International Journal of Evaluation and Research in Education (IJERE)
Vol. 15, No. 6, December 2026, pp. 5354~5367
ISSN: 2252-8822, DOI: 10.11591/ijere.v15i6.39863

Strategies for developing teachers' TPACK: a systematic literature review

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Article Info

Article history:

Received Apr 8, 2026
Revised Oct 25, 2026
Accepted Nov 4, 2026

Keywords:

Development strategies
Systematic literature review
Teacher professional development
Technology integration
TPACK

ABSTRACT

This systematic literature review synthesized empirical studies on strategies for developing teachers' technological pedagogical content knowledge (TPACK). Guided by preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020, the review searched Web of Science and Scopus for peer-reviewed English-language journal articles published between 2020 and 2025. Of 1,455 records identified, 24 studies were included after duplicate removal, screening, and full-text assessment. Methodological quality was appraised descriptively using the mixed methods appraisal tool (MMAT). Thematic synthesis identified four strategy types: TPACK-based training, web-based self-directed projects, TPACK-based course modules, and school-based activities. The findings show that strategy value cannot be judged by format alone. Evidence was more closely connected to classroom practice when teachers engaged in authentic design tasks, collaboration, enactment, feedback, reflection, and revision. Current studies remain constrained by short-term designs, reliance on questionnaires, and limited documentation of classroom transfer or student learning. In response, the review develops an integrative conceptual framework linking strategy types, learning mechanisms, contextual conditions, and forms of evidence documentation. The framework reframes TPACK development as a situated and evidence-informed process of teacher professional learning.

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1. INTRODUCTION

The Industrial Revolution 4.0 (4IR) and the rapid development of information and communication technology (ICT) have accelerated educational change in the 21st century [1]. The spread of the internet has enabled individuals worldwide to access and share information, completely changing the way information is disseminated and accessed. The popularity of smartphones and tablets has also enabled people to access information anytime, anywhere [2]. More recently, the rapid advancement of artificial intelligence (AI), big data, blockchain, and other emerging technologies has further reshaped both the demand for talent and the landscape of education. As they become widely embedded in education, it is clear that traditional knowledge frameworks are no longer sufficient to encompass the professional knowledge and competencies required for effective teaching in contemporary learning contexts. To address this challenge, technology was incorporated into the knowledge base of teaching, leading to the development of the technological pedagogical content knowledge (TPACK) framework, which distinguishes content knowledge, pedagogical knowledge, and technological knowledge while emphasizing their interaction in effective teaching [3], [4]. Since then, TPACK has been widely applied in studies of teacher education, teacher beliefs, classroom practice, and program evaluation [5].

Despite its wide application, TPACK is increasingly understood as a dynamic and revisable construct rather than a fixed model of teacher knowledge. Important issues remain unresolved, particularly in relation to conceptual boundaries, operationalization, and the treatment of contextual and methodological complexity [6]. Continued ambiguity in these areas risks theoretical stagnation and repetitive cycles of research [6]. In addition, context has been increasingly treated not merely as a background condition but as a distinct knowledge domain within TPACK, so that institutional, cultural, and policy conditions can be more systematically incorporated into understandings of teachers' technology-related practice [7]. Narrowly cognitive interpretations of TPACK have also been questioned. Scholars have therefore called for greater attention to teachers' emotions, beliefs, and values in order to develop a fuller account of professional knowledge in technology-rich teaching environments [8].

Previous reviews have provided important foundations for understanding the development of TPACK research, but their emphases remain different from the focus of this review. Review-of-review studies have shown that TPACK research still faces recurring conceptual and methodological issues. These include unclear construct boundaries, inconsistent operationalization, limited longitudinal evidence, and insufficient attention to student learning outcomes [6], [9]. Other reviews have focused on more specific aspects of TPACK research. These include contextual knowledge as an additional TPACK domain [7], teachers' TPACK self-efficacy and professional development [10], and TPACK assessment in mathematics education [11]. Reviews have also examined TPACK research in primary mathematics, science, STEM, and English language education [12], [13]. These reviews have clarified how TPACK has been conceptualized, measured, and applied across different disciplinary or thematic areas. Yet they provide limited guidance on how teachers' TPACK has been intentionally developed through empirical interventions. In particular, less is known about the design features, implementation conditions, outcome evidence, and methodological limitations of TPACK development efforts. This gap is important because claims about TPACK development depend not only on whether an intervention reports positive outcomes, but also on how the intervention is designed, implemented, and evaluated. A review with this focus is therefore needed to connect conceptual and measurement-oriented TPACK scholarship with the practical question of how teachers' TPACK development can be effectively supported.

Against this background, this study conducts a systematic literature review of empirical studies on teachers' TPACK development strategies. The review first synthesizes the major types of strategies used to develop teachers' TPACK and identifies their key characteristics and reported outcomes. It then examines the contextual conditions associated with their implementation and clarifies the limitations and evidence gaps in the current literature. Unlike previous reviews that have mainly focused on how TPACK is conceptualized, measured, or applied in specific domains, this review examines TPACK development from an intervention-oriented perspective. Its focus is not limited to identifying the types of strategies used in previous studies. More importantly, it examines how teacher learning was documented across different strategies, including the degree of evidence triangulation and the proximity of evidence to classroom practice. The synthesis shows that claims about TPACK development are more closely connected to practice when teachers are required to use technology in relation to concrete teaching problems, receive feedback, and revise their instructional decisions. On this basis, the review develops an integrative conceptual framework that organizes strategy types, learning mechanisms, contextual conditions, and forms of evidence documentation. The integrative conceptual framework is intended to support interpretation of how TPACK development is represented across existing empirical studies, rather than to test causal relationships among these dimensions. In order to achieve this objective, this review addresses the following research questions:

