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Research Article

Modulating and moderating teachers' instructional knowledge for quality science teaching: A TPACK model validation and extension using TIMSS 2023 data

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A distinctive aspect of science teaching is the use of various strategies to stimulate students' discovery-oriented curiosity. However, many instructional knowledge models overlook teaching methodology as a predictor of quality science instruction, as noted in the Technological Pedagogical Content Knowledge model. This study developed and tested a four-variable instructional knowledge model, which includes knowledge of teaching methodology, in contrast to Technological Pedagogical Content Knowledge model's three variables, incorporating professional development and teaching experience as moderating factors. A total of 25,078 teachers participated from 47 countries, with 22,490 completing the survey. The research utilised the grade-8 science teacher's data extracted from the 2023 edition of Trends in International Mathematics and Science Study (TIMSS). Data analysis was conducted using Partial Least Squares-Structural Equation Modelling (PLS-SEM). Model fit indicators showed an acceptable fit exceeding the standard threshold. The findings indicated that content, technology, methodology, and pedagogical knowledge are reliable predictors of quality science instruction, moderated by professional development and teaching experience. The significance of instructional knowledge for quality science teaching supports the recommendation for ongoing professional development for science teachers, regardless of their experience levels.

Keywords: Instructional quality; Learning technologies; Pedagogy; Teaching methods; TIMSS

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1. Introduction

Teaching science requires specific skills and strategies aimed at fostering discovery-oriented curiosity among students. The nature of science instruction necessitates that teachers possess competencies in subject matter knowledge, understanding of learners, instructional strategies, assessment, and general pedagogical knowledge (Nouri et al., 2021). This is crucial because the quality of science instruction significantly impacts student outcomes, including achievement and motivation (Kang et al., 2016). Research highlights various dimensions and factors that contribute to effective science instruction, including instructional clarity and support (Teig & Nilsen, 2022), teacher competency (Fauth et al., 2019), inquiry-based instruction (Capps & Crawford, 2013;

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Kersting et al., 2023), instructional tasks (Kang et al., 2016), and teacher preparation and development (Capps & Crawford, 2013; Nouri et al., 2021; Ramnarain et al., 2022).

The demanding nature of science teaching has necessitated the identification of various forms of knowledge that educators require to provide quality instruction. The foundational framework for quality instruction was established by Shulman (1986) who proposed Pedagogical Content Knowledge [PCK] and Mishra and Koehler (2006), who proposed a model and identified technology, pedagogy, and content knowledge [TPACK] as essential components of teacher knowledge. Mishra and Koehler argued that TPACK significantly contributes to discussions on technology adoption across theoretical, pedagogical, and methodological levels. However, the TPACK model does not cover teaching methods, which are crucial for effective science instruction.

Research indicates that both science content and methodology are vital for effective teaching. A teacher's intention to employ science content and methods is influenced by their skills as well as students' abilities to acquire meaningful knowledge (Zoupidis et al., 2022). Effective scientific teaching involves active learning strategies and methods that have been demonstrated to engage diverse student populations and promote a deeper understanding of science (Handelsman, 2004). Furthermore, Callahan and Dopico (2016) highlighted that knowledge of innovative teaching methods and the social context is essential for effective science education, enabling meaningful learning through impactful teaching. Numerous studies have concluded that active, inquiry-based, and interactive teaching methods are generally more effective than traditional approaches in science education. These methods not only enhance cognitive outcomes but also improve students' attitudes and engagement with science (Mukagihana et al., 2021; Schuster et al., 2018; Tsybulsky, 2018).

While technological knowledge is essential in today's educational landscape, the effectiveness of teaching methods in science education is a critical aspect that influences how teachers implement the curriculum content. It focuses on how various instructional strategies affect learning outcomes. However, there is a significant research gap regarding how teachers' knowledge of teaching methods impacts the quality of science instruction. Furthermore, existing frameworks of teachers' instructional knowledge often exclude teaching methodology—a crucial component in science teaching—and its effects on instructional quality. Consequently, this study aims to validate an extended framework of teachers' instructional knowledge concerning the quality of science instruction. It incorporates knowledge of teaching methodology using a Structural Equation Modelling [SEM] approach.

