



## From Perceived Competence to Classroom Practice: Teachers' TPACK in Muhammadiyah School Digital Ecosystems

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### Abstract

School digital transformation requires pedagogically meaningful technology integration and organizational support. This study examined teachers' Technological Pedagogical Content Knowledge (TPACK), the alignment of perceived competence, instructional planning, and classroom enactment, and the school digital ecosystem in two Muhammadiyah junior high schools in Jakarta. A convergent parallel mixed-methods multiple-case design combined a 32-item survey of 51 teachers with focus group discussions, six lesson plans, six recorded lessons, leadership interviews, and institutional documents. Descriptive statistics, thematic analysis, and cross-case integration were conducted using TPACK as the primary framework and SAMR as a supplementary lens. Teachers reported high perceived TPACK-related competence and contextual support (overall mean = 4.348/5). The six recorded lessons mainly demonstrated augmentation and modification, interpreted as technology functions rather than rankings of teaching quality. Integrated findings distinguish three analytical layers—perceived, planned, and enacted practice—within conditions of leadership, infrastructure, professional learning, collaboration, disciplinary characteristics, and organizational values. These layers offer an evidence-based analytical organization, not a new TPACK theory.

**Keywords:** Technological pedagogical content knowledge; Instructional planning; Enacted teaching; School leadership; Teacher competence; Professional learning

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## INTRODUCTION

Digital technologies increasingly shape instructional planning, learning resources, interaction, assessment, professional communication, and school management. Nevertheless, access to devices and platforms does not automatically improve learning (Joshi et al., 2025; Mena-Guacas et al., 2025; Mhlongo et al., 2023). Technology contributes educational value only when teachers make informed decisions about why a tool is used, how it supports a pedagogical strategy, and how it represents or transforms disciplinary content (Galeboe et al., 2025; Mena-Guacas et al., 2025). Consequently, school digital transformation should be treated as a pedagogical and organizational change rather than a procurement agenda (Haris et al., 2025; Sumarlan et al., 2024). Teachers occupy a central position in this transformation because they select tools, structure learning activities, mediate content, and respond to learners' needs. A projector, video, quiz application, learning management system, or interactive board can merely replace a conventional resource, but it can also support visualization, feedback, collaboration, inquiry, and knowledge construction (Barros-del Río et al., 2022; Ke et al., 2021; Tissenbaum & Slotta, 2019). The critical issue is therefore not whether technology is present, but whether its use is aligned with content, pedagogy, learners, and context. The Technological

Pedagogical Content Knowledge (TPACK) framework explains this alignment through the dynamic interaction of technological knowledge, pedagogical knowledge, and content knowledge (Mishra & Koehler, 2006), extending Shulman's (1986) pedagogical content knowledge. TPACK has become a widely used language for describing teachers' knowledge for technology-supported teaching. However, a persistent methodological concern is the dominance of self-report instruments. Such instruments are useful for mapping teachers' beliefs and perceived readiness, but high scores do not directly demonstrate the quality of instructional decisions or classroom enactment (Mourlam et al., 2021).

TPACK is also inherently contextual. Classroom conditions, subject characteristics, student access, infrastructure, school policy, leadership, technical support, professional learning, and collegial culture can enable or constrain what teachers do. Rosenberg and Koehler (2015) showed that context is often under-specified in TPACK research, while Brianza et al. (2022) emphasized its micro-, meso-, and macro-level dimensions. Accordingly, teacher knowledge should not be separated from the ecosystem in which it is enacted. This ecological perspective is particularly relevant in Muhammadiyah schools. These schools operate within a faith-based organizational network in which school leadership, the local Muhammadiyah branch, collaborative traditions, and the values of progressive Islam may shape institutional responses to digital change (Haris et al., 2025; Sumarlan et al., 2024). These organizational values may influence technology integration through leadership priorities, ethical expectations regarding technology use, professional learning, collegial collaboration, and the degree of autonomy and support provided to teachers. Yet, studies that connect teachers' TPACK, observed teaching, leadership, organizational support, and Muhammadiyah values remain limited. Although Indonesian TPACK studies have examined self-reported competence, particular disciplines, instructional interventions, lesson plans, and classroom performance, the evidence remains fragmented across different studies and data sources. More specifically, limited research has examined perceived competence, lesson planning, classroom enactment, and school-level ecosystem conditions simultaneously within the same mixed-methods investigation and organizational network.

This study addresses four gaps. Previous research has already distinguished self-reported from enacted TPACK (e.g., Mourlam et al., 2021); therefore, the present study does not claim novelty merely from making that distinction. Instead, it adds lesson planning as an intermediate analytical layer and examines how the three forms of evidence relate to school-level conditions. Empirically, it compares survey results with lesson plans, teacher explanations, and recorded teaching. Methodologically, it integrates quantitative and qualitative evidence through a convergent multiple-case design. Contextually, it examines two Muhammadiyah junior secondary schools supported by the same local branch while considering variation in their perceived and documented ecosystem conditions. The gap is therefore not the absence of TPACK measurement or of studies on digital teaching in isolation, but the limited opportunity to compare evidence from the same participants and schools across perceptions, instructional designs, and enacted lessons. Bringing these forms of evidence together provides a more cautious basis for judging apparent coherence, identifying partial discrepancies, and relating classroom decisions to documented organizational conditions. In this study, contextual evidence from principals and Muhammadiyah leadership helps interpret teaching practices; it is not treated as evidence that leadership independently causes higher teacher competence or superior classroom outcomes.

