that interest in STEAM education is spread among researchers from various countries and institutions, indicating the growth of a scholarly community focused on interdisciplinary, problem-oriented learning.

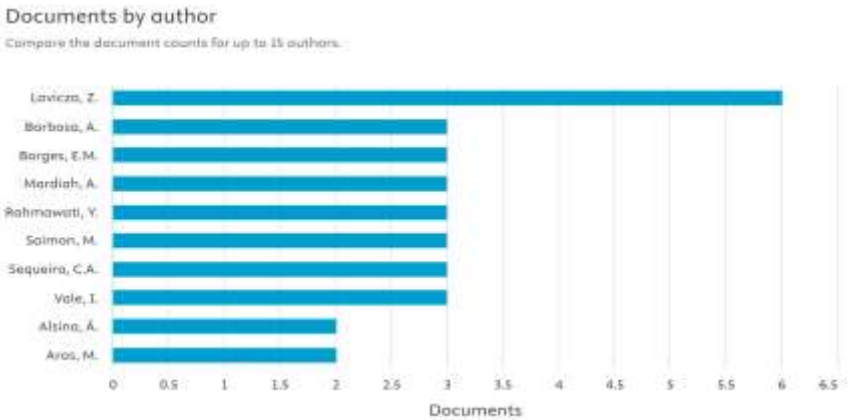

Figure 6. Scopus Database: Network country visualization

This distribution indicates that STEAM research is still dominated by a relatively small number of active and productive authors. The prominence of Lavicza, Z., who is affiliated with a European academic context, suggests that the global center of STEAM research remains concentrated within academic networks in developed countries. Nevertheless, the emergence of researchers from Asia, such as Mardiah and Rahmawati, reflects an expansion of global participation and growing interest in STEAM studies across diverse educational contexts. This development also highlights the need to strengthen cross-country research collaboration, particularly in the context of implementing STEAM in developing countries that face different educational characteristics, resources, and challenges.

The analysis of the third research question is directed toward identifying thematic clusters and emerging topics in STEAM education research. Through bibliometric mapping, this analysis reveals the interconnections among concepts and frequently occurring themes, such as digital technology integration, project-based learning, creativity, collaboration, and the application of STEAM to real-world problem solving. In addition, the findings highlight the emergence of new issues that occupy a strategic position in the development of STEAM research, including the application of artificial intelligence in STEAM learning, transdisciplinary approaches in primary and secondary education, and the development of authentic assessment capable of measuring higher-order thinking skills. These findings open opportunities for future research, particularly in exploring STEAM implementation models that align with local contexts, examining the effectiveness of arts integration in strengthening STEM literacy, and developing learning strategies that enhance students' readiness to face global challenges and achieve the Sustainable Development Goals.

The analysis of the third research question specifically focuses on identifying thematic clusters and emerging topics in STEAM education research. Using a bibliometric mapping approach, this analysis seeks to trace the relationships among concepts, identify recurring thematic trends, and determine the future directions of STEAM research.

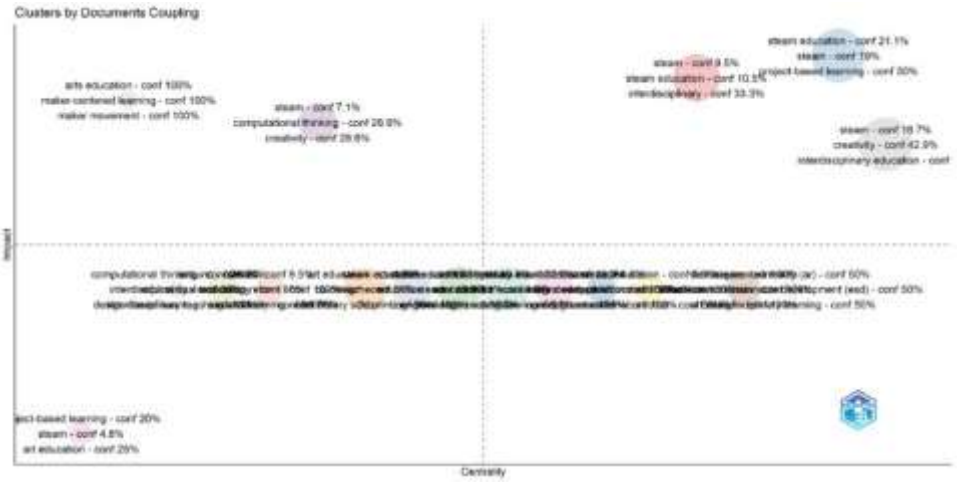

Figure 7. Source: Bibliometrix, Thematic Clusters of STEAM Education Research Based on Document Coupling Analysis