- What are the main types of strategies used to develop teachers' TPACK? (RQ1)
- What outcomes and forms of evidence documentation have been reported for these strategies, and what contextual conditions shaped their implementation? (RQ2)
- What methodological limitations and evidence gaps characterize the current research on TPACK development strategies? (RQ3)

2. METHOD

2.1. Review design and reporting guideline

This study used a systematic literature review design to synthesize empirical evidence on strategies for developing teachers' TPACK. To make the review process transparent and reproducible, the identification, screening, eligibility assessment, and inclusion of studies were organized with reference to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 statement [14]. Following this guidance, the review first defined the databases and search strings. The retrieved records were then screened for eligibility, assessed at full-text level, appraised for methodological quality, and synthesized thematically. Figure 1 presents the complete flow of records from initial identification to final inclusion.

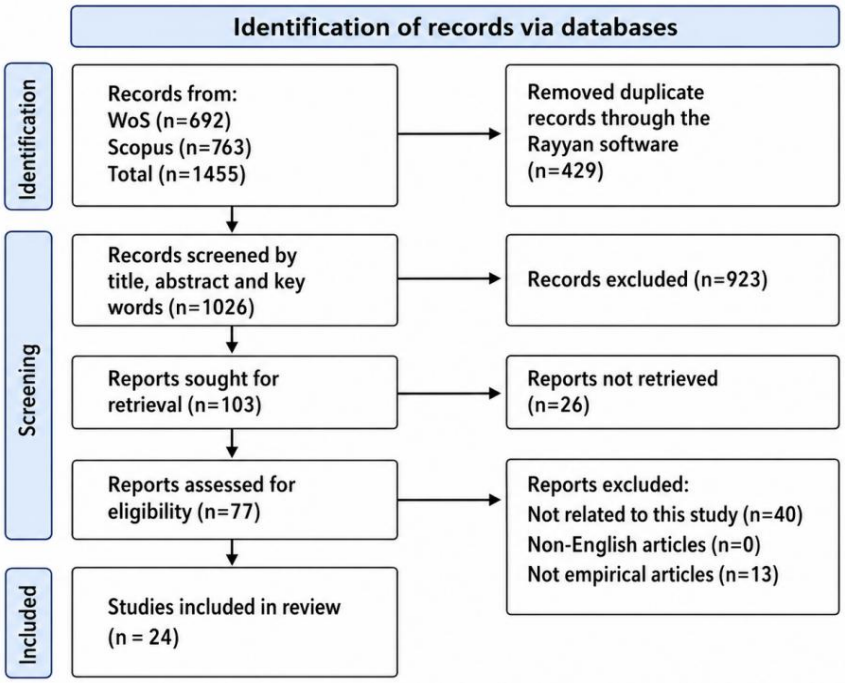


Figure 1. PRISMA flow diagram of study identification, screening, eligibility assessment, and inclusion

2.2. Database selection and search strategy

The literature search was conducted in the Web of Science Core Collection and Scopus on October 15, 2025. No additional database update was conducted after this date. These two databases were selected because they provide broad coverage of peer-reviewed research. Their coverage includes education, educational technology, psychology, computer science, and related interdisciplinary fields. Their combined use also reduces dependence on a single database and improves the coverage of systematic review searches [15], [16]. The search strategy was built around four groups of terms. The first group represented the core construct: "TPACK," "technological pedagogical content knowledge," and "TPCK." The second group identified the target participants, including "teacher," "educator," "pre-service teacher," and "in-service teacher." The third group captured development-oriented approaches, such as "professional development," "training," "workshop," "intervention," and "strategy." The fourth group captured evaluation-related terms, including "effectiveness," "impact," and "evaluation." Boolean operators, phrase searching, and truncation were used to increase the precision and coverage of the search. The complete search strings are presented in Table 1.

Table 1. Search string used in Web of Science and Scopus

No.	Database	Search string
1.	Web of Science	("TPACK" OR "technological pedagogical content knowledge" OR "TPCK") AND ("teacher*" OR "educator*" OR "in-service teacher" OR "pre-service teacher") AND ("professional development" OR "training" OR "workshop" OR "intervention" OR "strategy") AND ("effectiveness" OR "impact" OR "evaluation")
2.	Scopus	TITLE-ABS-KEY ("TPACK" OR "technological pedagogical content knowledge" OR "TPCK") AND TITLE-ABS-KEY ("teacher*" OR "educator*" OR "in-service" OR "pre-service") AND TITLE-ABS-KEY ("professional development" OR "training" OR "workshop" OR "intervention" OR "strategy")

The search was limited to peer-reviewed English-language journal articles published between 2020 and 2025. This period was selected to capture recent empirical work on TPACK development in a context of rapid educational digitalization and post-pandemic changes in teacher professional learning. Relevant subject areas were also applied to keep the search aligned with education and educational technology. In Web of Science, the selected areas included education and educational research, education scientific disciplines, educational psychology, computer science interdisciplinary applications, and education multidisciplinary. In Scopus, the selected areas included social sciences, computer science, psychology, arts and humanities, and decision sciences.