The study aimed to: (1) describe teachers' TPACK profiles in the two schools; (2) analyze how technology, pedagogy, and content were integrated in planning and classroom implementation; (3) identify ecosystem supports and constraints; and (4) integrate quantitative and qualitative evidence to explain convergence and divergence among perceived, planned, and enacted TPACK. Its contribution lies in using an integrated analytical model that connects perceived TPACK, planned TPACK, and enacted TPACK with leadership, infrastructure,

professional learning, collaboration, subject characteristics, and organizational values. The three layers were derived as an analytical organization of the present data rather than proposed as a new TPACK theory. In the proposed analytical model, teachers' knowledge informs—but does not automatically determine—instructional planning and classroom enactment. The relationship among these layers is situated within a school digital ecosystem comprising leadership, infrastructure, professional learning, collegial collaboration, and organizational values. These conditions can enable or constrain teachers' decisions, while subject characteristics, student access, workload, and pedagogical choices help explain why planned practices may not always be fully enacted. The scope is confined to descriptive survey profiles and qualitative evidence from two purposefully selected schools. Accordingly, the study does not claim causal effects, statistically significant school differences, or generalizability to all Muhammadiyah schools. The observed lessons illustrate context- and subject-sensitive enactment within the participating cases.

## **METHOD**

### **Research Type or Design**

The study adopted a convergent parallel mixed-methods design combined with a multiple-case study approach (Creswell & Clark, 2017). Quantitative and qualitative data were collected as parallel and complementary strands within the overall study period, analyzed separately, and then integrated through side-by-side comparison and joint displays. The quantitative and qualitative strands were given complementary status: the survey mapped teachers' self-perceived TPACK-related competence and contextual support, whereas the qualitative strand examined instructional planning, classroom enactment, and school-level ecosystem conditions. The TPACK instrument was administered on 5–6 February 2026. Instrument reliability was examined at SMP Muhammadiyah 1 Jagakarsa, South Jakarta, on 2 February 2026, while content-validity assessment was conducted between 2 and 10 February 2026. Teacher focus group discussions were conducted from 4 to 10 February 2026, principal interviews from 6 to 10 February 2026, and the Muhammadiyah branch interview and document checking from 10 to 18 May 2026. Integration was conducted after the quantitative descriptive results and qualitative themes had been developed independently.

The cases were SMP Muhammadiyah 8 and SMP Muhammadiyah 9 in South Jakarta, Indonesia. Both schools were associated with the Kebayoran Baru Muhammadiyah Branch, enabling comparison within a related organizational context while retaining differences in staff readiness, infrastructure, school culture, and digital development. The two schools were purposively selected because they were relevant to the study focus, operated under the same Muhammadiyah branch, and had developed digital-learning practices under different school-level conditions. The primary unit of analysis was teachers' TPACK practice, while the school digital ecosystem was examined as an enabling or constraining context rather than as an independently tested causal variable.

Data collection was conducted in several stages. The reliability trial was conducted at SMP Muhammadiyah 1 Jagakarsa, South Jakarta, on 2 February 2026. Content-validity assessment was conducted from 2 to 10 February 2026, and the TPACK questionnaire was administered at the two case schools on 5–6 February 2026. Teacher focus group discussions were conducted separately at each school from 4 to 10 February 2026, while principal interviews were conducted from 6 to 10 February 2026. The interview with the Muhammadiyah branch leader and the review of school and branch documents were conducted from 10 to 18 May 2026.

### **Participant, Sample, or Subject**

The accessible survey population consisted of 58 teachers. A total-sampling approach was employed, through which all teachers in the accessible population were invited to participate. Fifty-one teachers participated: 22 of 25 teachers in School 8 (88.00%) and 29 of

33 teachers in School 9 (87.88%), as in Table 1. The questionnaire also recorded respondents' gender, subject area, and length of teaching service; these characteristics were used to describe the sample rather than as the basis for inferential comparisons.

Qualitative participants included three teachers from each school, two principals, and the chairperson of the local Muhammadiyah branch. Qualitative informants were selected purposively according to their roles, teaching experience, involvement in school digital practices, and capacity to provide information relevant to TPACK enactment and the digital ecosystem. The six teachers were selected to represent different subject areas and were included based on the availability of corresponding focus group, lesson-plan, and recorded-lesson evidence. The qualitative corpus consisted of six teacher focus group participants, six lesson plans or teaching modules, six recorded lessons, three leadership interviews, and relevant school and branch documents.

The six recorded lessons represented Islamic Education, Mathematics, Science, Arts, Informatics, and Science in School 9. The different subject composition was intentionally retained to explore discipline-sensitive variations in technology integration. However, because the subjects were not fully matched across schools, classroom observations were used for within-case interpretation and illustrative cross-case synthesis rather than as a controlled basis for determining school-level superiority.