Additionally, a study by Kusaini et al. (2022) developed and validated an instrument to measure the constructs of instructional knowledge proposed by Mishra and Koehler (2006) within a specific context. However, the lack of international data, such as that from the Trends in International Mathematics and Science Study [TIMSS], may limit the study's external validity. In contrast, the present study utilized data from 47 countries as reported by the TIMSS 2023 findings. Furthermore, factors influencing the relationship between teachers' instructional knowledge and the quality of instruction are linked to professional development and teaching experience. Research indicates that professional development significantly enhances instructional quality by improving pedagogical skills, fostering collaborative learning, and boosting teacher confidence. In contrast, teaching experience alone does not consistently correlate with higher teaching quality without professional development (Dogan & Yurtseven, 2018; Graham et al., 2020; Tapadia, 2024). Therefore, this study hypothesizes that the relationship between teachers' instructional knowledge and the quality of instruction may be moderated by both professional development and teaching experience.

1.1. Conceptual Clarifications

The concepts of pedagogy and teaching methods are often intertwined, with each encompassing aspects of the other. Kashah (2023) defines pedagogy as the study of the principles and methods employed in education and training, emphasizing a comprehensive approach to learning.

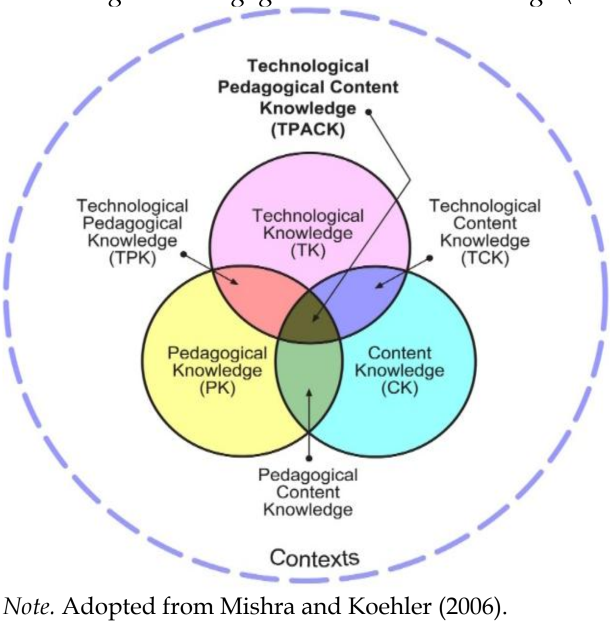
According to Ali et al. (2018), pedagogy shapes teaching strategies, teacher behaviours, and decision-making processes by considering learning theories and the diverse backgrounds and interests of students. Literature differentiates pedagogy as the practices involved in teaching children and young learners, in contrast to andragogy (Soultati, 2023) and with connections to heutagogy (Myburgh & Tammaro, 2013). This distinction explains the diminishing use of the term "pedagogy" in the context of teaching and learning activities at higher educational levels. While pedagogy provides overarching principles and frameworks for teaching, teaching methodology focuses on specific practical skills and techniques. Some scholars argue that pedagogy encompasses both the art and science of teaching, with teaching methods representing the scientific component (Ali et al., 2018; Jovanovska, 2019; Kashah, 2023). Others perceive pedagogy and teaching methods as distinct yet overlapping domains (Wall, 2018).

This study conceptualizes pedagogy as the art and science of teaching, asserting that teaching methodology is the scientific aspect. Consequently, in this context, pedagogy is understood to emphasize the artistic dimensions of teaching. Furthermore, many technologies developed before the Fourth Industrial Revolution [4IR] were aimed at enhancing the artistic elements of pedagogy, while contemporary and emerging educational technologies focus on advancing teaching methodologies.

2. Theoretical Model

The study adopted the Technological Pedagogical Content Knowledge [TPACK] model as its framework. Developed by Mishra and Koehler (2006), this model provides guidance for teachers on integrating technology into the classroom (see Figure 1). It outlines possible combinations of three types of instructional knowledge based on teachers' levels of technological proficiency (Akinyemi & Ojetunde, 2020) and the necessary conditions to achieve effective quality instruction.