2.3. Eligibility criteria

Eligibility criteria were specified before screening to keep the selection process consistent. Studies were included when they met the following criteria. First, they were peer-reviewed journal articles written in English and published between 2020 and 2025. Second, they reported qualitative, quantitative, or mixed-methods empirical findings. Third, they involved pre-service or in-service teachers and explicitly examined an intentional effort to develop teachers' TPACK. Studies were excluded when they did not directly address the purpose of the review. This included non-empirical papers, review articles, conceptual papers, conference abstracts, book chapters, studies focused only on general technology use, studies that only measured teachers' existing TPACK levels, studies that examined factors influencing TPACK without a development component, and studies involving participants other than teachers. The inclusion and exclusion criteria are summarized in Table 2.

Table 2. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
1. Language	English	Non-English articles
2. Document type	Peer-reviewed journal articles	Non-peer-reviewed publications, including conference abstracts, opinion pieces, and book chapters
3. Empirical research	Qualitative, quantitative, or mixed-methods empirical studies	Non-empirical studies, review studies, and concept papers
4. Timeline	Studies published between 2020 and 2025	Studies published before 2020
5. Study area	Studies focusing on teachers' TPACK development strategies, including methods, modules, trainings, and projects; participants were pre-service or in-service teachers in formal educational settings; TPACK development strategies were an explicit focus of the study and were supported by clearly reported findings	Studies unrelated to teachers' TPACK development strategies, such as those focusing only on the use of TPACK in teaching activities, the effects of TPACK levels, influencing factors, review topics, or assessment tools

2.4. Screening and study selection

All retrieved records were imported into Rayyan for duplicate removal and screening management. The initial search identified 1,455 records, including 692 records from Web of Science and 763 records from Scopus. After 429 duplicate records were removed, 1,026 unique records remained for title, abstract, and keyword screening. At this stage, 923 records were excluded because they did not meet the eligibility criteria. The remaining 103 reports were sought for retrieval, and 26 reports could not be retrieved. A total of 77 full-text articles were then assessed for eligibility. During full-text screening, 53 articles were excluded because they were not directly related to the purpose of the review, were not empirical studies, or did not examine TPACK development strategies. Finally, 24 studies were included in the final synthesis.

Two reviewers independently screened the titles, abstracts, keywords, and full texts. Disagreements were resolved through discussion until consensus was reached. All final inclusion and exclusion decisions were recorded to maintain a transparent audit trail. Inter-rater agreement for full-text screening was calculated using Cohen's kappa, which estimates agreement beyond chance in categorical decisions. The coefficient was $\kappa=0.82$, indicating high agreement between the reviewers [17].

2.5. Methodological quality assessment

Methodological quality was assessed using the mixed methods appraisal tool (MMAT) [18]. Consistent with MMAT guidance, the appraisal was used descriptively rather than as a basis for calculating an overall quality score. It helped identify recurring methodological strengths and limitations across the evidence base and supported a cautious interpretation of the reported findings.

Across the 24 included studies, several recurring methodological strengths were identified. Most studies showed a clear relationship between the research questions and the empirical data used to examine TPACK development strategies. Qualitative studies generally showed coherence between their research aims, data collection, analysis, and interpretation. They were particularly useful for explaining how TPACK development unfolded through practice-oriented learning activities. Mixed-methods studies added further value when they connected reported changes in TPACK with qualitative evidence from participants' reflections, teaching artefacts, classroom observations, or implementation records.

At the same time, the appraisal also identified several recurring methodological limitations. Many quantitative non-randomized studies relied on one-group pre-test post-test designs. These designs provided useful evidence of change, but they offered limited control over possible confounding influences, including participants' prior experience, course exposure, institutional context, and concurrent professional learning. Some studies included comparison groups, repeated measurements, performance artefacts, or classroom-based

evidence. However, the overall evidence base still depended substantially on self-reported TPACK outcomes. Therefore, reported improvements in TPACK should be interpreted cautiously. This is especially important when findings rely mainly on immediate self-reports and lack follow-up or practice-based evidence.

For mixed-methods studies, the degree of integration between qualitative and quantitative evidence varied across the reviewed literature. In some studies, qualitative findings mainly supplemented quantitative results by providing participants' perceptions or illustrative examples. In other studies, qualitative data provided a more direct account of how specific development strategies supported changes in teachers' technological, pedagogical, and content-related reasoning. This variation suggests that claims about TPACK development depend not only on the presence of multiple data sources, but also on how clearly these sources are integrated to explain the process and outcomes of teacher learning.

Potential sources of bias should also be acknowledged when interpreting the findings of this review. Publication bias may have influenced the evidence base because studies reporting positive or statistically significant outcomes are more likely to be published and indexed in major academic databases. Language bias may also be present because the review was limited to English-language publications. As a result, relevant studies published in other languages, local journals, dissertations, or institutional reports may not have been fully represented in the synthesis.

In the main text, the appraisal is reported descriptively to maintain transparency while avoiding the inappropriate conversion of MMAT responses into numerical scores or categorical quality labels. This approach allows the methodological strengths and limitations of the evidence base to inform interpretation without treating MMAT as a formal rating scale.

2.6. Data extraction and thematic synthesis

Data were extracted using a structured matrix aligned with the research questions. The core extraction fields included author and year, country, sample characteristics, research design, and the intervention or TPACK development strategy. Within these fields, additional details were recorded when reported in the original studies, including participant type, educational level, intervention duration, implementation setting, major learning activities, digital tools or platforms, data sources, and analysis methods. To guide data extraction and coding, several analytical terms were defined in advance. Authentic design was understood as a design-oriented learning task in which teachers designed, adapted, enacted, or evaluated technology-integrated teaching in relation to curriculum goals, learner needs, and classroom conditions. This definition was informed by situated learning, teacher professional learning, and design-oriented TPACK scholarship [19]–[21]. Learning mechanisms referred to the processes through which development strategies supported teacher learning, including collaboration, enactment, feedback, reflection, and iterative revision. This interpretation was guided by research on teacher professional learning and experiential learning [22], [23]. Evidence triangulation referred to the integration of multiple data sources, while proximity to classroom practice indicated how closely the reported evidence was connected to teaching artefacts, enacted teaching, classroom records, or other practice-based documentation. These definitions were used as operational coding boundaries rather than as universal definitions of the constructs. A separate methodological quality table was used to record the MMAT design category and item-level appraisal responses for each included study. Borderline exclusions were also documented to make the selection decisions more transparent.

