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Advancing SDG 4 Through TPACK in Chemistry Education: A Systematic Literature Review

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Abstract: This systematic literature review examines the implementation of Technological Pedagogical Content Knowledge (TPACK) in chemistry education in the post-pandemic learning context, with particular relevance to the advancement of Sustainable Development Goal 4 (SDG 4) on quality education. The study aims to identify how TPACK has been implemented in chemistry learning and to analyze its effectiveness and efficiency. The review followed PRISMA guidelines and analyzed eight empirical articles published between 2022 and 2024 from Garuda, ERIC, Taylor & Francis Online, and ScienceDirect. The findings show that TPACK implementation in chemistry education mainly involves the integration of technological, pedagogical, and content knowledge through digital tools such as simulations, web-based learning, flipped learning, and virtual platforms. Most studies focused on pre-service and in-service chemistry teachers, emphasizing the development of TPACK competencies and technology-supported instructional practices. The review indicates that TPACK contributes to more interactive, flexible, and meaningful chemistry learning, particularly in explaining abstract chemical concepts and improving student engagement and learning performance. In conclusion, TPACK plays an important role in supporting quality chemistry education and may contribute to the advancement of SDG 4, provided that its implementation is supported by adequate infrastructure, continuous professional development, and institutional commitment.

Keywords: Chemistry learning; SDG 4; Systematic literature review; TPACK

Introduction

The COVID-19 pandemic has accelerated the innovation and integration of technology in education. The global education landscape has experienced substantial changes, marked by a major shift from traditional face-to-face learning to online and technology-supported learning formats (Rathert & Ağçam, 2022; Hodges et al., 2024). Since the onset of the pandemic, the use of modern information and communication technology has become essential, either partially or fully, in the learning process (Alfalah, 2023). Teachers are now expected to continuously innovate in leveraging technology to create more engaging and meaningful learning opportunities for students (Xue et al., 2024; Salas-Rueda & Alvarado-Zamorano, 2024). However, these transformations also pose particular challenges in subjects such as chemistry, which often require practical activities and involve abstract and multi-representational concepts.

The use of technology in chemistry education continues to evolve through various innovations, such as hologram-based educational video games for chemistry practicums (Liesatyadharma et al., 2022), virtual reality applications (Viitaharju et al., 2023), and flipped classroom models (Anand, 2021). These developments encourage teachers to continuously improve their ability to integrate technology into the learning process. Nevertheless, technological innovation alone is not sufficient to support effective chemistry learning. Teachers must also apply appropriate pedagogical strategies (Su, 2023) and align them with chemistry content and students' learning needs. This condition is closely related to the Technological

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Pedagogical Content Knowledge (TPACK) framework introduced by Koehler (2006).

The TPACK framework in chemistry education is not only a pedagogical necessity but also a strategic response to maintain the continuity and quality of learning in the context of digital transformation. Chemistry, as a discipline characterized by complex, abstract, and representational concepts, can benefit greatly from TPACK because this framework enables teachers to combine appropriate technological tools, meaningful chemistry content, and effective instructional strategies. Recent studies continue to show that TPACK remains highly relevant for strengthening teachers' capacity to integrate technology meaningfully in science and chemistry-related learning contexts, particularly in response to contemporary instructional demands and rapidly evolving digital environments (Nugraheni & Srisawasdi, 2025; Čipková et al., 2024; Shambare & Jita, 2024). In addition, the integration of TPACK in chemistry education is relevant to the advancement of Sustainable Development Goal 4 (SDG 4), particularly in promoting quality education through effective, adaptive, and technology-enhanced learning environments. Current research also highlights that technology integration, digital competence, and sustainable educational practice are increasingly interconnected in efforts to improve the quality, inclusiveness, and responsiveness of education (Zaman & Anwar, 2024; Peña-Martínez et al., 2025). Therefore, examining the implementation of TPACK in chemistry education is important for understanding how quality learning can be strengthened in contemporary educational settings.