Based on Figure 7, which presents the *Clusters by Documents Coupling*, it can be observed that research related to STEAM education is grouped into several major thematic clusters that reflect the focus and developmental directions of studies in this field. The cluster with the highest influence and centrality is dominated by the theme of STEAM education (21.1%), which serves as the primary focus across various studies. This theme is followed by project-based learning (30%),

creativity (28.6%), and computational thinking (28.6%), indicating the important roles of innovation, creativity, and computational thinking in STEAM learning.

In addition, other clusters such as art education (25%), maker-centered learning (100%), and interdisciplinary education (33.3%) further emphasize the interdisciplinary nature of the STEAM approach. These clusters illustrate how STEAM research has evolved toward integrating arts, technology, and science through collaborative and contextual learning practices. Thus, the mapping results shown in Figure 3 indicate that current STEAM research increasingly highlights the relationships among creativity, project-based learning, and cross-disciplinary collaboration in supporting 21st-century educational innovation.

Further analysis was conducted using co-citation network visualization with Bibliometrix to address the third research question. This analysis aims to identify relationships among articles that are frequently cited together, thereby revealing patterns of scholarly collaboration and the main clusters that represent the global thematic focus of STEAM education research. The visualization displays connections among authors, publication years, and journal sources that form the intellectual network in this field. Based on the co-citation analysis using Bibliometrix, several major clusters can be identified, each represented by different colors, indicating scholarly communities with specific research focuses within STEAM education.

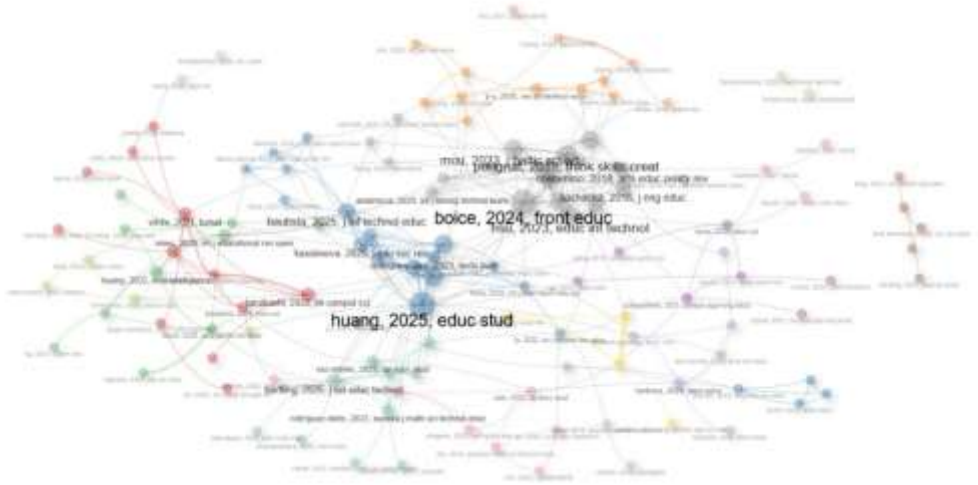

Figure 8. Source: Bibliometrix, Visualization of Co-Citation Network in STEAM Education Research

Based on Figure 8, the largest cluster centers on the works of Boice (2024) and Huang (2025), which are frequently co-cited. This cluster highlights themes related to interdisciplinary integration, creativity, and computational thinking within STEAM-based learning. These themes reflect a shift in research toward cross-disciplinary approaches that combine science, technology, and the arts to foster students' creative and critical thinking skills.

Another cluster emerging around Sochacka (2016), Constantino (2018), and Perignat (2019) emphasizes arts-based learning and design thinking, underscoring the importance of integrating the arts into science and technology education processes. This cluster represents the early foundation for the development of transdisciplinary learning approaches in STEAM research.

Additional research groups, such as those represented by Hsu (2023), Bautista (2025), and Rodrigues-Silva (2023), show a strong orientation toward pedagogical innovation and digital learning environments, which have become emerging trends alongside the increasing use of technology in STEAM learning. These findings indicate that STEAM education research continues to evolve in a more collaborative and interdisciplinary direction. The primary focus has

shifted from early STEAM curriculum implementation toward exploring the integration of creativity, computational thinking, and digital technology in modern educational practices.