The synthesis was conducted through thematic analysis, which supports the identification and interpretation of recurring patterns across textual evidence [24]. Extracted data related to the design, implementation, outcomes, and limitations of TPACK development efforts were imported into NVivo for coding. Two researchers first coded an initial subset of studies independently. The coding comparison was then used to refine code definitions and clarify inclusion boundaries before the remaining studies were coded [19]–[23], [25].

The initial coding focused on how TPACK development was designed, implemented, supported, and evaluated in the included studies. Similar codes were grouped into broader categories through repeated comparison across studies. The emerging themes were then checked against the coded data, extracted study characteristics, and the theoretical framing of TPACK development to ensure that they were both evidence-based and analytically meaningful. To strengthen coding reliability, a second researcher independently coded approximately 20% of the included studies. The NVivo code comparison function produced a Cohen's kappa value of 0.78, indicating substantial coding agreement [26].

Peer debriefing and reflexive checking helped strengthen the credibility of the thematic interpretation. During peer debriefing, the researchers reviewed the emerging themes against coded excerpts, intervention features, evidence types, and contextual conditions reported in the included studies. Reflexive checking helped examine whether assumptions about TPACK as a developmental and practice-based construct had overly influenced the synthesis. Disagreements and uncertainties were then used to refine

theme boundaries, clarify conceptual overlap, and reduce the risk of overgeneralizing from a limited evidence base. To support transparency, the extraction matrix, methodological quality appraisal table, coding decisions, peer discussion notes, and records of marginal exclusions were retained as an audit trail. This allowed the development of codes and themes to be traced back to the extracted evidence and review decisions.

3. RESULTS

3.1. Strategies for the development of teachers' TPACK

Regarding RQ1, the thematic synthesis showed that empirical studies used different forms of support to develop teachers' TPACK. These strategies were grouped according to their core design features, implementation settings, learning mechanisms, and reported evidence. As summarized in Table 3, four broad categories were identified: training based on the TPACK framework, web-based self-directed projects, TPACK-based course modules, and TPACK-based school-based activities.

The four categories in Table 3 were distinguished according to their dominant design logic rather than by a single activity format. Training based on the TPACK framework was usually organized as relatively short and structured professional development, with emphasis on targeted input, guided practice, and technology-integrated lesson design [27], [28]. Web-based self-directed projects placed greater emphasis on flexible access to digital resources, online platforms, and learner-managed exploration, although some studies also incorporated peer interaction and guided tasks [29]–[31]. TPACK-based course modules were more commonly embedded in pre-service teacher education. Through structured coursework, design projects, microteaching, and portfolio tasks, they supported learners in connecting technology, pedagogy, and content over a longer learning cycle [32]–[34]. School-based activities were more directly situated in teachers' daily professional contexts and usually involved collaborative lesson design, practicum-based inquiry, classroom implementation, observation, or reflection [35]–[38].

Although these categories are analytically useful, their boundaries were not completely fixed. Some interventions combined features of more than one strategy type, such as course-based modules that included collaborative lesson design or training programs extended through online learning. Therefore, the typology should be understood as a synthesis of dominant strategy patterns rather than as four mutually exclusive categories.

Table 3. Typology of TPACK development strategies and forms of evidence documentation

Main category	Typical forms	Documented outcomes and evidence features
Training based on the TPACK framework	Workshops, structured training, short-term PD, blended camps	Commonly reported immediate gains in TPACK awareness, technology-related knowledge, confidence, and lesson planning, with outcomes often documented through short-term self-report measures
Web-based self-directed projects	Personalized systems, online workshops, self-paced digital tasks, platform-supported learning	Provided flexible support for digital tool exploration and technology-supported planning, although outcomes were shaped by learner self-regulation, digital access, and online support
TPACK-based course modules	Course-embedded modules, methods courses, collaborative lesson design, microteaching tasks	Generated more practice-related documentation in pre-service teacher education when learners produced artefacts, lesson plans, digital resources, or performance-based outputs
TPACK-based school-based activities	Collaborative lesson design, CoP, lesson study, practicum-linked school inquiry	Were directly situated in practice-based contexts, with outcomes documented through collaborative planning, classroom implementation, observation, reflection, or school-based inquiry

3.2. Reported outcomes and forms of evidence documentation

Building on the typology summarized in Table 3, the reported outcomes of TPACK development strategies should be interpreted in relation to how evidence was documented across studies. Positive outcomes were reported in all four categories, but the forms of evidence used to support these outcomes differed. The main distinction was not whether a strategy was labelled as training, online learning, course-based learning, or school-based activity. A more relevant distinction concerned the extent to which each study documented teachers' use of TPACK in concrete instructional design. Such documentation included teaching artefacts, feedback records, revised lesson designs, microteaching performance, or classroom implementation of technology-supported teaching.

A clear difference can be seen between short-term perceptual gains and practice-based evidence. Training-based and web-based strategies often reported improvement in TPACK scores, technology-related confidence, tool familiarity, and willingness to integrate technology [27], [28], [30], [31]. These outcomes are useful because they show that structured support can quickly increase teachers' awareness and readiness.