TPACK consists of three primary domains of teacher knowledge, namely Technological Knowledge (TK), Pedagogical Knowledge (PK), and Content Knowledge (CK), which interact to support effective teaching in technology-integrated learning environments (Koehler, 2006; Karpudewan, 2024; Kosiol & Ufer, 2024). However, the essence of TPACK lies not only in these three domains individually, but also in the intersections among them. Pedagogical Content Knowledge (PCK) refers to the teacher's understanding of how specific chemistry content can be taught effectively. Technological Content Knowledge (TCK) refers to knowledge of how technology can be used to represent and transform chemistry content or chemical concepts. Technological Pedagogical Knowledge (TPK) refers to knowledge of how teaching and learning processes can be adapted and enhanced through technology. The integration of all these domains is reflected in TPACK, which represents a teacher's ability to design meaningful learning by aligning technology, pedagogy, and chemistry content in a coherent manner. This integration is highly relevant in chemistry education because teachers must not only master chemistry content, but also determine appropriate teaching strategies and technological tools to facilitate students' understanding.

The relevance of TPACK in chemistry education has become increasingly significant in the modern educational landscape because of the rapid development of digital technology, especially information and communication technology (O'Connor et al., 2023; Srisawasdi, 2012). However, although many studies have examined TPACK in different educational contexts, a focused synthesis of empirical evidence regarding its implementation and effectiveness specifically in post-pandemic chemistry education remains limited. Existing studies are still scattered across different contexts, participants, and instructional designs, making it difficult to identify overall patterns, dominant practices, and the reported effectiveness and efficiency of TPACK-based chemistry learning. This condition indicates the need for a systematic synthesis of recent studies in order to provide a clearer and more evidence-based understanding of the role of TPACK in chemistry education.

Accordingly, this study is important for two main reasons. First, chemistry education requires instructional approaches that can help learners understand abstract chemical concepts through appropriate representations, pedagogy, and technological support. Second, the rapid digital transformation of education has created an urgent need for evidence-based guidance for teachers, teacher educators, and researchers regarding effective technology integration in chemistry classrooms. The novelty of this study lies in its specific focus on empirical studies of TPACK implementation in chemistry education published between 2022 and 2024, particularly in the post-pandemic context, as well as its synthesis of both implementation patterns and the reported effectiveness and efficiency of TPACK-based chemistry learning. Therefore, this study conducts a Systematic Literature Review (SLR) to provide insight into effective practices, emerging trends, and research gaps in the field. Specifically, this systematic literature review addresses the following research questions: How is TPACK implemented in chemistry education? How effective and efficient is chemistry learning with the TPACK approach?

Method

This study employed a Systematic Literature Review (SLR) guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Kitchenham & Charters, 2007; Moher et al., 2010). The review was conducted in four stages: defining the inclusion and exclusion criteria, identifying the data sources and search strategy, assessing the quality of the selected studies, and coding and analyzing the data. The SLR approach was adopted to identify, evaluate, and synthesize relevant empirical studies on the implementation of TPACK in chemistry education. This method was selected because it offers a structured and transparent procedure for answering specific research questions based on recent empirical evidence (Moreira et al., 2024).

Inclusion/Exclusion Criteria

Articles that meet the inclusion and exclusion criteria listed in Table 1 will be analyzed for review research. This stage is carried out to decide whether the data found is suitable for use in SLR research or not.

Table 1. Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Primary empirical studies.	Non-empirical studies, such as conceptual papers, review papers, discussion papers, and opinion papers.
Peer-reviewed full text journal articles.	Conference papers, abstracts, dissertations, books, book chapters, and grey literature.
Studies specifically related to TPACK in chemistry education.	Studies not related to TPACK in chemistry education.
Articles published between 2022-2024.	Publications outside the specified year range.