Figure 1
Technological-Pedagogical Content Knowledge (TPACK) Model



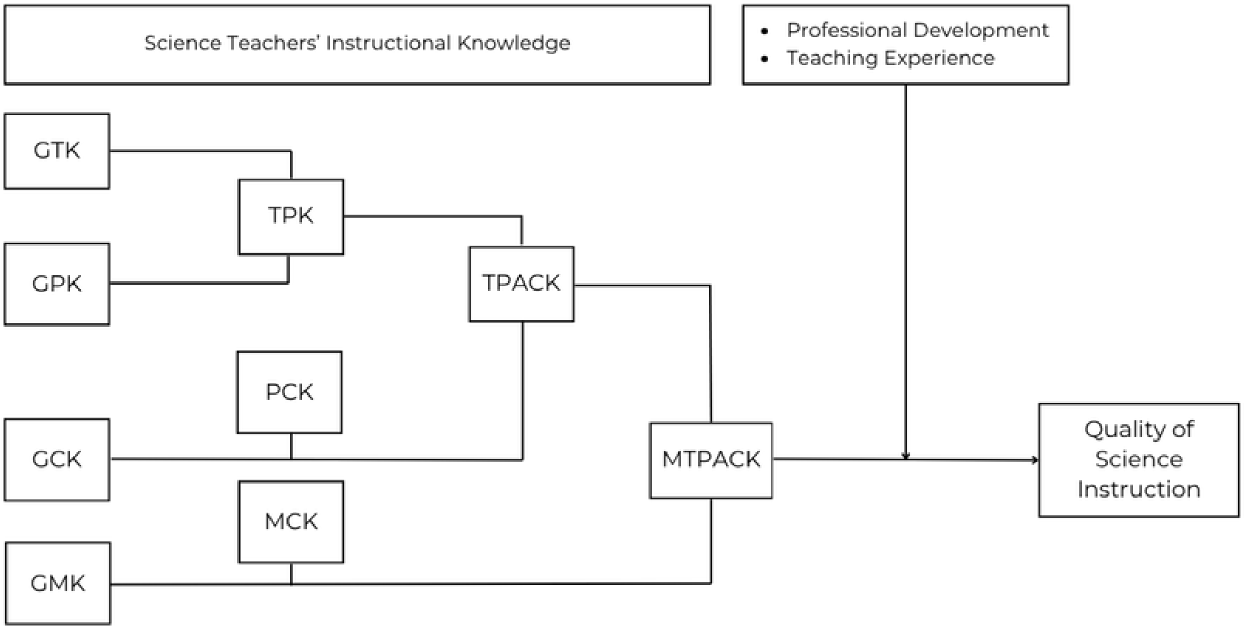
Note. Adopted from Mishra and Koehler (2006).

To achieve effective technological integration, Puentedura (2006) developed the Substitution, Augmentation, Modification, and Redefinition [SAMR] model, which outlines the trajectory for teachers to implement their knowledge of technology based on their proficiency relative to other instructional knowledge (Hamilton et al., 2016). While both frameworks highlight certain types of knowledge required for teaching and possible combinations for effective teaching, this study argues that teachers' knowledge is not fully comprehensive as suggested by Mishra and Koehler (2006) and Puentedura (2006) without specific reference to knowledge of teaching methodology.

Specifically, knowledge of teaching methodology is essential for effective and high-quality instruction, particularly in the sciences. Although various studies have explored the application of the TPACK model with differing levels of success and recommendations, the model has not been statistically tested to determine the relative importance of different types of knowledge for instructional quality. Therefore, this study proposes a new model, as illustrated in Figure 2.

Figure 2

Moderating Effect of Teachers' experience and Professional Development on the Relationship between instructional Knowledge and Quality of Science Instruction



Note. GTK: General knowledge of technology; GPK: general knowledge of pedagogy; TPK: Techno-pedagogical knowledge; GCK: General content knowledge; GMK: General methodological knowledge; PCK: Pedagogical content knowledge; TPACK: Technological pedagogical content knowledge; MCK: Methodological content knowledge; MTPACK: Methodological technological pedagogical content knowledge

Figure 2 illustrates the layers and levels of knowledge and the expected interactions in science teaching. The first layer represents general knowledge [GK] regarding Technology [T], Pedagogy [P], Content [C], and Teaching Methods [M] that teachers are expected to possess. The second layer combines general knowledge of pedagogy [GPK] with technology [GTK], resulting in techno-pedagogical knowledge [TPK] or other like PCK and MCK; the possible combination of these two coincides with the era when technologies such as projectors and computers were primarily used to facilitate teaching (Basilaia & Kvavadze, 2020). The third layer, TPACK, represents the integration of Technology, Pedagogy, and Content Knowledge, associated with the digitalisation era where teaching materials and content are converted into digital formats for enhanced pedagogical interaction, whether in-person or online (Ojetunde & Ramnarain, 2023a). The fourth layer, MTPACK, coincides with the advent of the Fourth Industrial Revolution, where technology influences teaching methods that shape content and pedagogy (learning interactions).