However, such evidence was often based on self-reported measures or one-group pre-test post-test designs, which makes it difficult to determine whether the reported gains were transferred into classroom practice. By comparison, course-based modules and school-based activities more often generated lesson plans, teaching videos, digital resources, microteaching performances, classroom implementation records, or reflective evidence [32], [37], [39], [40]. These forms of evidence were more closely connected to teachers' documented capacity to integrate technology, pedagogy, and content in instructional design.

The strategies also differed in their degree of contextual embeddedness. Short intensive training and online self-directed projects were more flexible and easier to implement across settings, but their outcomes were more vulnerable to participants' motivation, self-regulation, access to digital resources, and prior technology competence [29], [41], [42]. In contrast, school-based and practice-oriented activities were more directly situated in the contexts where teachers had to respond to curriculum demands, student characteristics, available technologies, and school routines [35], [36], [38]. This contextual embeddedness made the evidence more meaningful for classroom transfer, but it also made implementation more dependent on school culture, collaboration time, mentoring, and institutional support.

The review also shows that intervention duration alone did not explain differences in reported outcomes. Some short-term training programs reported positive gains when they were carefully structured around diagnosis, targeted support, and guided lesson design [27], [28]. Conversely, longer course-based or online activities did not necessarily generate more practice-related documentation unless they included iterative design, feedback, reflection, and performance-based tasks. Reported outcomes were more practice-oriented when teachers moved beyond learning about tools and made instructional decisions that connected technology with content goals and pedagogical methods.

Overall, claims about TPACK development were supported by a greater degree of evidence triangulation when strategies required teachers to work on authentic teaching tasks, receive feedback, and revise their instructional designs. These claims were more closely connected to practice when reported outcomes were documented through multiple data sources, such as teaching artefacts, lesson plans, classroom implementation records, reflective accounts, or feedback-based revisions. Strategies that relied mainly on tool demonstration or self-reported confidence provided useful evidence of perceived gains, but such evidence was less directly connected to enacted teaching practice. Therefore, the review does not support the conclusion that one strategy type is universally superior. It suggests that claims about TPACK development need to be interpreted according to the learning opportunities provided by the intervention and the forms of evidence used to document teacher learning.

3.3. Comparative analysis of contextual adaptability across different strategies

Building on the preceding analysis of strategy types and reported outcomes, this section compares the contextual adaptability of different TPACK development strategies. Context was conceptualized as a configuration of teacher characteristics, learner needs, school culture, digital resources, collaboration conditions, curriculum requirements, and policy expectations [22], [23], [43]. Based on the cross-study synthesis of the 24 included empirical studies, the comparison examined where each strategy appeared most suitable, how it supported TPACK development, and what constraints limited its transfer into practice. As summarized in Table 4, the four strategy types differed not only in format, but also in contextual requirements, dominant learning mechanisms, and implementation conditions.

Table 4. Contextual conditions and learning mechanisms across TPACK development strategies

Strategy type	Contextual conditions	Dominant learning mechanisms	Implementation constraints
Training based on the TPACK framework	Teachers needing rapid, focused support	Targeted input, guided practice, tool demonstration, and lesson design tasks	Limited follow-up and frequent reliance on short-term self-report evidence
TPACK-based course modules	Pre-service teacher education and course-based learning	Structured assignments, design projects, microteaching, portfolio work, and reflective revision	Limited use of comparison designs, follow-up evidence, or classroom transfer documentation
Web-based self-directed projects	Flexible or distributed professional learning contexts	Self-paced exploration, online resources, digital tool evaluation, and online collaboration	Dependence on learner self-regulation, stable digital access, and online support
TPACK-based school-based activities	Practice-embedded school contexts with opportunities for collaboration	Collaborative lesson design, classroom implementation, observation, peer discussion, and reflection	Dependence on school culture, mentoring, leadership support, and collaboration time

Across the four strategy types, contextual fit varied according to the purpose, setting, and support conditions of each intervention. TPACK-based training was commonly used when teachers needed rapid and focused support, particularly for awareness building, confidence development, and initial lesson planning.

Its reported outcomes were often documented through short intervention cycles, limited follow-up, and self-reported measures. Web-based self-directed projects offered flexible access to digital resources, although their implementation was shaped by participants' self-regulation, digital access, and online support. TPACK-based course modules were mainly situated in teacher education programs, where technology integration could be embedded in coursework, design projects, microteaching, and reflective assessment. TPACK-based school-based activities were situated closer to everyday teaching contexts and usually involved collaboration time, mentoring, institutional support, and opportunities for teachers to experiment, observe, and revise.

The comparison showed that contextual adaptability depended on the contextual conditions under which each strategy was implemented. The same strategy type was associated with different reported outcomes when implemented under different contextual and support conditions. Learning mechanisms were more clearly documented when teachers solved content-specific teaching problems, tried out technology-supported designs, received feedback, and revised their work. In these studies, TPACK development was often documented through more practice-based evidence. When such mechanisms were less clearly documented, reported outcomes were more often limited to awareness, confidence, or tool familiarity.

Contextual conditions shaped whether these mechanisms could operate effectively. Teacher readiness, digital infrastructure, curriculum demands, learner characteristics, school leadership, mentoring, and time for collaboration influenced how each strategy was implemented and evaluated. For example, a web-based project may be useful for teachers with stable digital access and strong self-regulation, but less suitable in settings with weak infrastructure or limited online support. Similarly, a school-based collaborative strategy may support classroom transfer more directly, but only when teachers have sufficient time, institutional backing, and opportunities for peer discussion.

