JPPIPA 11(1) (2025)

Jurnal Penelitian Pendidikan IPA

Journal of Research in Science Education

http://jppipa.unram.ac.id/index.php/jppipa/index

Exploring the Relationship Between STEM-Based Learning and TPACK: A Systematic Literature Review

Kinanti Pangestu[1*], Ikhlasul Ardi Nugroho[2], Unik Ambarwati[2], Puji Lestari[1]

[1] Magister Pendidikan Dasar, Fakultas Ilmu Pendidikan dan Psikologi, Universitas Negeri Yogyakarta, Indonesia
[2] Fakultas Ilmu Pendidikan dan Psikologi, Universitas Negeri Yogyakarta, Indonesia

Received: September 09, 2024
Revised: December 03, 2024
Accepted: January 25, 2025
Published: January 31, 2025

Corresponding Author:
Kinanti Pangestu
kinantipangestu.2022@student.uny.ac.id

DOI: 10.29303/jppipa.v11i1.9113

Abstract: This study explores the integration between STEM (Science, Technology, Engineering, and Mathematics) learning and the TPACK (Technological Pedagogical Content Knowledge) framework through a systematic literature review of articles published from 2018 to 2024. The review analyzes 11 Scopus-indexed studies selected using the Publish or Perish (PoP) application and relevant keywords. The findings reveal that the integration of STEM and TPACK positively impacts teacher efficacy and student engagement. This relationship is particularly evident in enhancing teaching practices and fostering students' TPACK skills, as demonstrated in studies utilizing mobile learning systems and workshops for creating electronic sound synthesizers. Factors such as self-efficacy, design thinking, and computational thinking are identified as significant predictors in this integration. The study highlights the potential of combining TPACK with STEM to improve educational outcomes and foster positive attitudes toward STEM among students. Although these findings provide valuable insights, further empirical validation is necessary to confirm the extent of STEM-TPACK integration's impact on teaching and learning. This research contributes to the discourse on advancing STEM education, emphasizing the importance of technology in addressing contemporary educational challenges and preparing learners for the future.

Keywords: Content Knowledge; STEM learning; Technological Pedagogical; TPACK

Introduction

In the education aftermath of a rapidly changing landscape, STEM-based learning — Science, Technology, Engineering, and Mathematics learning — has become an essential approach for nurturing 21st-century skills within students (Gitsaki & Robby, 2015). In addition, this pedagogical strategy is a way of bringing the disciplines that make up STEM more tightly together — it nurtures the critical thinking, creative, and problem solving abilities that represent the main challenges in a world where we walk in the society of the 21st-century(Jazuli, 2021; Selisne et al., 2019). Through this approach, STEM-based learning simulates the experience of working across silos on complex real-world problems, and gives students the tools needed to succeed throughout their future careers (Blake & Liou-Mark, 2014; Mater et al., 2022; Mustafa et al., 2016; Shekhar et al., 2014).

However, a gap remains in understanding how best to integrate STEM education with frameworks that enhance teaching effectiveness. At the heart of this integration is the TPACK framework (Technological Pedagogical Content Knowledge), which combines knowledge of content, pedagogy, and technology to create meaningful and engaging learning experiences ((Hoffmann, 2022; Liu, 2013; Yurdakul et al., 2013). While individual studies have explored STEM-based

How to Cite:
Pangestu, K., Nugroho, I. A., Ambarwati, U., & Lestari, P. (2025). Exploring the Relationship Between STEM-Based Learning and TPACK: A Systematic Literature Review. *Jurnal Penelitian Pendidikan IPA*, *11*(1), 56–64. https://doi.org/10.29303/jppipa.v11i1.9113

learning and TPACK separately, comprehensive insights into their interplay and practical implementation remain underexplored. This study addresses this gap by systematically analyzing literature to highlight the nuances of integrating TPACK into STEM education. The novelty of this research lies in its focus on the practical application of the TPACK framework within STEM contexts and its emphasis on identifying key predictors of successful integration, such as self-efficacy, design thinking, and computational thinking.

STEM (Science, Technology, Engineering, and Mathematics) is a term used to describe a group of scientific disciplines that form the foundation for thinking and research related to science and technology (Gagandeep & Verma, 2023a; Hildt et al., 2024). STEM encompasses the fields of science, technology, engineering, and mathematics.