DISCUSSION

The findings of this study demonstrate that STEAM education research has experienced substantial growth over the past decade, particularly from 2019 onward, with a marked surge during 2022–2025. This trend confirms that STEAM has evolved from an emerging concept into an established field of educational inquiry that responds to the demands of 21st-century learning. The increasing number of publications indicates a global recognition of the need for integrative, creative, and problem-oriented learning approaches that combine science, technology, engineering, arts, and mathematics.

The distribution of publications across countries and institutions reveals that STEAM research is still concentrated in regions with strong research ecosystems, such as the United States, China, and several European countries. The dominance of these regions reflects the presence of supportive educational policies, research funding, and academic networks that encourage interdisciplinary innovation. However, the growing contributions from countries in Asia and Southeast Asia, including Indonesia, suggest that STEAM is gaining relevance in diverse educational contexts. This expansion highlights the potential for broader global collaboration, particularly in adapting STEAM approaches to local educational needs and challenges in developing countries.

The bibliometric mapping further reveals that STEAM research is strongly associated with themes such as project-based learning, creativity, computational thinking, arts integration, and interdisciplinary education. These thematic clusters indicate a clear shift from early conceptual discussions of STEAM toward practical pedagogical applications that emphasize collaboration, contextual learning, and innovation. The prominence of maker-centered learning and arts-based approaches also underscores the distinctive contribution of the "A" (Arts) component in enriching STEM learning with creativity, design thinking, and reflective practice.

The co-citation analysis provides additional insight into the intellectual structure of STEAM research. Early foundational works emphasize arts integration and transdisciplinary learning, while more recent studies focus on pedagogical innovation, digital learning environments, and the integration of computational thinking and artificial intelligence. This evolution suggests that STEAM research is adapting to technological advancements and contemporary educational challenges, aligning with global priorities such as the Sustainable Development Goals (SDGs), which require critical thinking, creativity, and interdisciplinary collaboration.

Overall, the discussion highlights that STEAM education research is moving toward a more collaborative, transdisciplinary, and application-oriented direction. While the field has matured significantly, there remains a need for further exploration of context-sensitive implementation models, particularly in regions with different educational infrastructures and resource limitations. Future research should also examine how arts integration can effectively strengthen STEM literacy and how authentic assessment strategies can measure higher-order thinking skills within STEAM learning environments.

CONCLUSION

This study shows that research on STEAM education and interdisciplinary learning has developed significantly from 2015 to October 2025, as reflected in the consistent increase in publications and the dominant contributions from the United States, China, and several European countries, with figures and institutions such as Lavicza, Z., Johannes Kepler University Linz, and Universidade do Minho serving as major centers of productivity. The thematic analysis reveals that

project-based learning, creativity, computational thinking, and interdisciplinary education form the core of research development, followed by the emergence of new clusters such as arts-based learning and maker-centered learning, which signal a shift toward transdisciplinary approaches.

These findings imply that STEAM has become a strategic framework for designing 21st-century pedagogy that emphasizes creativity, collaboration, and cross-disciplinary integration. Future research is recommended to further explore STEAM within diverse cultural contexts and developing countries, examine the effectiveness of technology-enhanced STEAM approaches (e.g., AI, AR/VR), and develop more comprehensive evaluation models to assess the long-term impact of STEAM on students' competencies and the transformation of classroom practices.

REFERENCES

Allina, B. (2018). The development of STEAM educational policy to promote student creativity and social empowerment. *Arts Education Policy Review, 119*(2), 77–87. https://doi.org/10.1080/10632913.2017.1293749

Andreotti, E., & Frans, R. (2019). The connection between physics, engineering and music as an example of STEAM education. *Physics Education,* 54(4). https://doi.org/10.1088/1361-6552/ab1f5c

Anisimova, T. I., Sabirova, F. M., & Shatunova, O. V. (2020). Formation of design and research competencies in future teachers in the framework of STEAM education. *International Journal of Emerging Technologies in Learning, 15*(2), 204–217. https://doi.org/10.3991/ijet.v15i02.11537

Apiola, M., & Sutinen, E. (2021). Design science research for learning software engineering and computational thinking: Four cases. *Computer Applications in Engineering Education, 29*(1), 83–101. https://doi.org/10.1002/cae.22259