**Table 1.** Participants and qualitative evidence

| Data source                     | School 8                  | School 9                  | Total              |
|---------------------------------|---------------------------|---------------------------|--------------------|
| – Accessible teacher population | 25                        | 33                        | 58                 |
| – Teacher survey respondents    | 22                        | 29                        | 51                 |
| – Response rate                 | 88.00%                    | 87.88%                    | 87.93%             |
| – FGD teachers                  | 3                         | 3                         | 6                  |
| – Lesson plans/modules          | 3                         | 3                         | 6                  |
| – Recorded lessons              | 3                         | 3                         | 6                  |
| – Principals                    | 1                         | 1                         | 2                  |
| – Muhammadiyah branch leader    | —                         | —                         | 1                  |
| – School and branch documents   | According to availability | According to availability | Multiple documents |

## Instrument and Procedure

### *Survey instrument, validity, and reliability*

The survey comprised 32 five-point Likert items developed by adapting the TPACK framework of Mishra and Koehler (2006) to the context of teachers in Muhammadiyah schools. The instrument contained two analytically distinct groups of dimensions. The six core TPACK-related dimensions were technological knowledge (TK), pedagogical knowledge (PK), content knowledge (CK), technological pedagogical knowledge (TPK), technological content knowledge (TCK), and integrative TPACK. Two additional contextual dimensions were professional development and collaboration (PRO) and digital ecosystem support (EKO). PRO and EKO were contextual extensions rather than components of the original TPACK framework.

Each dimension comprised four items. Examples included “I am able to select digital technology appropriate to learning needs” for TK; “I understand various student-centered learning strategies” for PK; “I am able to select digital technology appropriate to the characteristics of the subject matter” for TCK; “I am able to integrate technology, pedagogy, and content simultaneously in teaching” for TPACK; “I collaborate with fellow teachers to improve digital-learning practices” for PRO; and “The school provides infrastructure and policies that support digital learning” for EKO.

Responses were recorded on a five-point scale ranging from 1 (strongly disagree) to 5 (strongly agree). The scores represented teachers' perceptions of their knowledge, capability, experience, and contextual support; they were not interpreted as direct performance-based

measurements of competence.

Because PRO and EKO were contextual extensions, their scores were reported separately from the six core TPACK-related dimensions. When all eight dimensions were summarized, the result was described as “overall TPACK-related competence and contextual support” rather than as a pure overall TPACK score.

Content validity was between 2 and 10 February 2026 by a three-member expert panel comprising Prof. Edy Sukardi, Rector of Universitas Muhammadiyah Bogor; Ahmad Said Matondang, Vice Dean of the Faculty of Sharia, Universitas Muhammadiyah Prof. Dr. Hamka, South Jakarta; and Lena Marlana, Director of Muhammadiyah Schools in Central Jakarta. The panel represented expertise in educational leadership, Islamic education, and Muhammadiyah school management.

Each expert assessed the relevance of every item using a four-point scale: 1 = not relevant, 2 = less relevant, 3 = relevant, and 4 = highly relevant. Ratings of 3 or 4 were classified as relevant when calculating the Content Validity Index. The panel also examined item clarity, consistency with the intended dimension, linguistic appropriateness, and suitability for the Muhammadiyah school context. Expert comments were used to improve wording, reduce possible overlap among items, and clarify the indicators before the instrument was administered.

All 32 items received a rating of 4 from each panel member. Consequently, all items achieved I-CVI = 1.00, with S-CVI/Ave = 1.00 and S-CVI/UA = 1.00. These values indicated unanimous expert agreement regarding item relevance. Nevertheless, content validity was interpreted as evidence of content relevance and did not, by itself, establish the full construct validity of the instrument.

A preliminary reliability trial was conducted at SMP Muhammadiyah 1 Jagakarsa, South Jakarta, on 2 February 2026. Internal consistency was evaluated using Cronbach's alpha, with  $\alpha \geq .70$  used as the acceptance criterion. Internal consistency was acceptable for every dimension, with coefficients ranging from  $\alpha = .758$  to  $\alpha = .867$ . The overall 32-item instrument demonstrated high internal consistency ( $\alpha = .961$ ), as shown in Table 2.

Composite reliability and average variance extracted were also examined using SmartPLS as supplementary checks of indicator consistency and convergent validity. SmartPLS was not used to test a structural model or causal relationships among constructs because the quantitative component of the study was descriptive. Reliability and content-validity results were therefore interpreted together with qualitative evidence and were not treated as proof of teachers' enacted competence.

**Table 2.** Survey dimensions and reliability

| Dimension | Dimension type       | Focus                                                                 | Items | Cronbach's $\alpha$ |
|-----------|----------------------|-----------------------------------------------------------------------|-------|---------------------|
| TK        | Core TPACK-related   | Use, selection, and adaptation of digital technology                  | 4     | .864                |
| PK        | Core TPACK-related   | Learner-centered strategies, assessment, and classroom management     | 4     | .841                |
| CK        | Core TPACK-related   | Subject-matter mastery and contextualization                          | 4     | .775                |
| TPK       | Core TPACK-related   | Technology for engagement, methods, feedback, and digital interaction | 4     | .763                |
| TCK       | Core TPACK-related   | Technology for representing, exploring, and deepening content         | 4     | .867                |
| TPACK     | Core TPACK-related   | Integrated instructional decision-making                              | 4     | .832                |
| PRO       | Contextual extension | Training, reflection, and                                             | 4     | .758                |

| Dimension             | Dimension type                  | Focus                                                                                                        | Items | Cronbach's $\alpha$ |
|-----------------------|---------------------------------|--------------------------------------------------------------------------------------------------------------|-------|---------------------|
| EKO                   | Contextual extension            | professional collaboration<br>Leadership, infrastructure,<br>policy, innovation culture, and<br>collegiality | 4     | .818                |
| Overall<br>instrument | TPACK-related and<br>contextual | All 32 items                                                                                                 | 32    | .961                |

*Note.* PRO and EKO are contextual extensions and not original TPACK domains. The original output labeled TCK as “TCK/PCK” and EKO as “ECO”; these labels were standardized as TCK and EKO in the final instrument.