Based on the cross-study synthesis, Figure 2 presents an integrative conceptual framework for interpreting TPACK development strategies. The integrative conceptual framework is not intended to test causal relationships among the four analytical dimensions. Instead, it organizes strategy types, learning mechanisms, contextual conditions, and forms of evidence documentation to guide interpretation of TPACK development across the reviewed studies.

As shown in Figure 2, strategy types describe the structural forms through which TPACK-related professional learning was organized. These included training, web-based self-directed projects, course modules, and school-based activities. Learning mechanisms refer to the processes through which teachers engaged with technology, pedagogy, and content. In the reviewed studies, these processes included authentic design, collaboration, enactment, feedback, reflection, and revision. Contextual conditions captured the factors that shaped implementation, such as teacher readiness, digital infrastructure, curriculum demands, learner characteristics, school culture, mentoring, and institutional support. Forms of evidence documentation described how claims about TPACK development were supported across studies. They included self-report measures, teaching artefacts, classroom records, reflective accounts, and other forms of practice-based evidence.

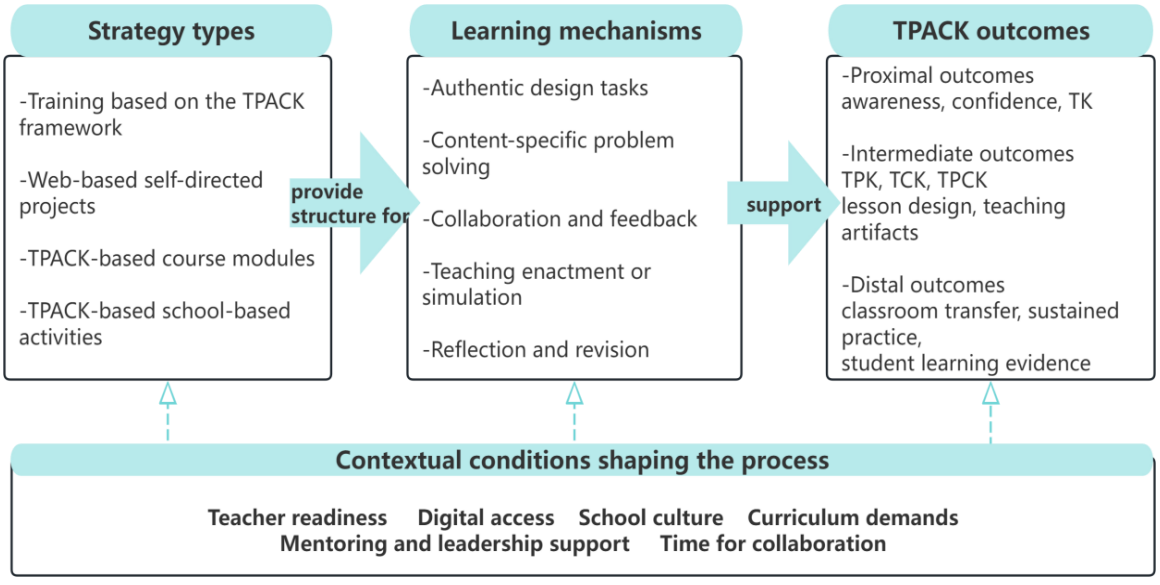


Figure 2. Integrative conceptual framework for interpreting TPACK development strategies

3.4. Key limitations and evidence gaps in current TPACK development strategy research

3.4.1. Limited generalizability across contexts

Among the 24 empirical studies included in this review, although the sample covers several Global South countries such as Tanzania, the Philippines, Thailand, Indonesia, South Africa, Turkey, and China, most TPACK development research has been conducted in relatively resource-advantaged settings. These settings include universities and key secondary schools in urban areas, as well as education-innovation pilot schools supported by policy initiatives [29], [32], [37], [44], [45]. Overall, the existing evidence mainly addresses which TPACK development strategies enhance teachers' TPACK in relatively favorable educational ecosystems. By contrast, systematic research remains scarce on how teachers develop TPACK in remote rural areas, small schools, or highly resource-constrained environments. At the same time, many samples were composed largely of volunteer teachers. This may have produced an "active participant bias" and limited the generalizability of the findings. The strategies may be less applicable to teachers with limited technological proficiency or fewer institutional, technological, and mentoring resources.

3.4.2. Imbalance in subject and educational stage representation

Research on TPACK development strategies shows a marked imbalance across subject areas and educational stages. The reviewed studies were concentrated mainly in mathematics [29], [37], [44], science [27], [28], [35], and language education [38], [41]. In contrast, arts, physical education, and social studies are addressed far less frequently. Furthermore, the preschool educational stage is virtually absent from the current sample of studies. Consequently, there remains a lack of systematic discussion of the developmental pathways of teachers' TPACK across different subject-knowledge structures. Evidence is also scarce on contextualized TPACK development strategies for pre-service and in-service preschool teachers.

3.4.3. Need for content renewal

The literature shows that most teacher TPACK development strategies remain centered on traditional ICT tools. These tools include generic digital applications, Web 2.0 tools, learning management systems, subject-specific software, classroom response systems, and conventional online course platforms. Examples include GeoGebra, graphing calculators, audience response systems (ARS), and Moodle. The content of these programs likewise focuses on how these technologies or products can be used more effectively to support teaching. By contrast, TPACK development initiatives designed around AI remain limited. One example in this review is the AI teaching-competency development scheme for K–12 computer science teachers [46]. Moreover, few studies systematically compare "traditional ICT competency development" with "AI-enhanced competency development" in fostering teachers' TPACK. Despite advances in AI, empirical evidence remains limited on how AI-based strategies may support teachers' TPACK development and how such development is documented across studies.