Arango-Caro, S., Langewisch, T., Ying, K., Haberberger, M. A., Ly, N., Branton, C., & Callis-Duehl, K. (2025). 3D plants: the impact of integrating science, design, and technology on high school student learning and interests in STEAM subjects and careers. *Disciplinary and Interdisciplinary Science Education Research,* 7(1). https://doi.org/10.1186/s43031-025-000xx

Ariza, J. Á., & Olatunde-Aiyedun, T. G. (2024). A systematic literature review on STEAM pre- and in-service teacher education for sustainability: Are teachers ready? *Eurasia Journal of Mathematics, Science and Technology Education, 20*(9). https://doi.org/10.29333/ejmste/14677

Baghirov, H. (2024). Impact Of Innovative Education On The Political And Social Life Of The Society; Impacto Da Educação Inovadora Na Vida Política E Social Da Sociedade; Impacto De La Educación Innovadora En La Vida Política Y Social De La Sociedad. *Revista de Gestao Social e Ambiental, 18*(6). https://doi.org/10.24857/rgsa.v18n6-xxx

Barbosa, A., & Vale, I. (2025). Rebuilding manipulatives through digital making in teacher education. *STEM Education, 5*(4), 515–545. https://doi.org/10.3934/steme.2025029

Barbosa, A., Vale, I., & Alvarenga, D. (2024). The use of Tinkercad and 3D printing in interdisciplinary STEAM education: A focus on engineering design. *STEM Education, 4*(3), 222–246. https://doi.org/10.3934/steme.2024013

Bautista, G., Saimon, M., Yunianto, W., El-Kasti, H. S., Lavicza, Z., & Fenyvesi, K. (2025). Challenges and opportunities in function art. *Journal of Information Technology Education: Innovations in Practice, 24.* https://www.informingscience.org/Publications

Beck, E., & Liyana Pathiranage, A. L. (2024). Enhancing chemical education through an epoxy resin crafting activity. *Journal of Chemical Education, 101*(8), 3550–3555. https://doi.org/10.1021/acs.jchemed.3c01234

Bertling, J. G., & Moore, T. C. (2021). The U.S. K–12 art education curricular landscape: A nationwide survey. *Studies in Art Education, 62*(1), 23–46. https://doi.org/10.1080/00393541.2020.1858008

Bertrand, M. G., & Namukasa, I. K. (2020). STEAM education: student learning and transferable skills. *Journal of Research in Innovative Teaching and Learning, 13*(1), 43–56. https://doi.org/10.1108/JRIT-01-2020-0004

Blanco-García, Y., Serrano, R. M., & Casanova, O. (2025). Toward a transversal education model: a review of digital and artistic-musical competencies (2014–2024). *Arts Education Policy Review, 126*(4), 240–254. https://doi.org/10.1080/10632913.2024.2345678

Bremmer, M., Heijnen, E., Hotze, A., Pijls, M., Beamer, E., & Roos, N. (2021). ArtsSciences Design-a-thon: Solving Complex Problems in Interdisciplinary Teams. *European Journal of STEM Education, 6*(1). https://doi.org/10.20897/ejsteme/9568

Broza, O., Azaryahu, L., & Hershkovitz, S. (2025). In-service teachers' and pre-service teachers' perceptions of interdisciplinary instruction combining music and mathematics. *Teacher Development, 29*(4), 668–691. https://doi.org/10.1080/13664530.2025.2398765

Carter, C. E., Barnett, H., Burns, K., Cohen, N., Durall, E., Lordick, D., Nack, F., Newman, A., & Ussher, S. (2021). Defining STEAM Approaches for Higher Education. *European Journal of STEM Education, 6*(1). https://doi.org/10.20897/ejsteme/9779

Casadio, F. (2021). Sharing Power: Leadership Lessons from Interdisciplinary Practices in an Art Museum. *Curator, 64*(3), 505–527. https://doi.org/10.1111/cura.12434

Desing, R. M., Pelan, R., Kajfez, R. L., Wallwey, C., Clark, A. M., & Gopalakrishnan, S. (2024). Identity Trajectories of Faculty Members through Interdisciplinary STEAM Collaboration Paired with Public Communication. *Education Sciences, 14*(5). https://doi.org/10.3390/educsci14050567

Diego-Mantecón, J.-M., Prodromou, T., Lavicza, Z., Blanco, T. F., & Ortiz-Laso, Z. (2021). An attempt to evaluate STEAM project-based instruction from a school mathematics perspective. *ZDM – International Journal on Mathematics Education, 53*(5), 1137–1148. https://doi.org/10.20897/ejsteme/9779