The STEM-based learning approach aims to integrate concepts from these four fields in a contextual, relevant, and challenging learning environment (Fajrina et al., 2020; Leung, 2019; Smith et al., 2022). Thus, students not only learn about each discipline separately but also develop a more holistic understanding and the ability to think critically, creatively, and innovatively in solving real-world problems (Fajrina et al., 2020; Gagandeep & Verma, 2023; Metpattarahiran, 2021).

The STEM approach emphasizes not only the mastery of subject matter but also the development of skills such as teamwork, problem-solving, analytical thinking, and effective communication (Gagandeep & Verma, 2023b; Pallavi, 2023). This aligns with the demands of the modern workforce, which requires individuals with a strong understanding of science and technology, as well as the ability to adapt to rapid changes and increasing complexity (Ola, 2022; Schmitt & Chan, 2014)

At the heart of effective STEM education is the TPACK framework (Technological Pedagogical Content Knowledge), which is crucial for enhancing teachers' instructional capabilities, particularly in integrating technology into learning environments (Incikabi & Tokmak, 2013a). TPACK provides a comprehensive model that combines knowledge of subject matter, pedagogy, and technology(Liu, 2013; Yurdakul et al., 2013), enabling teachers to create meaningful and engaging learning experiences (Hoffmann, 2022). This framework is especially pertinent in the context of STEM education, where the integration of technology is fundamental to teaching and learning processes.

This study conducts a systematic literature review to analyze articles related to TPACK and STEM, with a focus on the intricate process of implementing TPACK-STEM. The review highlights the development of TPACK instruments and the assessment of teachers' abilities to apply TPACK in STEM education. The findings underscore the multifaceted nature of integrating TPACK with STEM, which involves not only mastering content knowledge but also developing the pedagogical and technological skills necessary for effective teaching.

Moreover, the study emphasizes the importance of integrating various disciplines within STEM, addressing real-world problems, and adopting learner-centered approaches. Effective STEM activities require teamwork, effective communication, iterative redesign, and continuous assessment (Aydin Gunbatar et al., 2022; Cole et al., 2018). These elements are vital for fostering a comprehensive and engaging learning environment that promotes student involvement and achievement.

This research is particularly significant given the increasing demand for teaching strategies that align with rapid technological advancements. By exploring how STEM and TPACK interact, the study highlights pathways for enhancing teacher competencies and fostering student engagement. Furthermore, identifying factors that contribute to effective STEM-TPACK integration can guide the development of targeted professional development programs, ensuring that educators are well-equipped to navigate contemporary educational challenges. This study not only bridges theoretical and practical perspectives but also contributes to a deeper understanding of how to prepare educators and students for a future shaped by science and technology.

Method

This research is literature research with the Systematic Review method or commonly called Systematic Literature Review (SLR), which is a systematic technique for collecting, critically examining, integrating and collecting the results of various studies to find answers to specific research questions (Moher et al., 2016). The study commenced by identifying articles relevant to the research topic through a synthesis study process. Literature searches were conducted using electronic databases, including Scopus and Google Scholar, with the assistance of the Publish or Perish (PoP) application. Search terms were carefully selected based on keywords pertinent to the research variables, specifically "STEM learning" and "TPACK."

Articles deemed relevant were identified and selected through a filtering process based on several criteria. These criteria included articles published in Scopus-accredited journals or international conferences with full-text availability; publication years ranging from 2018 to 2024; a focus on STEM learning and

TPACK; articles written in English; publication in Scopus; and accessibility for review.

The search yielded 11 articles that met these criteria and were deemed suitable for the systematic review. These articles provide an in-depth analysis of STEM learning and TPACK, offering a foundation for exploring the integration of these concepts within educational contexts. The process flow chart illustrating the research steps on Figure 1.