### **Qualitative instruments**

The teacher focus group guide was semi-structured and examined teachers' experiences in selecting, using, and evaluating digital technology; the relationship between technology, pedagogy, and subject content; student responses; constraints; school support; professional development; and teacher collaboration. Focus group discussions were conducted separately at each school, recorded with participants' permission, and transcribed verbatim.

Semi-structured principal interviews examined digital-development vision, school policy, infrastructure, teacher training, instructional supervision, teacher empowerment, equitable access, digital safety, collaboration, and program evaluation. The ISTE Standards for Education Leaders were used only as an operational guide for organizing interview questions and not as a separate theoretical construct or assessment standard. The interview with the Muhammadiyah branch leader examined educational direction, school development, institutional support, professional development, external collaboration, organizational culture, and support for instructional innovation.

Recorded-lesson analysis examined the purpose of technology use, alignment with subject content, pedagogical strategies, teacher and student roles, classroom interaction, assessment, and changes in the learning task. TPACK served as the primary analytical framework, while SAMR was used as a supplementary lens to describe the function of technology in particular learning activities. SAMR was not treated as a linear hierarchy of teaching quality, and a lesson was not considered inferior merely because its dominant function was augmentation or modification.

Lesson plans and teaching modules were examined to identify learning objectives, subject content, methods, digital media, teacher and student activities, assessment, and the intended function of technology. These plans were compared with focus group explanations and recorded lessons to examine correspondence and partial discrepancies among intended and enacted practice. Supporting documents included school vision and mission statements, professional-development programs, training records, supervision documents, technology-related policies, school profiles, and relevant Muhammadiyah branch documents.

### **Data Analysis**

Survey data were analyzed descriptively using frequencies, percentages, means, and standard deviations at the item, dimension, school, and combined-sample levels. The five response categories were scored from 1 to 5. To make the descriptive classifications reproducible, equal-width intervals were applied: 1.00–1.80 = very low, 1.81–2.60 = low, 2.61–3.40 = moderate, 3.41–4.20 = high, and 4.21–5.00 = very high. These categories were descriptive aids rather than empirically validated diagnostic thresholds.

No inferential comparison was claimed because the study was designed to map contextual tendencies rather than test causal or statistically significant differences. Accordingly, differences between School 8 and School 9 were interpreted only as descriptive patterns within the participating samples.

Qualitative data were coded and analyzed thematically following iterative familiarization, coding, theme construction, review, and definition (Braun & Clarke, 2006) together with the processes of data condensation, data display, and conclusion drawing

described by Miles et al. (2014). The first author, who conducted the fieldwork, performed the initial coding and maintained analytic memos and an audit trail. The study did not employ a formal independent inter-coder reliability coefficient; instead, the credibility of interpretation was strengthened through repeated examination of the source data, comparison across methods and participants, supervisory review, and attention to evidence that did not support the dominant pattern.

Recorded lessons were analyzed at the level of instructional activities rather than assigned a single unqualified label for the entire lesson. Observed TPACK tendencies were determined by examining the alignment among the learning objective, subject content, pedagogical strategy, role of technology, teacher and student activity, interaction, and assessment. Descriptors such as “partial alignment” or “relatively coherent integration” were interpretive summaries and not scores from a standardized observation scale.

Analysis was first conducted within each school by bringing together its survey, focus group, lesson-plan, recorded-lesson, principal-interview, and documentary evidence. Cross-case analysis was subsequently used to identify shared and contrasting patterns. Its purpose was not to rank the schools but to explain how different school and subject conditions were associated with different forms of TPACK enactment.

### **Mixed-Methods Integration**

Integration was undertaken at the design, method, and interpretation levels. At the design level, the quantitative and qualitative strands addressed the same overarching focus: teachers’ TPACK practices and their digital-ecosystem context. At the method level, questionnaire dimensions were linked to the focus group questions, interview topics, lesson-plan analysis, and recorded-lesson observations. At the interpretation level, quantitative results and qualitative themes were compared through side-by-side narratives and joint displays.

Four integration relationships were distinguished. “Convergent” indicated that quantitative and qualitative evidence supported the same interpretation. “Complementary” indicated that one source elaborated or explained the other. “Partially divergent” indicated that the sources differed in degree or manifestation—for example, high perceived TPACK accompanied by limited evidence of student digital production in a particular recorded lesson. “Unsupported” indicated that a proposition appeared in one source but could not be corroborated because another source contained insufficient evidence.

Integration occurred after the initial quantitative and qualitative analyses. The researchers re-examined the joint displays and underlying evidence when interpretations differed. The resulting meta-inferences connected teachers’ perceived competence, instructional planning, classroom enactment, subject characteristics, and school ecosystem conditions without treating any single source as the sole representation of competence.