In science education, the experimental/laboratory method is a prominent teaching methodology. MTPACK facilitates the use of virtual laboratories along with its associated pedagogy and teaching content. Inquiry-Based Learning [IBL] is another well-known method in science teaching, and the incorporation of Virtual Reality [VR] has enhanced IBL with its relevant pedagogical approaches applicable to instructional content. Scaffolding is a widely recognized teaching strategy, not only in science; the emergence of intelligent tutors/agents has integrated scaffolding within Intelligent Tutoring Systems [ITS]. Therefore, it can be argued that knowledge of how to integrate technology into science teaching extends beyond the instructional content and pedagogy proposed by Mishra and Koehler (2006) and Puentedura (2006). In summary, in the present era, the knowledge and incorporation of teaching methods within the TPACK framework have informed the development of advanced learning technologies such as Virtual Laboratories [VL], Virtual Reality [VR], and Intelligent Tutoring Systems [ITS], which are driving contemporary science instruction.

Additionally, possible factors that can influence the causal relationship between instructional knowledge and the quality of science teaching, such as professional development and teaching experience, were incorporated into the model. It is hypothesized that teachers' teaching experience, measured by the number of years spent in teaching, along with professional development, could impact the relationship between teachers' instructional knowledge and the quality of instruction, as illustrated in Figure 2.

2.1. Relationship between Teachers’ Knowledge of Teaching Methodology and Quality of Science Instruction

Science instruction employs various methodologies, including laboratory/experimental methods, inquiry-based learning, problem-based learning, and project-based learning. Among these, the 5E instructional model, argument-driven inquiry-based laboratory instruction, socio-scientific issues-based instruction, the jigsaw method, instructional technology, and material design courses have been identified as the most effective for pre-service science teachers (Mukagihana, 2021; Ramnarain & Schuster, 2014). Teaching science through inquiry-based methods, such as visits to authentic university laboratories and analyzing adapted primary literature, effectively enhances students' understanding of the nature of science (Tsybulsky, 2018). The primary distinction between science and other subject areas lies in the discovery-oriented methodologies that stimulate curiosity and inquiry among learners during classroom instruction. Reports indicate that high-quality science instruction, whether through guided inquiry-based methods, direct instruction, or explicit teaching of the nature of science, improves student learning outcomes (Aditomo & Klieme, 2019; Teig & Nilsen, 2022). This study proposes that understanding teaching methodology is crucial for delivering high-quality science instruction. Thus, the hypothesis is as follows:

H1: There is no significant effect of teachers' knowledge of methodology on the quality of science instruction.

2.2. Relationship between Teachers’ Content Knowledge and Quality of Instruction

The relationship between teachers' content knowledge and the quality of instruction is complex and multifaceted. While teacher content knowledge is important, its direct impact on instructional quality and student outcomes is often mediated by other factors, such as instructional practices (Sutherland et al., 2022). A study by Blömeke et al. (2022) revealed that teacher knowledge content and skills mediate the relationship between teacher knowledge and students' learning progress in mathematics, with no direct effects of teacher knowledge found.

Additionally, Baumert et al. (2010) reported that teachers' pedagogical content knowledge significantly enhances student progress in secondary-level mathematics through cognitive activation and individualized learning support. Many studies have indicated that academic content knowledge has a substantial effect on student achievement (Gess-Newsome et al., 2019). However, there is a lack of research on the influence of teachers’ content knowledge on the quality of instruction, particularly in the sciences. This study seeks to examine the relationship between these two constructs by testing the following hypothesis:

H2: There is no significant influence of teachers' instructional content knowledge on the quality of science instruction.