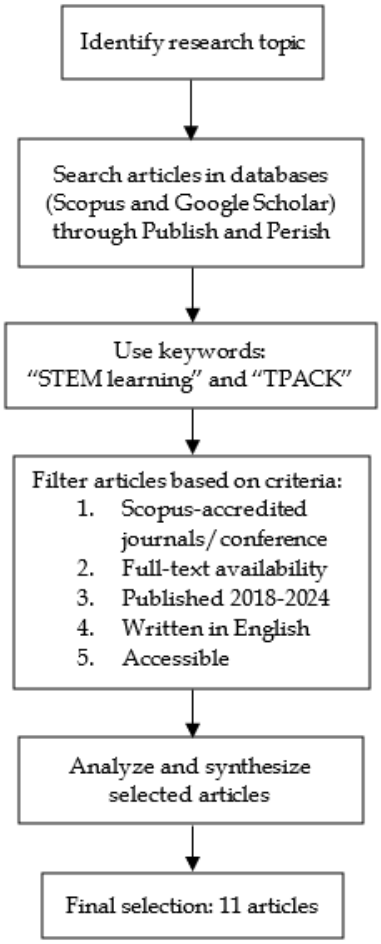

Figure 1. The Research Steps

Result and Discussion

The Study Result

The review of 23 articles resulted in 11 studies meeting the specified criteria for inclusion. These articles explore various aspects of integrating Technological Pedagogical Content Knowledge (TPACK) into STEM education, with a focus on teacher development, innovative teaching strategies, and student outcomes. Key findings include the effectiveness of STEM-TPACK design-based learning in preparing teachers to integrate technology, the value of personalized mobile learning systems for enhancing TPACK, and the critical role of frameworks like ISLE-based STEM approaches in supporting technology integration.

Several studies on Table 1, emphasize the predictors and factors influencing TPACK development. For instance, science teaching self-efficacy, computational thinking, and design thinking are identified as key contributors to TPACK in integrated STEM education. Additionally, adaptive online courses and coding activities are highlighted for improving preservice teachers' pedagogical approaches and technological knowledge. These findings underline the importance of tailored training and tools to foster teacher readiness and confidence in implementing STEM-TPACK.

The articles also explore the broader implications of TPACK in professional development and STEM education. Long-term studies reveal the importance of sustaining teacher learning through frameworks like TPACK, with lessons drawn from multi-year professional development programs. The research underscores the need for ongoing support and resources to ensure teachers can effectively integrate technology and pedagogy, preparing them to meet the demands of modern STEM education.

Table 1. Articles obtained from Scopus

Author & Year	Title	Results
(Chai, 2019)	Teacher Professional Development for Science, Technology, Engineering and Mathematics (STEM) Education: A Review from the Perspectives of Technological Pedagogical Content (TPACK)	This article provides rich insights into the professional development of teachers in STEM education and highlights the importance of TPACK in preparing teachers to meet the complex demands of teaching in the technological era
(Chai et al., 2020)	Indonesian science, mathematics, and engineering preservice teachers' experiences in stem-tpack design-based learning	The article concludes that STEM-TPACK design-based learning can provide valuable experiences for prospective STEM teachers in developing the skills and knowledge necessary to integrate technology into their teaching.
(Chai et al., 2020a)	Surveying Chinese teachers' technological pedagogical STEM knowledge: A pilot validation of STEM-TPACK survey	The findings from the pilot study indicate that the STEM-TPACK survey demonstrates adequate reliability and validity in assessing the technological pedagogical knowledge of Chinese teachers. The authors discuss the

Author & Year	Title	Results
		implications of this study, emphasizing the importance of understanding teachers' TPACK for effective technology integration in STEM education.
(Kajonmanee et al., 2020)	A personalised mobile learning system for promoting STEM discipline teachers' TPACK development	This article presents the development and implementation of a personalized mobile learning system to enhance the development of STEM discipline teachers' TPACK. The study demonstrates the system's effectiveness in improving teachers' knowledge and skills in integrating technology in STEM education. These findings contribute to the understanding of innovative approaches to support the professional growth of STEM teachers.
(Purwaningsih et al., 2020)	Improving the problem-solving skills through the development of teaching materials with STEM-PjBL (science, technology, engineering, and mathematics-project based learning) model integrated with TPACK (technological pedagogical content knowledge)	The article underscores the importance of integrating the STEM-PjBL model with TPACK in enhancing students' problem-solving abilities. It highlights the potential of this integrated approach to promote critical thinking, collaboration, and technological competence, thus preparing students to face the challenges of the STEM field and the digital era.
(Durak et al., 2023)	Examining the predictors of TPACK for integrated STEM: Science teaching self-efficacy, computational thinking, and design thinking	This article investigates predictors of TPACK for integrated STEM education, with a specific focus on science teaching efficacy, computational thinking, and design thinking. The findings indicate that these factors play a crucial role in shaping educators' TPACK, emphasizing the importance of considering these predictors in teacher education and professional development initiatives in the STEM field.
(Umutlu, 2022)	TPACK leveraged: A redesigned online educational technology course for STEM preservice teachers	The research of this article are: 1. Redesigned online course enhanced preservice STEM teachers' pedagogical approaches. 2. Hands-on coding improved technological knowledge and lesson design integration. Study offers design implications for online teacher education courses.
(Sari et al., 2021)	Analysis TPACK framework in ISLE-based STEM approach model: Case study	This article provides valuable insights into the use and effectiveness of the TPACK Framework in supporting the integration of technology, pedagogy, and content knowledge in STEM education. The findings contribute to understanding how the TPACK Framework can be applied in ISLE-based STEM approaches and provide information for teacher training and professional development programs in STEM education.
(Meletiou-Mavrotheris & Paparistodemou, 2024)	Sustaining Teacher Professional Learning in STEM: Lessons Learned from an 18-Year-Long Journey into TPACK-Guided Professional Development	This article discusses the professional development of STEM/STEAM teachers, where mathematics is also an integral part of the approach. In the article, researchers explain how they implemented the TPACK framework in the context of mathematics learning enhanced by ICT. They describe their journey in conceptualizing and applying TPACK in the professional development of STEM/STEAM teachers, which includes mathematics as an essential component. Therefore, the article connects STEM with TPACK in the context of professional development for teachers in these fields.
(Chen & Tse, 2023)	A Survey of Pre-service and In-service Biology Teachers' Technological Pedagogical Content Knowledge (TPACK) in Implementing STEM Education	The article explains that the study aimed to examine the level of Technological Pedagogical Content Knowledge (TPACK) of biology teachers in implementing STEM education. In the article, the research used the STEM-TPACK framework to assess the readiness of biology teachers in integrating technological, pedagogical, and content knowledge in the context of STEM education.