3.4.4. Limitations in research design and evidence

Existing research on TPACK development strategies exhibits several methodological limitations that warrant attention. First, the evidence base relies heavily on self-report data, such as TPACK scales, reflective journals, and interview transcripts, while classroom observations, analyses of teaching artefacts, and student learning outcomes were reported less frequently [32], [37]. Second, findings across studies were not always aligned across data sources. Some studies reported limited changes in quantitative TPACK scores, while qualitative evidence indicated changes in teachers' beliefs and professional identities [29]. In contrast, other studies reported increases in self-reported TPACK without clearly linking these changes to classroom behavior or student outcomes [46]. These inconsistencies suggest the need for research designs that include comparison groups, longer-term tracking, and more diverse evidence sources. Mixed-methods designs, longitudinal tracking, comparison or control groups, and evidence triangulation would help clarify whether reported TPACK gains are reflected in teaching practice. Such designs would also support a more careful examination of the relationship between self-perceived TPACK development and observable teaching practices.

3.4.5. Absence of long-term tracking for beliefs and practices

Within the field of teacher professional development, a growing body of qualitative research shows that such strategies influence not only teachers' TPACK but also their understandings of students, their professional beliefs, and their conceptions of lifelong learning [29], [45]. However, these shifts in awareness and affect are typically documented on the basis of one-off interviews or isolated reflective texts, with little sustained tracking of teachers after the completion of the programs. This limitation makes it difficult to trace how TPACK development strategies shape teachers' career trajectories and classroom teaching over extended periods. Consequently, longitudinal research is needed to move beyond static measures of

knowledge. Future studies could draw on theories of teacher identity, affect, and agency. This would help conceptualize TPACK development as a dynamic process involving cognitive, affective, and professional-identity dimensions [47], [48].

4. DISCUSSION

4.1. From strategy types to conditions for meaningful TPACK development

The main contribution of this review lies not in classifying TPACK development strategies, but in explaining why strategy type alone is insufficient for interpreting reported outcomes. The synthesis suggests that TPACK development becomes more meaningful when teachers are required to connect technology, pedagogy, and content in response to concrete instructional problems. The integrative conceptual framework developed in this review therefore shifts attention from the internal structure of TPACK to the conditions under which such knowledge becomes teachable, observable, and transferable. The integrative conceptual framework does not replace existing TPACK frameworks that describe the relationships among technological knowledge, pedagogical knowledge, and content knowledge. Its contribution is to shift attention from what forms of knowledge teachers need to how such knowledge may develop through intervention-based professional learning. It suggests that TPACK development should be examined through the interaction among strategy design, learning mechanisms, contextual conditions, and forms of evidence documentation. This positioning is important because the reviewed studies varied substantially in research design, duration, participants, implementation settings, and outcome measures. In this way, the review adds a practice-oriented perspective to earlier TPACK syntheses, which have focused mainly on conceptual development, contextual dimensions, assessment practices, or subject-specific applications [7], [11], [12], [49].

The distinction between self-reported gains and practice-based evidence reflects a broader conceptual tension in TPACK research. TPACK can be treated as a measurable knowledge construct, which allows researchers to examine teachers' perceived competence and compare intervention outcomes through survey instruments. Yet, TPACK is also a situated form of professional knowledge that develops when teachers make instructional decisions in relation to content goals, learner needs, available technologies, and classroom conditions [21], [50], [51]. Survey-based measures can therefore indicate changes in perceived readiness, whereas practice-based evidence is needed to examine how teachers coordinate technology, pedagogy, and content in context-sensitive teaching decisions.

The differences in reported outcomes can be interpreted through situated learning and teacher professional learning. From this perspective, TPACK development is not produced simply by longer exposure to training or greater access to digital tools. It develops when teachers work on authentic teaching problems, collaborate with others, receive feedback, reflect on their decisions, and revise technology-supported designs [20]–[23], [43]. This also explains why TPACK development should not be understood as a linear movement from low to high knowledge levels. Technology, pedagogy, and content are continuously coordinated through situated professional judgement, especially when teachers select tools, align technology use with pedagogical intentions, and respond to contextual constraints.

For this reason, variation in evidence should not be understood as statistical effect size, as the included studies were too heterogeneous for meta-analysis. It refers to the degree of evidence triangulation, the proximity of evidence to classroom practice, and the extent to which data sources were integrated. Teaching artefacts, lesson plans, classroom records, and reflective accounts can provide more informative evidence than questionnaire scores alone when they show how teachers justify technology choices, align them with content goals, respond to learner needs, and revise their work [19], [25], [38]. However, practice-based evidence should not be idealized. A completed lesson plan or teaching artefact becomes meaningful only when it documents pedagogical reasoning, contextual responsiveness, and feedback-based refinement.

4.2. Contextual fit and underexplored areas

The synthesis reinforces the view that context is not a background variable in TPACK development, but a condition that shapes what strategies can be implemented, what support is available, and what counts as meaningful technology integration. This interpretation is consistent with the view of TPACK as situated professional knowledge rather than a decontextualized set of technical skills [7], [52]. A strategy that works in a supported university course or innovation-oriented school may not transfer directly to rural schools, preschool settings, or institutions with limited digital infrastructure. TPACK development therefore needs to be designed around the teaching problems, content demands, resource conditions, and learner needs that teachers actually encounter.