### **Qualitative Trustworthiness**

Qualitative trustworthiness was addressed through source triangulation, method triangulation, repeated review of recorded lessons, within-case analysis, cross-case comparison, maintenance of an audit trail, reflexive analytic memos, and examination of negative or discrepant evidence. Teacher statements were compared with lesson plans, recorded lessons, leadership interviews, and institutional documents. Clarification was sought when contextual terms or participant statements required confirmation; however, the complete thematic analysis was not delegated to participants as a form of comprehensive member validation. Transferability was supported through contextual descriptions of the schools, subjects, participants, and digital ecosystems, while dependability and confirmability were supported by retaining coded transcripts, analytic decisions, documentary evidence, and methodological records.

### **Ethical Procedures**

The study proceeded after institutional permission had been obtained from the relevant

university, Muhammadiyah branch, and participating schools. Participation was voluntary, and teachers, principals, and the Muhammadiyah branch leader received information concerning the study purpose, forms of participation, use of data, confidentiality, and the right to withdraw. Consent was obtained before questionnaire administration, focus group discussions, interviews, and lesson recording. School procedures concerning the recording of students were followed. Participant identities were replaced with codes, including S8-G1 to S8-G3 and S9-G1 to S9-G3 for teachers, KS8 and KS9 for principals, and PCM-01 for the Muhammadiyah branch leader. Digital data were stored securely, access was restricted to the research team, and identifiable student images were not used in publication without appropriate permission.

## RESULTS AND DISCUSSION

### Teachers' Perceived TPACK Profiles

The weighted overall mean across the two schools was 4.348 out of 5, indicating a strongly positive self-perception of TPACK-related competence and contextual support. School 8 obtained an overall mean of 4.135 (high), while School 9 obtained 4.509 (very high). School 9 reported descriptively higher mean scores in every dimension. Because no inferential tests were conducted, these differences indicate sample-specific descriptive patterns and should not be interpreted as statistically significant or generalizable school-level differences. The largest gaps occurred in TPK (0.464), EKO (0.463), and TCK (0.443), whereas the smallest appeared in CK (0.236) and PK (0.254), as in Table 3 and Figure 1. Thus, the difference between the cases was less pronounced in fundamental pedagogical and content knowledge than in the perceived capacity to connect technology with pedagogy and content and in the strength of ecosystem support.

**Table 3.** Mean scores across the eight dimensions

| Dimension | School 8 | Category  | School 9 | Category  | Difference |
|-----------|----------|-----------|----------|-----------|------------|
| TK        | 4.193    | High      | 4.526    | Very high | 0.333      |
| PK        | 4.125    | High      | 4.379    | Very high | 0.254      |
| CK        | 4.307    | Very high | 4.543    | Very high | 0.236      |
| TPK       | 4.114    | High      | 4.578    | Very high | 0.464      |
| TCK       | 4.091    | High      | 4.534    | Very high | 0.443      |
| TPACK     | 3.989    | High      | 4.397    | Very high | 0.408      |
| PRO       | 4.034    | High      | 4.422    | Very high | 0.388      |
| EKO       | 4.227    | Very high | 4.690    | Very high | 0.463      |
| Overall   | 4.135    | High      | 4.509    | Very high | 0.374      |

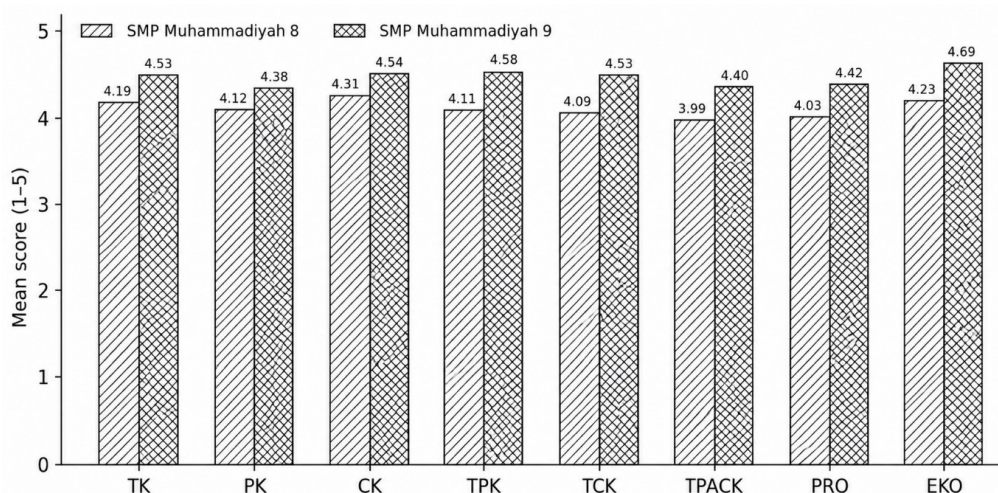


**Figure 1.** Comparison of teachers' self-reported TPACK-related dimensions

The comparatively lower TPACK scores in both schools are analytically important. Teachers reported greater confidence in technology operation and subject knowledge than in

fully integrated instructional decision-making. This pattern is consistent with the view that TPACK is not the simple sum of component knowledge. It requires context-sensitive decisions about representation, learner activity, assessment, and classroom orchestration (Fabian et al., 2024; Park et al., 2025; Uçar & Sahin, 2026). However, the present descriptive data did not directly test whether integrated design was cognitively or practically more demanding. The result also reinforces cautions that self-report evidence should be interpreted as perceived capacity rather than direct proof of enacted performance (Coman & Richardson, 2006; Paap et al., 2024).