2.3. Teachers’ Technology Knowledge and Quality of Instruction

Teachers' technological knowledge alone does not directly enhance instructional quality; it must be integrated with pedagogical and content knowledge to be effective. This integration, as outlined in the Technological Pedagogical Content Knowledge model, is essential for improving teaching effectiveness (Adipat et al., 2023; Akinyemi & Ojetunde, 2019; Rosyidi et al., 2024). Research shows that most pre-service teachers who demonstrate inadequate knowledge of technology weaken the quality of instruction (Ramaligela, 2020). Continuous professional development is vital for teachers to effectively integrate technology into the classroom and enhance instructional quality (Adipat et al., 2023; Rohaan et al., 2010). Literature consistently reports that the effect of teachers' technological knowledge on the quality of instruction grows over time. Zheng et al. (2023) suggest that as teachers become more adept at using technology, they experience increased flexibility, a wider range of content coverage, and improved instructional quality. Consequently, the present study hypothesises that:

H3: Teachers' technology knowledge has no significant influence on the quality of science instruction.

2.4. Teachers' Pedagogical Knowledge and Quality of Instruction

The link between teachers' pedagogical knowledge and the quality of instruction is a critical area of research in education. Pedagogical knowledge encompasses general pedagogical knowledge [GPK] (König et al., 2021; König & Pflanzl, 2016;) and is a subset of pedagogical content knowledge (Fauth et al., 2019; Gess-Newsome et al., 2019;), both of which are consistently associated with instructional quality and student outcomes. Teachers' GPK is positively correlated with instructional quality, incorporating effective classroom management, teaching methods, and teacher-student relationships. It serves as a significant predictor of instructional quality, even when considering other factors such as teacher education and experience (König et al., 2021). Similarly, PCK is crucial for delivering high-quality instruction and enhancing student achievement, as research has demonstrated that it positively affects instructional quality, which in turn impacts student learning outcomes (Baumert et al., 2010; Kunter et al., 2013). Furthermore, instructional quality, influenced by teachers' pedagogical knowledge, plays a mediating role in the relationship between teacher competence and student outcomes (Blömeke et al., 2022). The present study, however, examines the direct relationship between pedagogical knowledge and the quality of science instruction. Therefore, the hypothesis is:

H4: Teachers' pedagogical knowledge has no significant direct influence on the quality of science instruction.

2.5. Moderating Effects of Teaching experience and professional Development on Quality of Instruction

Studies suggest that teaching experience generally enhances the quality of instruction and student satisfaction, particularly in supportive environments and smaller classes. However, the effect may plateau or decline after many years, but targeted support and professional development are beneficial for all teachers irrespective of their years of teaching (Graham et al., 2020; Podolsky, 2019). Graham et al. (2020) also revealed that there is no significant evidence indicating that beginning teachers (0-3 years of experience) provide lower quality instruction compared to their more experienced counterparts. However, a decline in teaching quality is observed for teachers with 4-5 years of experience, highlighting the need for targeted support during this period.

While teaching experience has limited moderating effects on instructional quality, Ko and Chung (2015) suggest that continuous professional development and engagement in professional learning activities are crucial for maintaining and enhancing teaching quality, regardless of experience level. Furthermore, studies that establish the relationship between teachers' instructional knowledge and the quality of instruction have typically been conducted in specific contexts. There is a paucity of research investigating the moderating effect of teacher professional development and teaching experience on the relationship between teachers' instructional knowledge, including knowledge of teaching methodology, and the quality of teaching in the sciences. This highlights a research gap that the present study intends to address. Thus, the hypothesis is formulated as follows:

H5: Teachers' teaching experience and level of professional development have no significant moderating effect on the relationship between teacher instructional knowledge (pedagogical, technological, content, and methodological knowledge) and the quality of science instruction.

2.6. Research Questions

The following research questions guide the study:

RQ 1) How significant is the various instructional knowledge of science teachers to the quality of science teaching during classroom instructional activities?

RQ 2) Can teaching experience and professional development moderate the relationship between teachers' instructional knowledge and the quality of instructional delivery?