The literature search was conducted in four databases, namely ScienceDirect, Garuda, Taylor & Francis Online, and ERIC, to identify empirical studies related to TPACK in chemistry education published between 2022 and 2024. The search was performed using the keywords “TPACK” OR “TPCK” AND “Chemistry education” OR “Chemistry learning” OR “Chemistry teaching.” These keywords were selected to ensure that the search focused on the educational context of chemistry rather than on chemical substances or materials.

Data Source and Search Strategies

The literature search was conducted in four databases, namely ScienceDirect, Garuda, Taylor & Francis Online, and ERIC, to identify empirical studies related to TPACK in chemistry education published between 2022 and 2024. The search was performed using the keywords “TPACK” OR “TPCK” AND “Chemistry education” OR “Chemistry learning” OR “Chemistry teaching.” These keywords were selected to ensure that the search focused on the educational context of chemistry rather than on chemical substances or materials.

Table 2. Initial records identified across databases

Database	Count
Science Direct	174
Garuda	520
Taylor and Francis Online	267
Eric Journal	247
Result	1.208

The databases selected represent a diverse range of high-quality academic resources, ensuring comprehensive coverage of international and regional research publications. The search strategy involved the use of specific keywords related to TPACK and chemistry education to maximize the relevance of the articles retrieved. The initial search yielded 1,208 articles, indicating a high level of research activity in this field. However, stringent application of inclusion and exclusion criteria was necessary to filter out studies that did not meet the empirical focus or contextual relevance required for this systematic review. This rigorous selection process underscores the commitment to synthesizing only the most pertinent and high-quality evidence available.

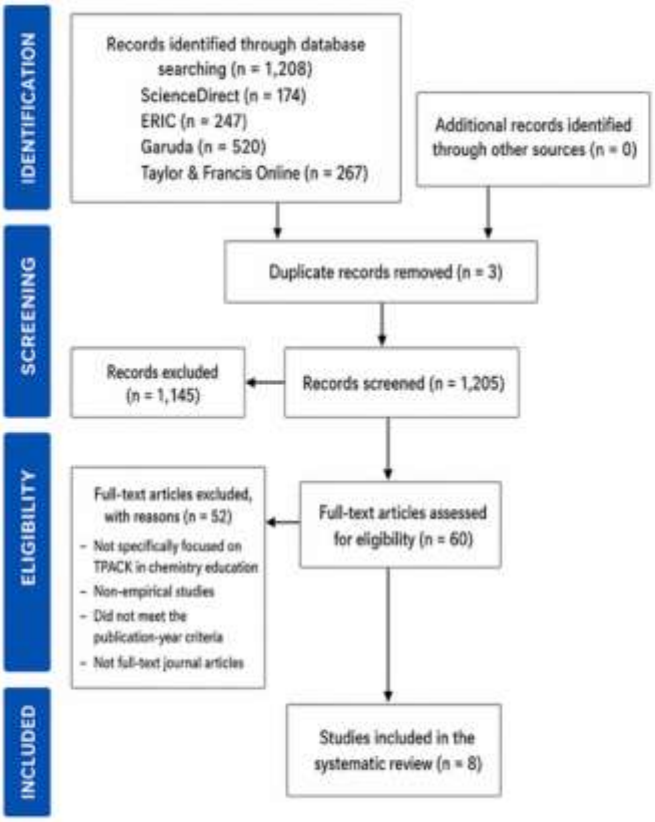

Figure 1. PRISMA flow diagram

The initial search identified 1,208 records across four databases, consisting of 174 records from ScienceDirect, 520 from Garuda, 267 from Taylor & Francis Online, and 247 from ERIC. No additional records were identified through other sources. After removing 3 duplicate records, 1,205 records remained for title and abstract screening. At this stage, 1,145 records were excluded because they did not meet the inclusion criteria. The full texts of 60 articles were then assessed for eligibility, and 52 articles were excluded for various reasons, such as not specifically focusing on TPACK in chemistry education, being non-empirical studies, not meeting the publication-year criteria, or not being full-text journal articles. As a result, 8 studies were finally included in the systematic review.