### Enacted TPACK and the Functional Depth of Technology Use

Observation showed that all six teachers used digital resources in purposeful ways, but the depth and distribution of learner participation varied. Technology supported presentation, visualization, access to information, discussion, task completion, simulation, and assessment. Most lessons were located between augmentation and modification, while clear evidence of redefinition was limited (Table 4).

The labels in Table 4 summarize observed alignment among content, pedagogy, technology, and learner participation. They are descriptive tendencies rather than performance grades. Because the lessons represented different subjects, the table supports within-lesson and illustrative cross-case interpretation but not controlled school-level comparison.

**Table 4.** Synthesis of recorded lesson observations

| Code/subject                | TPACK tendency                                            | Dominant SAMR function          | Main observation                                                                           |
|-----------------------------|-----------------------------------------------------------|---------------------------------|--------------------------------------------------------------------------------------------|
| – S8-G1 / Islamic Education | Partial alignment; primarily teacher-directed             | Augmentation                    | Digital media enriched and contextualized content, but remained mainly teacher-controlled. |
| – S8-G2 / Mathematics       | Relatively coherent content–pedagogy–technology alignment | Modification                    | Technology supported discussion, presentation, visualization, and problem solving.         |
| – S8-G3 / Science           | Pedagogically active with limited student technology use  | Augmentation                    | Active pedagogy was strong, but students' direct digital participation was limited.        |
| – S9-G1 / Arts              | Visualization-supported content and production            | Augmentation–early modification | Digital visualization and demonstration supported comic production.                        |
| – S9-G2 / Informatics       | Technology integrated as content, medium, and work tool   | Modification                    | Technology functioned as medium, work tool, and object of learning.                        |
| – S9-G3 / Science           | Contextually aligned visualization and assessment         | Augmentation–modification       | Technology supported visualization, resources, simulation, and assessment.                 |

Subject characteristics shaped these choices. In Mathematics, GeoGebra connected abstract representation, affective engagement, and design activity. One teacher explained, “This is GeoGebra on the web, to help make mathematics less frightening ... students enjoy creating 3D designs” (S8-G2, FGD, 4–10 February 2026). In Informatics, technology was inseparable from both content and practice. In Arts and Science, visualization and demonstration were central, although students did not always manipulate tools directly. These patterns illustrate why TPACK must remain discipline-sensitive: the pedagogically appropriate role of technology differs according to the epistemic and representational demands of each subject (Çelik et al., 2026; Zhang, 2022).

Teachers also described technology as normalized within their instructional repertoire. As one participant stated, “Using technology is certainly necessary nowadays ... we have to

use visual and auditory modes ... alongside learning videos” (S8-G1, FGD, 4–10 February 2026). This normality is an achievement, but normalization should not be mistaken for transformation. A lesson may be digitally fluent while still concentrating control, explanation, and task design in the teacher. Where consistent with the learning objectives and classroom context, professional learning may help teachers expand students’ agency in selecting tools, generating representations, collaborating, investigating, and producing authentic digital outcomes (Aleksieva et al., 2025; Crompton & Sykora, 2021; Ivanov et al., 2025; Siddiq et al., 2024). Such agency does not require every lesson to reach redefinition; an augmentation- or modification-level activity may remain pedagogically effective when it is appropriately aligned with the intended learning.

### Alignment Among Perceived, Planned, and Enacted TPACK

The integrated analysis produced both convergence and partial divergence. Survey, focus group, lesson-plan, and observation evidence converged on teachers’ operational technology competence, subject knowledge, and routine use of digital resources. For example, teachers’ high perceived TK was reflected in lesson plans that included digital resources and in recorded lessons using devices, platforms, videos, GeoGebra, simulations, and online assessment. This represents convergence among perceived, planned, and enacted evidence at the level of operational technology use.

Planning sometimes exceeded what was visible in a single recorded lesson. One teacher’s description and instructional plan for a Microsoft Teams learning sequence included web links, Canva, e-books, comics, videos, quizzes, evaluation, and assessment, whereas only part of that sequence was observable in the recorded lesson. Conversely, some teachers reporting positive TPK and TPACK still enacted lessons in which students had limited opportunities to manipulate digital tools or create digital products. These cases represent partial divergence in degree rather than direct contradiction: perceived competence concerned teachers’ broader experience, planning represented intended practice, and recordings captured situated performance during only one lesson.

Leadership, infrastructure, training, supervision, and collegial support complemented these teacher-level findings by explaining the opportunities available for enactment. Nevertheless, available support did not guarantee identical classroom practices because enactment was also shaped by subject demands, student access, teacher choices, workload, and the limited observation window (Table 5).