School-based collaborative activities illustrate this situated view of teacher learning. They support TPACK development through shared lesson design, classroom implementation, observation, mentoring, and reflection within the social, material, and institutional conditions of everyday teaching [20], [22], [23], [43]. Their closer alignment with classroom transfer can be explained by teachers' opportunities to test technology

integration against curriculum demands, student responses, available technologies, and school routines. Even so, these strategies depend on time, leadership support, mentoring, and a collaborative culture.

This contextual interpretation also explains why the underrepresented areas identified in the Results are not merely gaps in coverage. Preschool education, resource-constrained settings, less represented subject areas, and AI-mediated teaching contexts raise different questions about developmental appropriateness, infrastructure, curriculum expectations, ethical use, and pedagogical judgement. Their limited representation indicates that current evidence on TPACK development remains uneven in contextual reach.

4.3. Implications for teacher education, professional development, and policy

The findings have several implications for teacher education. TPACK should not be taught as a separate technology course detached from subject pedagogy. Instead, technology integration should be embedded in subject methods courses, lesson design, microteaching, practicum preparation, and reflective assessment. Pre-service teachers need repeated opportunities to work on technology-integrated lesson design, explain their instructional decisions, receive feedback, and improve their work. Through this process, they can better understand how technology supports content representation and the organization of learning. For practicing teachers, single workshops may provide initial support, but sustained TPACK development requires follow-up practice, classroom experimentation, peer collaboration, mentoring, observation, and revision. Professional learning communities, lesson study, coaching, and collaborative design cycles are therefore useful when they connect TPACK development with teachers' curriculum, students, resources, and institutional conditions.

Evaluation practices also need to include more diversified forms of evidence documentation. If TPACK development continues to be evaluated mainly through questionnaires, only a limited part of teacher learning will be captured. This concern is consistent with recent TPACK assessment reviews showing that questionnaire scales remain common, while performance-based, observation-based, and content-specific measures are used less consistently [6], [11]. Future evaluation should therefore combine self-report measures with practice-based evidence, such as lesson plans, teaching artefacts, microteaching performance, classroom observation, reflective journals, peer feedback, and, where appropriate, evidence from student learning. Such evidence triangulation would help distinguish between increased confidence in using technology and teachers' demonstrated capacity to integrate technology, pedagogy, and content in teaching.

At the policy level, the review suggests that investment in teacher digital competence should not focus only on infrastructure, platforms, or tool-centered training. Policies should also create the professional conditions that make TPACK development possible. This means that technology integration should be connected to curriculum standards, teacher education requirements, and practicum expectations. At the institutional level, schools and teacher education programs also need mentoring systems, meaningful professional development evaluation, and protected time for collaborative planning. Without these conditions, technology integration policies may increase teachers' exposure to digital tools without substantially improving the quality of teaching with technology.

4.4. Limitations and future research

This review has several limitations. First, the search was limited to Web of Science Core Collection and Scopus. Although these databases provide broad coverage of peer-reviewed international literature, relevant studies indexed in other databases may have been missed. Second, only English-language peer-reviewed journal articles were included. This decision improved consistency in screening and analysis, but it may have excluded studies published in other languages, local journals, conference proceedings, books, or policy reports. Third, the review focused on studies published between 2020 and 2025. This time frame was appropriate for capturing recent TPACK development research in a rapidly changing digital education context, but it may have excluded earlier intervention studies that contributed to the development of the field. Fourth, the included studies were highly heterogeneous in research design, educational stage, subject area, sample size, intervention duration, data sources, and outcome measures. This heterogeneity made thematic synthesis appropriate, but it limited the possibility of estimating comparative effectiveness statistically.

Future research should adopt designs with comparison groups, longer follow-up periods, and more diverse evidence sources. More studies are needed to examine whether TPACK development is reflected in observable changes in teaching practice, instructional quality, and student learning. Such studies should include evidence that is more directly connected to classroom transfer, teaching artefacts, and longer-term professional practice. Future work should also give greater attention to underrepresented teaching contexts. Preschool education deserves particular consideration, as do resource-constrained settings, less represented subject areas, and teaching contexts increasingly shaped by AI. These directions would help clarify how teachers develop, enact, and sustain TPACK in real educational settings.

5. CONCLUSION

This systematic literature review synthesized empirical studies published between 2020 and 2025 on strategies for developing teachers' TPACK. The review identified four broad strategy types: training based on the TPACK framework, web-based self-directed projects, TPACK-based course modules, and TPACK-based school-based activities. Across these strategies, positive outcomes were generally reported, especially in teachers' technology-related knowledge, confidence, instructional planning, and awareness of technology integration. These outcomes need to be interpreted carefully because the included studies used different forms of evidence documentation to support claims about TPACK development.

The main contribution of this review is that it moves beyond identifying strategy types and clarifies how claims about TPACK development should be interpreted. The value of a strategy depends not only on its format, but also on its design quality, evidence documentation, and contextual fit. Claims about TPACK development were more directly connected to practice when teachers engaged in authentic tasks, feedback, collaboration, revision, and multiple forms of evidence documentation.

Overall, this review contributes a practice-oriented understanding of TPACK development as a situated and evidence-informed process of teacher professional learning. The integrative conceptual framework developed in this review does not redefine the components of TPACK. It clarifies how TPACK development strategies may be interpreted through learning mechanisms, contextual conditions, and forms of evidence documentation. Future research should use comparison designs, longer follow-up periods, and richer evidence sources to examine how teachers develop, enact, and sustain TPACK in real teaching contexts. Greater attention should also be given to preschool education, resource-constrained settings, less represented subject areas, and teaching contexts shaped by AI.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this study because no new datasets were generated or analyzed. All data supporting the findings of this review are available within the cited literature.

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