Dong, J., & Ran, M. (2024). The Application and Effectiveness of Interdisciplinary Integration Education in Teaching Interior Design and Environmental Design. *Applied Mathematics and Nonlinear Sciences, 9*(1). https://doi.org/10.2478/amns-2024-xxxx

Dorsey, Z. A. (2019). Exacting collaboration: performance as pedagogy in interdisciplinary contexts. *Research in Drama Education, 24*(3), 397–401. https://doi.org/10.1080/13569783.2019.1621453

Graham, M. A. (2021). The disciplinary borderlands of education: art and STEAM education. *Infancia y Aprendizaje, 44*(4), 769–800. https://doi.org/10.1080/02103702.2021.1981156

Graybeal, G. M., & Ferrier, M. B. (2023). Examination of Pedagogy and Instructional Innovation to Create Entrepreneurs in the Media and Technology Fields. *Entrepreneurship Education and Pedagogy, 6*(1), 110–134. https://doi.org/10.1177/25151274211012345

Guo, M. (2023). STEAM Education Concept in English Teaching Practice Process Based on Big Data Evolutionary Network Influence Analysis. *EAI Endorsed Transactions on Scalable Information Systems, 10*(6). https://doi.org/10.4108/eetsis.v10i6.4472

Henriksen, D. (2014). Full STEAM ahead: Creativity in excellent STEM teaching practices. *The STEAM Journal, 1*(2), 15. https://scholarworks.wmich.edu/steamjournal/vol1/iss2/15

Hetherington, L., Chappell, K., Ruck Keene, H., Wren, H., Cukurova, M., Hathaway, C., Sotiriou, S. A., & Bogner, F. X. (2020). International educators' perspectives on the purpose of science education and the relationship between school science and creativity. *Research in Science and*

Technological Education, 38(1), 19–41. https://doi.org/10.1080/02635143.2019.1700494

Hinterplattner, S., Skogø, J. S., Hörmann, C., & Sabitzer, B. (2020). The Children's Congress: A Benefit to All Levels of Schooling by Strengthening Computational Thinking. *International Journal of Learning, 6*(4), 241–246. https://doi.org/10.18848/2327-7955/CGP/v06i04/241-246

Huang, Y., & Liu, X. (2022). The analysis and research of STEAM education based on the TAM algorithm model to improve the learning effectiveness of higher vocational engineering students. *Evolutionary Intelligence, 15*(4), 2597–2607. https://doi.org/10.1007/s12065-021-00635-2

Jensen, C., Kotaish, M., Chopra, A., Jacob, K. A., Widekar, T. I., & Alam, R. (2019). Piloting a methodology for sustainability education: Project examples and exploratory action research highlights. *Emerging Science Journal, 3*(5), 312–326. https://doi.org/10.28991/esj-2019-01190

Jeong, H.-M., Kwon, H., & Kim, S.-H. (2023). A Meta-Analytic Approach for Examining the Effects of STEAM Education Programs in South Korea. *Africa Review, 5*(1). https://africareview.com

Jho, H., Hong, O., & Song, J. (2016). An analysis of STEM/STEAM teacher education in Korea with a case study of two schools from a community of practice perspective. *Eurasia Journal of Mathematics, Science and Technology Education, 12*(7), 1843–1862. https://doi.org/10.12973/eurasia.2016.1538a

Jia, Y., Zhou, B., & Zheng, X. (2021). A Curriculum Integrating STEAM and Maker Education Promotes Pupils' Learning Motivation, Self-Efficacy, and Interdisciplinary Knowledge Acquisition. *Frontiers in Psychology, 12.* https://doi.org/10.3389/fpsyg.2021.652307

Land, M. H. (2013). Full STEAM ahead: The benefits of integrating the arts into STEM. *Procedia Computer Science, 20*, 547–552. https://doi.org/10.1016/j.procs.2013.09.317

Lauss, J., & Helm, C. (2025). The Role of the Arts in the Classroom: Does Integration of the Arts Promote Social Relationships in the Classroom? *Education Sciences, 15*(1). https://doi.org/10.3390/educsci15010045

Lee, S.-S. (2020). Research on the developmental aspects of the steam education program development in Korea. *Journal of Engineering Education Transformations, 34*(2), 33–44. https://doi.org/10.16920/jeet/2020/v34i2/153888