Quality Assesment

The quality assessment stage was conducted to evaluate the methodological rigor and relevance of the selected studies. Each study was assessed using six criteria covering the clarity of research aims, the adequacy of methods, the clarity of context, the contribution of the findings to the literature, the robustness of the methodology in supporting the conclusions, and the extent to which study limitations were acknowledged. Each criterion was scored using a three-point scale: 1 for "Yes," 0.5 for "Partially," and 0 for "No." (Alfaisal et al., 2024):

Q1: Are the research aims clearly specified?
Q2: Are the methods or techniques clearly described?
Q3: Is the study context clearly specified?
Q4: Do the findings contribute meaningfully to the literature?
Q5: Is the methodology sufficiently robust to support the conclusions?
Q6: Are the limitations of the study clearly acknowledged?

Table 3. Quality assessment result

Study	Q1	Q2	Q3	Q4	Q5	Q6	Total	Percentage (%)
A1	1.0	1.0	1.0	1.0	0.5	0.5	5.0	83.33
A2	1.0	1.0	1.0	0.5	0.5	0.0	4.0	66.67
A3	1.0	1.0	1.0	1.0	1.0	0.5	5.5	91.67
A4	1.0	1.0	1.0	1.0	0.5	0.5	5.0	83.33
A5	1.0	1.0	1.0	1.0	0.5	0.5	5.0	83.33
A6	1.0	1.0	1.0	1.0	0.5	0.5	5.0	83.33
A7	1.0	1.0	1.0	1.0	0.5	0.5	5.0	83.33
A8	1.0	1.0	1.0	1.0	0.5	0.5	5.0	83.33

Data Coding & Analysis

Each selected study was coded based on publication year, main focus of TPACK in chemistry education, research methodology, educational level, database source, type of technology applied, and principal findings related to implementation, effectiveness, and efficiency. The coded data were analyzed thematically to identify patterns, similarities, and differences across studies. This procedure enabled a structured synthesis of the current state of TPACK implementation in chemistry education and helped identify areas that require further research.

Result and Discussion

A total of 8 studies met the inclusion criteria and were included in this systematic review. The selected studies were published between 2022 and 2024 and were retrieved from Garuda, ERIC, and Taylor & Francis Online. Although ScienceDirect yielded records at the initial identification stage, none met the final eligibility criteria after screening and full-text assessment. This result indicates that the inclusion criteria applied in this review were relatively specific, particularly in relation to publication year, empirical design, and direct relevance to TPACK in chemistry education.

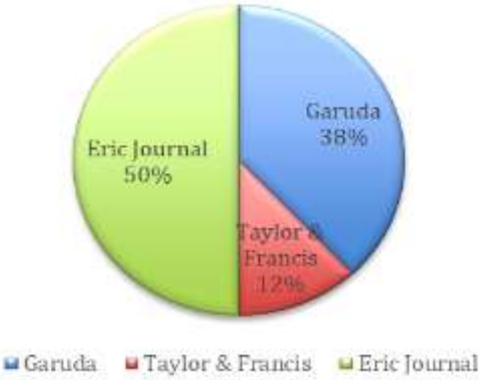

Figure 2. Distribution of research based on database

The distribution of research across databases as depicted in Figure 2 highlights the diversity and coverage of the selected articles. The majority of studies were sourced from Garuda and Eric Journal, indicating a strong contribution from both Indonesian and international educational research communities. Meanwhile, Taylor & Francis Online contributed a smaller but significant portion of the studies, suggesting the growing interest in the integration of TPACK in chemistry education at a global level. No articles were retrieved from ScienceDirect that matched the strict inclusion criteria, reflecting the specificity of the research focus required. This distribution emphasizes the importance of accessing a variety of databases to capture a comprehensive and representative view of the research landscape on TPACK implementation in chemistry learning.