Author & Year	Title	Results
(Mangundu, 2023)	STEM Preservice Teachers' e-Readiness for Online Multimodal Teaching Methods Usage in Pietermaritzburg, South Africa: Analysis Through the Adapted TPACK Framework	In the context of this research, TPACK is one of the factors influencing the readiness of preservice STEM teachers in using multimodal online teaching methods. The article explains that preservice STEM teachers need to have confidence in using multimodal online resources and the right technological pedagogical content knowledge to integrate STEM with online teaching.

The Implementation of STEM-TPACK in Education

The implementation of STEM (Science, Technology, Engineering, and Mathematics) within the context of TPACK (Technological, Pedagogical, and Content Knowledge) requires synergy among the key components of learning: content, pedagogy, and technology, to create meaningful learning experiences (Azaahra et al., 2024; Chai, Rahmawati, et al., 2020; Silva et al., 2021). This approach is crucial in STEM-based learning that focuses on solving real-world problems and equipping students with 21st-century skills (Arslan & Genc, 2024; Fajrina et al., 2020a) .

The STEM-TPACK Approach

The STEM TPACK approach involves comprehensive integration of content, pedagogy, and technology (Arslan & Genc, 2024; Incikabi & Tokmak, 2013b; Niess, 2018). Content emphasizes an in-depth understanding of the disciplines of science, technology, engineering, and mathematics(ZAN & Asrizal, 2024). Pedagogy focuses on effective teaching strategies that foster student engagement and active participation (Putra et al., 2021). Technology encompasses tools and digital platforms that facilitate and enhance the learning process (Nazifah & Asrizal, 2022; Putra et al., 2021). Through this approach, teachers are encouraged to address students' individual needs by providing project- or problem-based learning opportunities. They can also design learning experiences relevant to real-life situations using technology-based simulations or experiments, thereby building students' technological literacy and critical thinking skills (Azhar et al., 2022; ZAN & Asrizal, 2024).

Challenges in Implementing STEM-TPACK

Despite its potential, implementing STEM TPACK presents significant challenges. Pedagogical challenges arise from teachers' perceived unpreparedness to integrate STEM pedagogy. Concerns about the reduction of fundamental science concepts during STEM integration, difficulties in meeting diverse student learning needs, and inadequate pedagogical infrastructure further complicate this issue. Additionally, curriculum challenges emerge as the integrated nature of STEM curricula often makes them rigid and difficult to adapt. Teachers frequently struggle to align interdisciplinary domains, such as Biology and Geometry, while maintaining coherence in content delivery.

Structural challenges also hinder implementation. School policies and organizational structures often restrict the time and resources allocated to STEM learning. Issues such as insufficient infrastructure and frequent curriculum revisions exacerbate these limitations. Furthermore, student-related challenges include motivational and ability-related barriers, with teachers sometimes underestimating students' problem-solving capabilities, which can undermine their enthusiasm for learning. Assessment challenges also persist, as the lack of reliable evaluation tools makes it difficult for teachers to accurately measure students' STEM performance. The debate between individual versus group evaluation methods adds another layer of complexity.