3. Methodology

The study employed a cross-sectional approach to data collection, meaning that data were gathered from different cohorts of science teachers. The data used for this study were extracted from the Trends in International Mathematics and Science Study (TIMSS) 2023, released in February 2025. This dataset includes information from science teachers in 47 countries across various continents. Specifically, the grade-8 science version of the data was utilized, encompassing multiple variables that elicited responses from teachers in the participating countries. A total of 25,078 teachers from 47 countries completed the questionnaire; however, after removing incomplete cases, 22,490 responses were used for data analysis.

3.1. Demographic Characteristics

The demographic characteristics of the respondents (teachers who participated) revealed that 67.4% were female, 31.4% were male, and 1.2% identified as neither male nor female. In terms of age, 2.3% of the sample teachers were below 25 years, 9.8% were between 25-29 years, 27.6% fell within the 30-39 years age range, 28.6% were 40-49 years old, 21.8% were 50-59 years, and 9.0% were aged 60 years or older. The mean teaching experience of the sample teachers was 16.49 years, with a standard deviation of 11.00.

Regarding the respondents' level of formal education, 48.6% held bachelor's degrees, 44.1% had master's degrees, and 3.1% possessed PhD equivalents, while 2.5% had education below the bachelor's level. Additionally, 12.1% were Physics teachers, 11.1% were Biology teachers, 10.9% were Chemistry teachers, 9.7% were Earth science teachers, 9.7% taught integrated science, and 12.6% taught a combination of two subjects. The preferred languages of response among the sample teachers indicated that 22.9% preferred English, 10.7% preferred Arabic, 2.3% preferred French, while others responded in different languages.

3.2. Instrumentation

The teachers' version of the TIMSS 2023 data consists of various variables that measure teachers' professional constructs, classroom activities, and expertise related to general and specific subjects, including Biology, Chemistry, Physics, Earth science, and Mathematics. While all subjects except Mathematics are classified as science, the content knowledge of science teachers is measured in terms of proficiency in Biology, Chemistry, Physics, and Earth science. Additionally, the data includes measures of teachers' knowledge of methodology, technology, and pedagogy, as well as their professional development experiences and the quality of instruction. Table 1 presents the various related constructs included in the data along with the corresponding codes used for them.

The constructs were revalidated to ensure their suitability for the analytical procedures in the present study. The reliability and validity of the constructs are detailed under the validation procedure.

Table 1
Construct's Code and the number of Items

Construct	*Code*	*Acronym*	*Number of Items*
Biology Content	BTBS22AA- BTBS22AP	CKB	16
Chemistry Content	BTBS22BA- BTBS22BJ	CKC	10
Physics Content	BTBS22CA- BTBS22CM	CKP	13
Earth Science Content	BTBS22DA-BTBS22DL	CKE	14
Knowledge of Methodology	BTBS16A- BTBS16H	MEK	8
Knowledge of Technology	BTBS20C- BTBS20DF	TEK	9
Knowledge of Pedagogy	BTBS15A- BTBS15AI	PEK	9
Professional Development	BTBS25AA-BTBS25BH	TPD	16
Quality of instruction	TBG012A- TBG012AG	QOI	7

3.3. Validation Procedure

In addition to the initial validation conducted before the data collection, the items of each construct were further validated using the TIMSS 2023 data to assess their suitability for the proposed analytical procedures. The coefficients for reliability and validity statistics are presented under each section.

3.4. Reliability

Three statistics—Cronbach's Alpha reliability coefficient, composite reliability, and Average Variance Extracted [AVE]—were estimated, as presented in Table 2, to assess the reliability of the constructs.

Table 2
Reliability Coefficients of the Constructs in the Study

Construct	*Cronbach's alpha*	*Composite reliability (rho_a)*	*Composite reliability (rho_c)*	*Average variance extracted (AVE)*
CKB	0.984	0.985	0.986	0.854
CKC	0.990	0.990	0.991	0.915
CKE	0.973	0.985	0.980	0.800
MEK	0.978	0.978	0.981	0.866
PEK	0.944	0.945	0.953	0.692
CKP	0.990	0.990	0.991	0.892
TPD	0.969	0.971	0.972	0.682
QOI	0.942	0.943	0.953	0.742
TEK	0.911	0.918	0.921	0.565

The results revealed that the Cronbach's Alpha reliability coefficients ranged from 0.911 to 0.990, exceeding the benchmark of 0.70, indicating that the constructs are reliable. The composite reliability also ranged from 0.918 to 0.991, surpassing the cutoff mark of 0.70. Additionally, the Average Variance Extracted ranged from 0.565 to 0.915, exceeding the benchmark of 0.5. These findings indicate that the constructs used in the study are reliable and can explain a significant percentage of the variance in the concepts being measured.