The map in Figure 3 illustrates a strong interconnection between concepts such as teaching, technology, and scientific with the core elements of the TPACK framework, namely pedagogical content knowledge (PCK), technological content knowledge (TCK), and content knowledge. This indicates that the integration of technology in education does not stand alone, but is closely linked to content understanding and appropriate pedagogical strategies. The appearance of keywords such as subject-specific pedagogy and chemistry learning in a separate cluster suggests that TPACK-based instructional approaches are developed contextually, particularly in chemistry education. Moreover, the close association among keywords reveals that the studies tend to integrate various aspects ranging from digitalization in learning and scientific approaches to the development of teachers' professional knowledge into a unified framework. Therefore, this visualization reflects the trend in the literature to emphasize the importance of synergy between technology, pedagogy, and content in enhancing the quality of science learning, especially in chemistry.

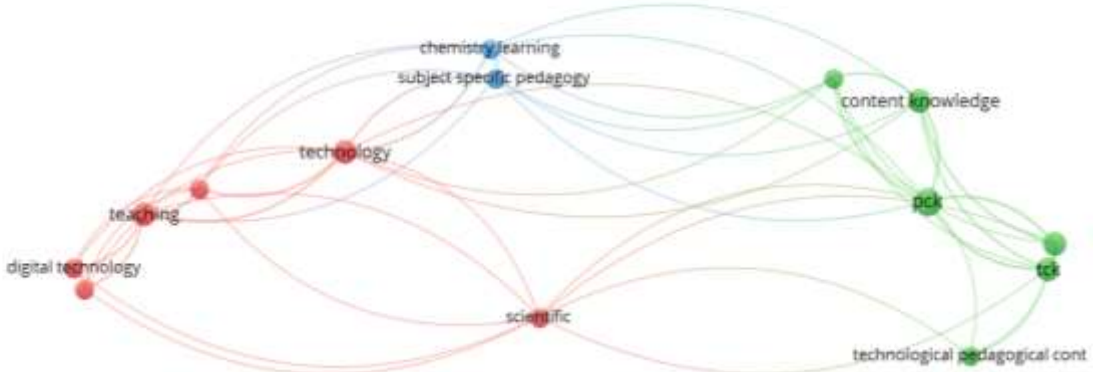

Figure 3. Visualization of keyword co-occurrence network

RQ1: How is the Implementation of TPACK in Chemistry Learning?

The reviewed studies demonstrate the seven components of TPACK—TK, PK, CK, PCK, TCK, TPK, and TPACK—with particular emphasis on the competencies of prospective chemistry teachers in integrating technology, pedagogy, and chemistry content in instructional practice. These findings suggest that TPACK in chemistry education is not merely about mastering separate domains of knowledge, but about creating meaningful interactions among them in classroom learning (Koehler, 2006; Purba et al., 2023; Karpudewan, 2024). Recent studies further confirm that TPACK remains a useful framework for understanding teachers' integration of emerging technologies and for evaluating the quality of such integration in subject-specific contexts (Fabian et al., 2024; Backfisch et al., 2025; Feldman-Maggor et al., 2025). In chemistry education, TK is particularly important because teachers use simulations, visualizations, augmented reality, and other interactive tools to represent abstract concepts such as particulate processes, molecular geometry, and element reactivity, which are often difficult for students to understand through conventional explanation alone (Karpudewan, 2024; Alharbi, 2025). Meanwhile, CK refers to mastery of chemistry content, PK concerns instructional strategies, PCK relates to transforming content into teachable forms, TCK concerns the suitability of technology for chemistry content, and TPK refers to the alignment of technology with pedagogy. Together, these domains constitute TPACK, which supports more meaningful, accurate, and technology-enhanced chemistry instruction.