Teachers face additional burdens related to support, including designing STEM curricula, managing extra preparation time for STEM pedagogy, and meeting high expectations from schools and policymakers. The integration of technology is often impeded by the unavailability of adequate devices in schools and insufficient technical training for teachers. Local contexts further impact implementation, as resource constraints in remote areas and cultural differences in defining STEM priorities create unique obstacles.

Evidence of STEM-TPACK Integration Impact

Research underscores the positive relationship between STEM and the TPACK framework. For instance, Chai, Jong, et al., (2020b) highlighted the importance of integrating STEM education with the TPACK framework for teacher professional development. Their study demonstrated that TPACK factors predict teachers' efficacy in implementing STEM education, particularly in fostering integrative STEM efficacy. Similarly, Chai, Rahmawati, et al., (2020) found that preservice teachers with STEM experience exhibited higher efficacy in TPACK knowledge, further

supporting the link between STEM education and teacher professional growth.

Additional studies have reinforced these findings. Chai, (2019) provided rich insights into the professional development of teachers in STEM education, emphasizing the importance of TPACK in addressing the complex demands of modern teaching. Kajonmanee et al., (2020) demonstrated the effectiveness of a personalized mobile learning system in enhancing STEM teachers' TPACK, contributing to innovative approaches for professional growth. (Purwaningsih et al., (2020)underscored the integration of the STEM-PjBL model with TPACK in improving students' problem-solving skills, fostering critical thinking, collaboration, and technological competence.

Durak et al., (2023) identified critical predictors of TPACK for integrated STEM, such as science teaching self-efficacy, computational thinking, and design thinking. This highlights the importance of considering these factors in professional development initiatives. Meanwhile, Umutlu (2022) showed how a redesigned online course leveraging TPACK enhanced preservice STEM teachers' pedagogical approaches and technological integration.

Furthermore, Sari et al. (2021) examined the application of the TPACK framework in ISLE-based STEM approaches, providing insights into its effectiveness in teacher training and professional development. Meletiou-Mavrotheris & Paparistodemou (2024) discussed their 18-year journey in applying TPACK for STEM/STEAM teacher professional development, connecting mathematics and ICT in the process. Chen & Tse (2023)evaluated biology teachers' TPACK readiness for STEM education, emphasizing the importance of integrated technological, pedagogical, and content knowledge. Lastly, Mangundu (2023) analyzed preservice STEM teachers' e-readiness for online multimodal teaching using an adapted TPACK framework, stressing the role of confidence and technological competence.

The integration of STEM and the TPACK framework offers promising avenues for advancing teacher efficacy and student engagement. By addressing challenges through innovative pedagogies, professional development, and infrastructure improvement, educators can create effective, relevant, and meaningful STEM learning experiences. While existing research highlights the benefits of STEM-TPACK integration, further empirical studies are necessary to fully establish its impact on both teacher efficacy and student outcomes, ensuring sustainable progress in STEM education.

Conclusion

The literature review concludes that integrating STEM (Science, Technology, Engineering, and Mathematics) with the TPACK (Technological Pedagogical Content Knowledge) framework positively impacts teacher efficacy and student engagement. This integration enhances teaching effectiveness and fosters student learning outcomes, particularly through factors such as self-efficacy, design thinking, and computational thinking. While further empirical validation is necessary, the findings highlight the potential of STEM-TPACK integration in addressing contemporary educational challenges and improving STEM education.

Acknowledgments
This research was funded by the LPDP RI (Lembaga Pengelolaan Dana Pendidikan Republik Indonesia). We gratefully acknowledge their financial support, which made this study possible.

Author Contributions
Conceptualization, original draft preparation, analysis: K.P.; Conceptualization, supervision, review writing: I.A.N.; Journal resources, methodology: U.A.; Translation into English, formatting into template: P.L. All authors have read and agreed to the published version of the manuscript.

Funding
The APC was funded by LPDP RI (Lembaga Pengelolaan Dana Pendidikan Republik Indonesia).