3.5. Validity of the Constructs

Three possible validity measures—cross-loading, Fornell-Larcker criterion, and the Heterotrait-Monotrait Method (HMM)—were employed to establish the discriminant validity of the constructs. While all three approaches yielded acceptable results, the HMM was reported for ease of interpretation, as presented in Table 3.

Table 3
Construct Validity Using Heterotrait-Monotrait Approach

Construct	CKB	CKC	CKE	MEK	PEK	CKP	TPD	QOI
CKB								
CKC	0.456							
CKE	0.666	0.443						
MEK	0.163	0.171	0.169					
PEK	0.164	0.185	0.167	0.649				
CKP	0.406	0.558	0.485	0.164	0.179			
TPD	0.136	0.141	0.156	0.501	0.584	0.142		
QOI	0.134	0.140	0.150	0.450	0.471	0.129	0.387	

Discriminant validity measures the distinctiveness of each construct, ensuring that the constructs in the model do not measure the same concept. The general assumption behind the Heterotrait-Monotrait Method [HMM] is that the relationship coefficients between a construct and others should not reach 1.0. In other words, the correlation coefficients among constructs in the model must not exceed the cutoff mark of 0.80. From Table 3, it can be observed that the intercorrelation coefficients among the constructs are significantly less than 0.80, indicating that the constructs in the model possess discriminant validity.

3.6. Analytical Procedure

As an alternative to Covariance-Based Structural Equation Modelling [CB-SEM], Partial Least Squares Structural Equation Modelling [PLS-SEM], a variance-based SEM, was adopted for the analysis of the data in this study. This choice was made primarily because both the measurement and structural models need to be built and tested to validate the constructs and determine the significance of causal relationships among the variables in the model. This is achieved through path algorithms and bootstrapping procedures. While the path algorithm estimates the coefficients of reliability and validity of the measurement model, bootstrapping is used to test the significance of causal relationships and moderations.

4. Results

The preliminary results of the analysis reveal two distinct outputs: the model quality evaluation criteria, as presented in Table 4, and the path model diagram, shown in Figure 2.