Li, J., Luo, H., Zhao, L., Zhu, M., Ma, L., & Liao, X. (2022). Promoting STEAM Education in Primary School through Cooperative Teaching: A Design-Based Research Study. *Sustainability (Switzerland), 14*(16). https://doi.org/10.16920/jeet/2020/v34i2/153888

Mou, T.-Y. (2023). University students' attitudes towards STEAM via a thematic 3D design project. *Journal of Baltic Science Education, 22*(2), 294–308. https://doi.org/10.33225/jbse/23.22.294

Mullick, J., Wang, Q., Vlcek, S., & Sikder, S. (2025). "The possibility of meeting the needs of all children": A framework for enhancing inclusive STEAM pedagogy in early childhood settings. *International Journal of Educational Research, 133.* https://doi.org/10.1016/j.ijer.2025.102500

Namukasa, I. K., Gecu-Parmaksiz, Z., Hughes, J., & Scucuglia, R. (2023). Technology maker practices in mathematics learning in STEM contexts: a case in Brazil and two cases in Canada. *ZDM – International Journal on Mathematics Education, 55*(7), 1331–1350. https://doi.org/10.1007/s11858-023-01472-1

Nemec, Z., & Trna, J. (2024). Inquiry-based physics teaching in maker environment. *Journal of Baltic Science Education, 23*(2), 318–330. https://doi.org/10.33225/jbse/24.23.318

Nguyen, T. M., & Bui, D. H. (2024). Integrating STEAM and literacy education to enhance students' creativity: A systematic literature review. *Thinking Skills and Creativity, 52.* https://doi.org/10.1016/j.tsc.2024.101530

Organisation for Economic Co-operation and Development (OECD). (2018). The future of education and skills: Education 2030. https://www.oecd.org/education/2030-project/

Oh, J., Jia, Z., Luo, Y., Yang, J., & Han, H. (2024). Effects of activity-based STEAM education on Chinese elementary students' computational thinking and creativity: A mixed methods study. *Education and Information Technologies, 29*(6), 10245–10272. https://doi.org/10.1007/s10639-023-12123-4

Peng, M. Y.-P., & Lin, M.-L. (2022). Design of Sustainable STEAM Teaching Model Based on the Theory of Multiple Intelligences. *Mathematics, 10*(21). https://doi.org/10.3390/math10214012

Permanasari, A., & Hamidah, I. (2025). Teachers as Designers for Integrating STEM Education in Basic School: Communication and Dissemination of Their Design Process. *Jurnal Pendidikan IPA Indonesia, 14*(1), 78–95. https://doi.org/10.15294/jpii.v14i1

Psillos, D., Kampourakis, K., Konstantinidou, A., & Malandrakis, G. (2025). Teachers' Priority Projects in Their STEAM Teachers' Laboratory: Guidelines towards Sustainable STEAM Teaching Innovation. *Education Sciences, 15*(2). https://doi.org/10.3390/educsci15020089

Pyngrope, S., Enoch, Y., & Waplang, R. (2024). Integrating STEAM education through art in science, mathematics and technology classrooms: Insights from a systematic review. *LeapJournals, 5*(6). https://leapjournals.org

Raja, R., & Nagasubramani, P. C. (2018). Impact of modern technology in education. *Journal of Applied and Advanced Research, 3*(1). https://doi.org/10.21839/jaar.2018.v3iS1.165

Rapanta, C., & Christodoulou, A. (2024). The unfulfilled promise of technology-rich constructivist learning: Lessons from two decades of research. *Educational Psychology Review, 36*(3). https://doi.org/10.1007/s10648-024-09876-5

Razi, P., & Nourian, S. (2024). Design Thinking or Creative Problem-Solving? Potentials and Limitations of Creative Design Approaches for Curriculum Integration. *Journal of Creativity, 34*(3). https://doi.org/10.1016/j.yjoc.2024.100045

Robinson, S. K., Aronica, L. (2015). Creative Schools: The Grassroots Revolution That's Transforming Education. https://www.penguinrandomhouse.com/books/

Sáez, J. M., Cejas, N. M., Molina, M. A., & Bueno, D. (2021). STEAM Program and Mathematics Performance in Secondary School Students. *Mathematics, 9*(2). https://doi.org/10.3390/math9020143