**Table 5.** Joint display of quantitative and qualitative findings

| Quantitative finding      | Qualitative evidence                                                                          | Integration                   | Interpretation                                                 |
|---------------------------|-----------------------------------------------------------------------------------------------|-------------------------------|----------------------------------------------------------------|
| – High TK in both schools | Teachers used devices, platforms, videos, applications, and online resources.                 | Convergent                    | Operational digital competence is established.                 |
| – Very high CK            | Content explanations and examples were appropriate to each subject.                           | Convergent                    | Content mastery is a foundational strength.                    |
| – High/very high EKO      | Leadership, branch support, facilities, training, supervision, and platforms were documented. | Complementary and convergent  | The ecosystem enables TPACK enactment.                         |
| – Positive TPK and TCK    | Tools were selected in relation to pedagogy and disciplinary representation.                  | Partially divergent in degree | Integration occurs, but unevenly across teachers and subjects. |
| – TPACK lower than        | Observed practices                                                                            | Complementary                 | Perceived integrative                                          |

| Quantitative finding | Qualitative evidence                    | Integration | Interpretation                                                                                                                             |
|----------------------|-----------------------------------------|-------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| several components   | clustered at augmentation–modification. | /qualifying | competence was not uniformly visible in the six observed lessons; pedagogical appropriateness cannot be inferred from SAMR category alone. |

*Note.* Convergent = sources supported the same interpretation; complementary = one source elaborated another; partially divergent = sources differed in degree or manifestation; unsupported = evidence from one source was not corroborated by another.

This partial divergence is not a contradiction. The survey captured perceived knowledge and the breadth of teachers' prior experience; lesson plans captured intended practice; and videos captured situated enactment in a limited time window. A teacher's explanation of a Microsoft Teams learning sequence, for example, included web links, Canva, e-books, comics, videos, quizzes, evaluation, and assessment, even though not all these practices appeared in a single recorded lesson. The evidence therefore supports a three-layer model: perceived TPACK, planned TPACK, and enacted TPACK. Valid interpretation requires examining their relationships rather than privileging one source as the sole truth.

### The School Digital Ecosystem as A Condition for Enactment

The cross-case analysis showed that the two schools followed a common trajectory but differed in ecosystem maturity. For this study, ecosystem support was interpreted from four sources: the EKO survey dimension, leadership interviews, evidence of infrastructure and platforms, and documents concerning training, supervision, collaboration, and routine digital practices. School 8 showed positive but unevenly translated support, whereas School 9 showed stronger perceived EKO support and more consistently documented organizational arrangements. These descriptions do not constitute a validated "ecosystem maturity" scale. Moreover, because the recorded lessons represented different subjects, classroom observations were used only as supporting illustrations and not as the primary basis for ranking the schools (Table 6).

**Table 6.** Cross-case synthesis

| Aspect                                     | School 8                                              | School 9                                             |
|--------------------------------------------|-------------------------------------------------------|------------------------------------------------------|
| – Overall score                            | 4.135; high                                           | 4.509; very high                                     |
| – Strongest dimensions                     | CK and EKO                                            | EKO and TPK                                          |
| – Relative lowest dimension                | TPACK                                                 | PK, followed by TPACK                                |
| – Observed practice pattern                | Adaptive and functional                               | Structured and relatively consistent                 |
| – SAMR functions observed in three lessons | Augmentation, with some modification                  | Augmentation–modification                            |
| – Main strength                            | Content mastery and pedagogical flexibility           | Ecosystem support and technology–content integration |
| – Evidence-informed implication            | Integrated design and students' digital participation | Pedagogical depth and transformation of activity     |
| – Perceived and documented school support  | Positive but translated unevenly                      | Strong and more systematic                           |

*Note.* Cross-school differences are descriptive. The observed lessons involved different subjects, and therefore subject characteristics may be confounded with school-level conditions. Each school contributed three subject-specific recorded lessons.

Leadership and the Muhammadiyah branch contributed through vision, facilities, platforms, training opportunities, supervision, collaboration, and encouragement of innovation.

The evidence suggests the following analytical chain: leadership and branch priorities supported facilities, platforms, professional learning, and supervision; these provisions expanded teachers' opportunities to select and use digital resources; and the recorded lessons showed consequences such as digital visualization, online resources, simulations, presentation, and assessment. However, support was not equally translated into classroom practice. Ecosystem resources operate as opportunities rather than deterministic causes: teachers still mediate them through beliefs, experience, subject demands, workload, and student access. This explains why teachers working within a related organizational network displayed both shared patterns and meaningful variation.

The faith-based context added a possible ethical and collegial dimension. A teacher argued that technological competence must remain connected to "character and morals" and to participation in professional learning communities and communities of practice that emphasize practice rather than sharing alone (S8-G2, FGD, 4–10 February 2026). Leadership and organizational evidence also indicated that Muhammadiyah values could operate through expectations for responsible technology use, collective learning, and alignment between innovation and educational purpose. Given the limited number of direct statements, this finding should be interpreted as an emerging contextual theme rather than evidence of a universally established organizational effect. This finding suggests an extension of the idea of a digital ecosystem beyond infrastructure. In this context, an effective ecosystem combines technical provision, pedagogical learning, organizational coordination, moral purpose, and collective responsibility (Khan et al., 2026; Mizova et al., 2026; Ramdana et al., 2026; Timotheou et al., 2023).