TPACK facilitates chemistry learning across the macroscopic, submicroscopic, and symbolic levels of representation by helping teachers integrate technology, pedagogy, and chemistry content in a coherent way. This is important because chemistry understanding depends on students' ability to connect observable phenomena with particle-level explanations and symbolic representations. Digital tools such as simulations, visualization media, and immersive technologies can support submicroscopic reasoning, while also linking it to macroscopic observations and symbolic expressions. In this way, TPACK strengthens the representational nature of chemistry knowledge and supports the construction of more meaningful conceptual understanding (Bedin et al., 2023; Feldman-Maggor et al., 2025; Alharbi, 2025).

In addition, the results of the analysis of the eight articles indicate that the implementation of TPACK in chemistry learning goes far beyond merely integrating technology into instructional delivery; it also contributes significantly to creating an innovative, interactive, and student-centered learning environment. This, in turn, supports the enhancement of 21st-century skills such as creativity, collaboration, communication, and critical thinking, which are essential for preparing both students and teachers to become adaptable, responsible, and competitive individuals in a rapidly changing world. The strategies most frequently used include the utilization of virtual simulations, project-based learning approaches, the use of virtual laboratories, and flipped classroom models. Virtual simulations enable both students and teachers to visualize and manipulate molecular structures and reaction mechanisms, thereby strengthening conceptual understanding, especially at macroscopic, microscopic, and symbolic levels. Project-based learning involves both students and teachers in designing and investigating real-world problems related to chemistry, fostering creativity and collaboration. The use of virtual laboratories provides a platform that is safer, more practical, and more flexible for conducting experiments, while the flipped classroom model allows students and teachers to prepare in advance and maximize in-person sessions for more interactive and in-depth learning.

Table 4. Article review results

Authors (year)	Methods used	Participants and sampling	TPACK application	Main findings
Hairida et al. (2023)	Research and development using the ADDIE model; qualitative and quantitative data collection; expert validation, questionnaires, and pilot testing	50 active chemistry teachers; convenience sampling	Development of a self-assessment instrument to measure chemistry teachers' TPACK ability	The instrument was valid and reliable for assessing chemistry teachers' TPACK ability.
Solikhin & Rohiat (2023)	Descriptive quantitative study using a TPACK questionnaire covering seven aspects	Chemistry education students enrolled in a microteaching course; sampling technique not clearly specified	Measurement of the TPACK profile of prospective chemistry teachers in microteaching	The prospective chemistry teachers' TPACK was generally categorized as good.
Purba et al. (2023)	Mixed-method study using questionnaires and interviews	16 pre-service chemistry teachers; sampling technique not clearly specified	Analysis of TPACK competencies using digital media, animations, and simulations	Pre-service chemistry teachers demonstrated good TPACK competence, although support is still needed to strengthen instructional strategies.
Karlsson & Nilsson (2023)	Quantitative and qualitative approach using self-recorded videos, reflective writing, adapted CoRe, and T-CoRe with video annotation	87 secondary science student teachers; sampling technique not clearly specified	Use of T-CoRe and video annotation to capture student teachers' TPACK development	The approach helped make student teachers' TPACK more visible; however, only 58.00% demonstrated all three knowledge intersections clearly.
Yamtinah et al. (2024)	Design-based research with iterative development and evaluation cycles	35 volunteer students and 37 students in experimental groups; expert review involving 8 experts	Development of web-based TPACK scaffolding for chemistry teacher education	Web-based TPACK scaffolding supported pre-service chemistry teachers in improving their TPACK skills.
Widyasari et al. (2022)	Mixed-method design with embedded qualitative support; Rasch model stacking-racking analysis	34 pre-service chemistry teachers from Indonesia; sampling technique not clearly specified	Implementation of flipped learning and subject-specific pedagogy in an e-learning environment	TPACK ability improved after the intervention, indicating that flipped learning positively affected pre-service teachers' TPACK.
Bedin et al. (2023)	Qualitative study with an interpretive paradigm based on online survey data	324 higher education chemistry students from public institutions in Brazil; voluntary participation	Integration of TPACK and Johnstone's Triangle to understand chemistry teaching and learning	The study revealed weaknesses in ICT integration in chemistry teaching and highlighted the need to strengthen teachers' digital competencies.
Jammeh et al. (2024)	Explanatory sequential mixed-method design using lesson observation and performance data	7 teachers and 142 students; convenience sampling	Application of the TPACK model in smart classrooms at the secondary school level	Teachers' use of TPACK improved chemistry learning performance, although limited digital infrastructure remained a major challenge.