Conflicts of Interest
The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results

References

Arslan, H. O., & Genc, M. (2024). The stem education approach for conceptual learning. In *Transdisciplinary Approaches to Learning Outcomes in Higher Education*. https://doi.org/10.4018/979-8-3693-3699-1.ch002

Aydin Gunbatar, S., Ekiz Kiran, B., Boz, Y., & Roehrig, G. H. (2022). A closer examination of the STEM characteristics of the STEM activities published in NSTA journals. *Research in Science and Technological Education*. https://doi.org/10.1080/02635143.2022.2121692

Azaahra, R., Rahmawati, Y., & Yusmaniar. (2024). An Analysis of Preservice Chemistry Teachers' Competences in Designing STEM-TPACK Learning. *AIP Conference Proceedings*, *2982*(1). https://doi.org/10.1063/5.0182982

Azhar, A., Irawan, D., & Ramadhan, K. (2022). STEM Education Implementation to Enhance Student Learning Outcomes in Optics Concept. *Jurnal Penelitian Pendidikan IPA*, *8*(2), 1023–1029. https://doi.org/10.29303/jppipa.v8i2.1525

Blake, R. A., & Liou-Mark, J. (2014). Enhancing diversity in STEM interdisciplinary learning. In *STEM Education: Concepts, Methodologies, Tools, and Applications* (Vols. 2–3). https://doi.org/10.4018/978-1-4666-7363-2.ch054

Chai, C. S. (2019). Teacher Professional Development for Science, Technology, Engineering and Mathematics (STEM) Education: A Review from the Perspectives of Technological Pedagogical Content (TPACK). *Asia-Pacific Education Researcher*, *28*(1), 5–13. https://doi.org/10.1007/S40299-018-0400-7/METRICS

Chai, C. S., Jong, M., & Yan, Z. (2020a). Surveying Chinese teachers' technological pedagogical STEM knowledge: A pilot validation of STEM-TPACK survey. *International Journal of Mobile Learning and Organisation*, *14*(2), 203–214. https://doi.org/10.1504/IJMLO.2020.106181

Chai, C. S., Jong, M., & Yan, Z. (2020b). Surveying Chinese teachers' technological pedagogical STEM knowledge: A pilot validation of STEM-TPACK survey. *International Journal of Mobile Learning and Organisation*, *14*(2), 203–214. https://doi.org/10.1504/IJMLO.2020.106181

Chai, C. S., Rahmawati, Y., & Jong, M. S. Y. (2020). Indonesian Science, Mathematics, and Engineering Preservice Teachers' Experiences in STEM-TPACK Design-Based Learning. *Sustainability 2020, Vol. 12, Page 9050*, *12*(21), 9050. https://doi.org/10.3390/SU12219050

Chen, F., & Tse, A. W. C. (2023). A Survey of Pre-service and In-service Biology Teachers' Technological Pedagogical Content Knowledge (TPACK) in Implementing STEM Education. *ACM International Conference Proceeding Series*, 489–494. https://doi.org/10.1145/3629296.3629374

Cole, R., Lantz, J. M., Ruder, S., Reynders, G. J., & Stanford, C. (2018). Enhancing learning by assessing more than content knowledge. *ASEE Annual Conference and Exposition, Conference Proceedings*, *2018-June*.

Durak, H. Y., Uslu, N. A., Bilici, S. C., & 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/TABLES/7

Fajrina, S., Lufri, L., & Ahda, Y. (2020a). Science, technology, engineering, and mathematics (STEM) as a learning approach to improve 21st century skills: A review. *International Journal of Online and Biomedical Engineering*, *16*(7), 95–104. https://doi.org/10.3991/ijoe.v16i07.14101

Fajrina, S., Lufri, L., & Ahda, Y. (2020b). Science, technology, engineering, and mathematics (STEM) as a learning approach to improve 21st century skills: A review. *International Journal of Online and Biomedical Engineering*, *16*(7), 95–104. https://doi.org/10.3991/ijoe.v16i07.14101

Gagandeep, & Verma, J. (2023a). Analyzing meta-cognitive and critical thinking to develop skills and re-skills for STEM literacy. In *STEM: A Multi-Disciplinary Approach to Integrate Pedagogies, Inculcate Innovations and Connections*.

Gagandeep, & Verma, J. (2023b). Analyzing meta-cognitive and critical thinking to develop skills and re-skills for STEM literacy. In *STEM: A Multi-Disciplinary Approach to Integrate Pedagogies, Inculcate Innovations and Connections*.