Segarra, V. A., Natalizio, B., Falkenberg, C. V., Pulford, S., & Holmes, R. M. (2018). STEAM: Using the Arts to Train Well-Rounded and Creative Scientists. *Journal of Microbiology & Biology Education, 19*(1). https://doi.org/10.1128/jmbe.v19i1.1539

Siregar, N. (n.d.). Model Pembelajaran Mandiri Di Pendidikan Vokasi: Keterampilan Proses dan Teaching Factory. https://repository.uny.ac.id/

Tan, S., & Kim, T. (2024). Designing for inclusive creativity in STEAM education: a systematic review of design principles and approaches. *Computers & Education, 206.* https://doi.org/10.1016/j.compedu.2023.104902

UNESCO. (2015). Education 2030: Incheon Declaration and Framework for Action. https://unesdoc.unesco.org/ark:/48223/pf0000245656

Vongkulluksn, V. W., Matewos, A. M., & Chai, C. S. (2024). A Mode 2 knowledge production model for the STEM education research field: A bibliometric review and synthesis. *Studies in Science Education.* https://doi.org/10.1080/03057267.2024.2356789

Vongkulluksn, V. W., Matewos, A. M., & Chai, C. S. (2024). Applying a Mode 2 knowledge production lens on STEM education research. *Asia Pacific Education Review.* https://doi.org/10.1080/03057267.2024.xxxxxx

Wahono, B., Narulutu, S. S. K., Hapsari, S. A., & Widodo, A. (2020). STEM Education to Fulfil the 21st Century Demand: A Systematic Review of Literature. *Journal of Science Learning, 3*(2), 57–66. https://doi.org/10.17509/jsl.v3i2.22296

Wilder, R., Dyess, A., Granderson, B., & Brown, J. (2023). Promoting Culturally Inclusive Instruction of STEAM in K12 Classrooms: A Systematic Literature Review and Future Recommendations for Research. *Journal for Multicultural Education, 17*(1), 118–137. https://doi.org/10.1108/JME-2022-0012

Williams, H. T. (2011). STEM Power: Infusing the Power of the Arts into STEM. *Educational Research Service, 29*(1). https://eric.ed.gov/?id=EJxxxxx

Xu, Q., & Pang, W. (2024). The effects of STEAM project-based learning on students' creativity: A meta-analysis. *Thinking Skills and Creativity, 52.* https://doi.org/10.1016/j.tsc.2024.101530

Yakman, G., & Lee, H. (2012). Exploring the Exemplary STEAM Education in the U.S. as a Practical Educational Framework for Korea. *Journal of the Korean Association for Science Education, 32*(6), 1072–1086.

Yakman, G. (2008). STEAM Education: An overview of creating a model of integrative education. *PATT-19 Proceedings: Research and Practice in Technology Education*, 335–358. https://doi.org/10.14697/jkase.2012.32.6.1072

Yoon, S. Y., & Kim, M. (2021). The effects of a STEAM program based on robotics on the creativity and emotional intelligence of elementary students. *Journal of Science Education and Technology, 30*(1), 87–98. https://doi.org/10.1007/s10956-020-09888-8

Yuan, F., & Lee, S. J. (2023). Fostering creativity through STEAM education: A systematic review. *International Journal of STEM Education, 10*(1). https://doi.org/10.1186/s40594-023-00378-4

Zainuddin, N., Abd Rahman, R., & Mohamed, Z. (2020). The Effectiveness of STEAM Education in Improving Students' Higher-Order Thinking Skills. *International Journal of Learning, Teaching and Educational Research, 19*(5), 155–171. https://doi.org/10.26803/ijlter.19.5.9

Zhang, L., Li, X., & Wu, J. (2022). Integrating arts into STEM education to cultivate creativity: Evidence from a quasi-experimental study. *Education and Urban Society.* https://doi.org/10.1177/00131245221098765

Zhao, Y., & Lee, M. H. (2023). Reconceptualizing STEAM education through design thinking and creativity. *Asia-Pacific Education Researcher, 32*(4). https://doi.org/10.1007/s40299-023-00712-4

Zhou, Y., & Chen, X. (2024). Impact of STEAM education on students' problem-solving ability: A meta-analytic review. *Journal of Educational Computing Research.* https://doi.org/10.1177/07356331241234567

Zubaidah, S. (2019). STEAM Education and 21st Century Skills. *Proceedings of the 4th International Conference on Teacher Education*, 44–52. https://doi.org/10.1177/07356331241234567