This also shows that technology is not merely a tool but a significant medium for bridging macroscopic, microscopic, and symbolic representations, thereby making the learning process more meaningful. Furthermore, TPACK supports educators (teachers) in designing more flexible and creative instructional methods, tailored to the unique characteristics and needs of their students. This approach helps foster greater activity, motivation, and understanding of abstract chemical concepts, while also empowering teachers to implement innovations in their instructional practices. Thus, the implementation of TPACK contributes significantly to the realization of more meaningful, interactive, and relevant chemistry learning in the digital era, while preparing both students and teachers to become scientifically literate, creative, and adaptable individuals.

RQ2: How is the Effectiveness and Efficiency of Chemistry Learning with the TPACK Approach?

Mastery of the three components of TPACK, namely content, pedagogy, and technology, is essential to produce an effective and efficient learning process (Hairida et al., 2023). The TPACK framework enhances the integration of technology in chemistry teaching effectively. As in the study of Yamtinah et al. (2024) on the use of web-based TPACK improves the TPACK skills of prospective chemistry teacher students. Through the integration of TPACK, educators are empowered to use various technological instruments to explain complex concepts in the realm of chemistry. For example, the application of chemical reaction simulations and three-dimensional molecular models facilitates students' ability to visualize chemical phenomena that are often difficult to articulate through textual descriptions or static images alone. Empirical evidence has shown significant improvements in student understanding when compared to traditional pedagogical approaches (Jammeh et al., 2024).

The TPACK framework improves the efficiency of educational management. Educators are provided with greater ease and speed in the task of monitoring, providing constructive feedback, and connecting student progress. The incorporation of technological tools into the evaluation process, such as digital quizzes or interactive exercises, further accelerates the measurement timeline and facilitates real-time adaptation of learning. TPACK presents significant potential to improve the effectiveness and efficiency of chemistry education. Through the application of appropriate technology, educators can provide learners with more engaging, relevant, and adaptive educational experiences. Despite the challenges that may arise such as the lack of limitations of digital tools, the advantages provided by TPACK make it a viable methodology to be implemented in modern chemistry learning. To achieve successful implementation of TPACK, significant support is essential in the areas of technological infrastructure, professional development for educators, and educational policies that facilitate the integration of technology into the learning environment (Widyasari et al., 2022; Solikhin & Rohiat, 2023; Karlsson & Nilsson, 2023; Purba et al., 2023; Yamtinah et al., 2024).

Conclusion

The reviewed studies indicate that TPACK has significant potential to support meaningful, interactive, and technology-enhanced chemistry learning. By aligning technology, pedagogy, and chemistry content, TPACK can help teachers address abstract concepts and improve the quality of instruction. However, because this review was based on only a limited number of selected studies, the findings should be interpreted carefully. Future research is needed to examine the long-term effects of TPACK implementation across different chemistry topics and educational settings. Overall, TPACK remains a relevant framework for strengthening quality chemistry education in the modern educational landscape.

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Author Contributions
Conceptualization, writing—original draft preparation, visualization, A.F.S.Y. and I.Z.; methodology, A.F.S.Y., I.Z., and H.; formal analysis, investigation, A.F.S.Y., I.Z., N., and M.; resources, A.F.S.Y., I.Z., N., M., and H.; writing—review and editing, I.Z., N., M., and H.; supervision, H.; project administration, I.Z.; funding acquisition, A.F.S.Y. and H. All authors have read and approved the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest in this research.

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