Gitsaki, C., & Robby, M. A. (2015). Evaluating the use of mobile technology in math education: A case study. In *Mobile Learning and STEM: Case Studies in Practice*. https://doi.org/10.4324/9781315745831-4

Hildt, E., Laas, K., Miller, C. Z., & Brey, E. M. (2024). Building Inclusive Ethical Cultures in STEM. In *International Library of Ethics, Law and Technology* (Vol. 42). https://doi.org/10.1007/978-3-031-51560-6_1

Hoffmann, M. M. (2022). Creating teacher leaders through early teacher support. In *Handbook of Research on the Educator Continuum and Development of Teachers*. https://doi.org/10.4018/978-1-6684-3848-0.ch024

Incikabi, L., & Tokmak, H. S. (2013a). Integrating technology into mathematics teaching: A TPACK (technological, pedagogical, content knowledge)-based course design for college students. In *Research Perspectives and Best Practices in Educational Technology Integration*. https://doi.org/10.4018/978-1-4666-2988-2.ch015

Incikabi, L., & Tokmak, H. S. (2013b). Integrating technology into mathematics teaching: A TPACK (technological, pedagogical, content knowledge)-based course design for college students. In *Research Perspectives and Best Practices in Educational Technology Integration*. https://doi.org/10.4018/978-1-4666-2988-2.ch015

Jazuli, A. (2021). Reviving the role of mathematics in science through STEM. *Journal of Physics: Conference Series*, *1778*(1). https://doi.org/10.1088/1742-6596/1778/1/012031

Kajonmanee, T., Chaipidech, P., Srisawasdi, N., & Chaipah, K. (2020). A personalised mobile learning system for promoting STEM discipline teachers' TPACK development. *International Journal of Mobile Learning and Organisation*, *14*(2), 215–235. https://doi.org/10.1504/IJMLO.2020.106186

Leung, A. (2019). Exploring STEM Pedagogy in the Mathematics Classroom: a Tool-Based Experiment Lesson on Estimation. *International Journal of Science and Mathematics Education*, *17*(7), 1339–1358. https://doi.org/10.1007/s10763-018-9924-9

Liu, S.-H. (2013). Exploring the instructional strategies of elementary school teachers when developing technological, pedagogical, and content knowledge via a collaborative professional development program. *International Education Studies*, *6*(11), 58–68. https://doi.org/10.5539/ies.v6n11p58

Mangundu, J. (2023). STEM Preservice Teachers' e-Readiness for Online Multimodal Teaching Methods Usage in Pietermaritzburg, South Africa: Analysis Through the Adapted TPACK Framework. *African Journal of Research in Mathematics, Science and Technology Education*, *27*(2), 137–154. https://doi.org/10.1080/18117295.2023.2232667

Mater, N. R., Haj Hussein, M. J., Salha, S. H., Draidi, F. R., Shaqour, A. Z., Qatanani, N., & Affouneh, S. (2022). The effect of the integration of STEM on critical thinking and technology acceptance model. *Educational Studies*, *48*(5), 642–658. https://doi.org/10.1080/03055698.2020.1793736

Meletiou-Mavrotheris, M., & Paparistodemou, E. (2024). Sustaining Teacher Professional Learning in STEM: Lessons Learned from an 18-Year-Long Journey into TPACK-Guided Professional Development. *Education Sciences 2024, Vol. 14, Page 402*, *14*(4), 402. https://doi.org/10.3390/EDUCSCI14040402

Metpattarahiran, C. (2021). STEM Education for Developing Undergraduates' 21st Century Skills. *Journal of Multidisciplinary in Social Sciences*, *17*(3), 82–87.

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L. A., Estarli, M., Barrera, E. S. A., Martínez-Rodríguez, R., Baladia, E., Agüero, S. D., Camacho, S., Buhring, K., Herrero-López, A., Gil-González, D. M., Altman, D. G., Booth, A., … Whitlock, E. (2016). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Revista Espanola de Nutricion Humana y Dietetica*. https://doi.org/10.1186/2046-4053-4-1

Mustafa, N., Ismail, Z., Tasir, Z., & Mohamad Said, M. N. H. (2016). A meta-analysis on effective strategies for integrated STEM education. *Advanced Science Letters*, *22*(12), 4225–4288. https://doi.org/10.1166/asl.2016.8111

Nazifah, N., & Asrizal, A. (2022). Development of STEM Integrated Physics E-Modules to Improve 21st Century Skills of Students. *Jurnal Penelitian Pendidikan IPA*, *8*(4), 2078–2084. https://doi.org/10.29303/jppipa.v8i4.1820