### **Implications for Professional Learning and School Improvement**

The findings suggest that generic technology workshops are insufficient. Professional development should be differentiated according to teachers' existing profiles and organized around authentic subject-specific design problems. Useful formats include lesson design studios, peer observation, coaching, collaborative planning, microteaching with digital tools, and structured reflection on student participation (Cabbeke et al., 2025; Guo et al., 2025). School supervision should examine not merely whether technology is used, but whether it strengthens representation, inquiry, interaction, feedback, inclusion, and learner agency (Consoli et al., 2025; Haleem et al., 2022; Hinostroza et al., 2024; Raave et al., 2024).

At the school and branch levels, improvement requires stable infrastructure, accessible technical support, repositories of tested learning resources, cross-school communities of practice, and documentation of exemplary lessons (Haris et al., 2025). More importantly, ecosystem policies should articulate criteria for pedagogically meaningful technology use that are responsive to learning objectives, subject demands, learner agency, and classroom conditions. SAMR can support reflection on task function, but it should never replace pedagogical judgment. A modified task is not automatically superior; quality depends on alignment with learning goals, content, learners, ethics, and context (Ahmadfard, 2026; Darling-Hammond et al., 2020; Evangelou & Xenos, 2025; Tsao, 2025).

This study involved only two schools within one Muhammadiyah branch and therefore does not represent all Muhammadiyah schools. Quantitative evidence was based on self-assessment and descriptive analysis; it did not test statistical significance or causal relationships. The survey may also be affected by common-method and social-desirability biases because all TPACK-related quantitative dimensions were measured through self-report. The scores should therefore be interpreted as perceived competence and contextual support rather than demonstrated performance. Six recorded lessons represented particular topics, classes, and moments rather than each teacher's full annual practice. Three observed teachers per school cannot represent the full diversity of enacted practices among all 51 survey participants. In addition, the subjects observed differed between schools—Islamic Education, Mathematics, and Science in School 8, compared with Arts, Informatics, and Science in School

9. Subject-specific affordances, particularly the direct role of technology in Informatics, may therefore be confounded with apparent school-level differences. The completeness of lesson plans, interview coverage, and recording duration also varied. Student and parent perspectives and direct measures of learning outcomes were not included. These limitations require cautious transfer of the findings and point to the value of longitudinal, multi-site, and performance-based research.

## CONCLUSION

Teachers in both Muhammadiyah schools reported positive perceptions of TPACK-related competence and contextual support, with a weighted mean of 4.348 and descriptively higher means in School 9 across the eight dimensions. Nevertheless, the integrated evidence showed that perceived competence, planning, and classroom enactment were related but not identical. Teachers demonstrated self-reported operational technology knowledge, strong content knowledge, and purposeful use of digital media, while observed practice remained concentrated at augmentation to modification and only rarely indicated redefinition. The study contributes an integrated analytical interpretation of TPACK evidence as three related layers—what teachers perceive they can do, what they plan, and what they enact—situated within school ecosystem conditions. The three-layer organization was derived from the present findings and should not be interpreted as a newly developed TPACK theory.

Sustainable TPACK development requires more than devices and one-off training. It depends on subject-sensitive professional learning, pedagogical-digital supervision, collaborative cultures, reliable infrastructure, leadership coherence, and organizational values that connect innovation with ethical and educational purpose. For Muhammadiyah schools, branch-level collaboration may support this process through cross-school mentoring, lesson-design clinics, resource repositories, and systematic documentation of practice. These strategies are implications derived from the findings and were not directly tested as interventions in this study. Future studies should include students' perspectives, performance-based assessment, learning outcomes, multiple observers, broader school samples, and longitudinal evidence of change.

## RECOMMENDATION

As evidence-informed implications rather than tested interventions, schools may organize sustained and subject-sensitive professional learning focused on the alignment among technology, learning objectives, content, student participation, and assessment. Pedagogical-digital supervision, peer observation, collaborative lesson design, and cross-school resource sharing may help teachers examine discrepancies among perceived, planned, and enacted TPACK. Infrastructure and technical support should be accompanied by opportunities for reflective experimentation. Future research should test these strategies directly and involve more schools, subject-matched observations, performance-based TPACK measures, and student learning or engagement outcomes.

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## AUTHOR CONTRIBUTIONS STATEMENT

| Name of Author              | C | M | So | Va | Fo | I | R | D | O | E | Vi | Su | P | Fu |
|-----------------------------|---|---|----|----|----|---|---|---|---|---|----|----|---|----|
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| Siti Inganah                |   |   |    | ✓  |    |   |   |   |   | ✓ |    | ✓  |   |    |
| Lud Waluyo                  |   |   |    | ✓  |    |   |   |   |   | ✓ |    | ✓  |   |    |

## CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

## INFORMED CONSENT

Written informed consent was obtained before questionnaire administration, focus group discussions, interviews, and lesson recording. Participation was voluntary; participant identities were anonymized, and procedures for student recording were followed in accordance with school requirements.

## ETHICAL APPROVAL

Formal ethics committee approval was not required under the applicable institutional policy for this non-interventional educational study. Institutional permission was obtained from the relevant university, Muhammadiyah branch, and participating schools before data collection. The formal request for research permission was issued by the Directorate of Postgraduate Studies, Universitas Muhammadiyah Malang (Letter No. E.5./103/DPPs-UMM/I/2026, dated 30 January 2026).

## DATA AVAILABILITY

The data contain identifiable school and participant information and are not publicly available. De-identified materials may be shared by the corresponding author upon reasonable request, subject to institutional approval and participant consent.

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