Niess, M. L. (2018). Introduction to teachers' knowledge-of-practice for teaching with digital technologies: A technological pedagogical content knowledge (TPACK) framework. In *Teacher Training and Professional Development: Concepts, Methodologies, Tools, and Applications* (Vol. 1). https://doi.org/10.4018/978-1-5225-5631-2.ch07

Ola, D. E. (2022). Pace of technology changes, need for adaptation, and demand for skills: Skills adaptation for quickly evolving technology-based workplaces. In *Sustainability and the Future of Work and Entrepreneurship for the Underserved*. https://doi.org/10.4018/978-1-6684-4322-4.ch019

Pallavi, N. (2023). The application of meta-cognitive, critical thinking, collaborative, cooperative and skill based learning strategies in STEM. In *STEM: A Multi-Disciplinary Approach to Integrate Pedagogies, Inculcate Innovations and Connections*.

Purwaningsih, E., Sari, A. M., Yuliati, L., Masjkur, K., Kurniawan, B. R., & Zahiri, M. A. (2020). Improving the problem-solving skills through the development of teaching materials with STEM-PjBL (science, technology, engineering, and mathematics-project based learning) model integrated with TPACK (technological pedagogical content knowledge). *Journal of Physics: Conference Series*, *1481*(1), 012133. https://doi.org/10.1088/1742-6596/1481/1/012133

Putra, P. D. A., Ahmad, N., Wahyuni, S., & Narulita, E. (2021). Analysis of the Factors Influencing of Pre-service Science Teacher in Conceptualization of STEM Education: Self-Efficacy and Content Knowledge. *Jurnal Penelitian Pendidikan IPA*, *7*(SpecialIssue), 225–230. https://doi.org/10.29303/jppipa.v7ispecialissue.877

Sari, I. M., Yusibani, E., Irwandi, I., Sofyan, H., & Suherman. (2021). Analysis TPACK framework in ISLE-based STEM approach model: case study. *Journal of Physics: Conference Series*, *1882*(1), 012147. https://doi.org/10.1088/1742-6596/1882/1/012147

Schmitt, N., & Chan, D. (2014). Adapting to rapid changes at work definitions, measures and research. In *Individual Adaptability to Changes at Work: New Directions in Research*. https://doi.org/10.4324/9780203465721-11

Selisne, M., Sari, Y. S., & Ramli, R. (2019). Role of learning module in STEM approach to achieve competence of physics learning. *Journal of Physics: Conference Series*, *1185*(1). https://doi.org/10.1088/1742-6596/1185/1/012100

Shekhar, S., Caglar, F., Dukeman, A., Hou, L., Gokhale, A., Kinnebrew, J. S., & Biswas, G. (2014). A collaborative K-12 STEM education framework using traffic flow as a real-world challenge problem. *ASEE Annual Conference and Exposition, Conference Proceedings*.

Silva, R., Costa, C., & Martins, F. (2021). Using Mathematical Modelling and Virtual Manipulatives to Teach Elementary Mathematics. In *Communications in Computer and Information Science: Vol. 1384 CCIS*. https://doi.org/10.1007/978-3-030-73988-1_6

Smith, K., Maynard, N., Berry, A., Stephenson, T., Spiteri, T., Corrigan, D., Mansfield, J., Ellerton, P., & Smith, T. (2022). Principles of Problem-Based Learning (PBL) in STEM Education: Using Expert Wisdom and Research to Frame Educational Practice. *Education Sciences*, *12*(10). https://doi.org/10.3390/educsci12100728

Umutlu, D. (2022). TPACK leveraged: A redesigned online educational technology course for STEM preservice teachers. *Australasian Journal of Educational Technology*, *38*(3), 104–121. https://doi.org/10.14742/AJET.4773

Yurdakul, I. K., Ferhan Odabasi, H., Sahin, Y. L., & Coklar, A. N. (2013). A TPACK course for developing pre-service teachers' technology integration competencies: From design and application to evaluation. In *Research Perspectives and Best Practices in Educational Technology Integration*. https://doi.org/10.4018/978-1-4666-2988-2.ch013

ZAN, A. maharani, & Asrizal. (2024). Development of Ethno-STEM Integrated Digital Teaching Material with Augmented Reality to Promote Students' 21st Century Skills. *Jurnal Penelitian Pendidikan IPA*, *10*(9), 6798–6808. https://doi.org/10.29303/jppipa.v10i9.8249