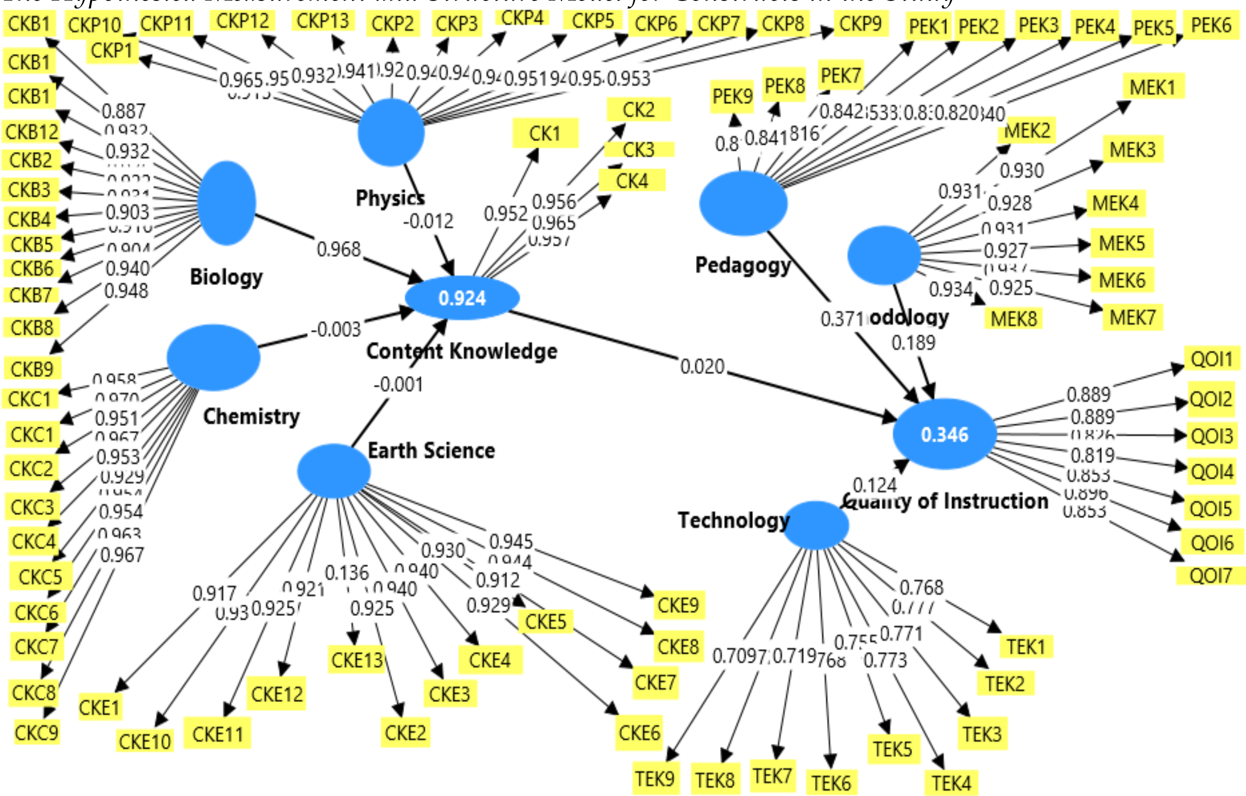
Table 4
Model Evaluation Criteria

Criteria	*Saturated model*	*Estimated model*
Chi-square	287039.308	287072.494
NFI	0.903	0.903
SRMR	0.048	0.048
d_G	2.117	2.117
d_ULS	8.431	8.479

The results from Table 4 present the coefficients of various model fit indicators. The analysis revealed a Norm Fit Index (NFI) of 0.903, which exceeds the benchmark of ≥0.9, indicating that the model can explain 90.3% of its intended purpose. Additionally, the Standardised Root Mean Square Residual [SRMR] was found to be 0.05, well below the benchmark of ≤0.1 (Henseler et al., 2014). The values of d_G (2.11) and d_ULS (8.47) further suggest that the model is a good fit. Figure 3 illustrates the factor loadings for the inner (Measurement) model, as well as the causal relationships and coefficients, along with the R^2 of the outer (Structure) model.

Figure 3

The Hypothesied Measurement and Structure Model for Constructs in the Study



The results indicate that Physics, Chemistry, Biology, and Earth Science together account for 92.4% of the content knowledge in science, with Biology (β = 0.968) explaining the largest portion. Additionally, Content (β = 0.02), Technology (β = 0.12), Methodology (β = 0.19), and Pedagogical Knowledge (β = 0.37) collectively account for 34.6% of the total variance in the quality of science instruction. This implies that pedagogical knowledge has a greater impact on the quality of science instruction compared to other types of knowledge. The significance of the causal relationships between various kinds of teachers' knowledge and the quality of science instruction is presented as responses to the research questions.

4.1. Research Question 1: How significant is the various instructional knowledge of science teachers to the quality of science teaching during classroom instructional activities?

The answer to Research Question 1 explains the relationship between various types of science instructional knowledge and the quality of instruction, as presented in Table 5.

The results in Table 5 show the mean weight of each construct, the standard deviation [STDEV], and the magnitude of effect (t-statistics). The findings reveal that knowledge of science teaching methodology (β = 0.188, t = 10.095, p < 0.05), pedagogy (β = 0.37, *t* = 16.79, *p* < .05), technology (β = 0.124, *t* = 9.693, *p* < .05), and content (β = 0.020, *t* = 3.877, *p* < .05) significantly influence the quality of science instruction. The *t*-statistics indicate that knowledge of pedagogy, methodology, technology, and content are important in that order. This suggests that pedagogical knowledge is the strongest predictor of quality instruction, followed by knowledge of teaching methodology. Therefore, knowledge of pedagogy and teaching methods emerge as the top predictors of quality science instruction.

Table 5
Causal Relationship between Teachers' Instructional Knowledge and Quality of Teaching

Pathway	*Original sample (O)*	*Sample mean (M)*	*Standard deviation (STDEV)*	*T statistics (|O/STDEV|)*	*P-value*
Biology → Content Knowledge	0.968	0.968	0.002	466.318	<.001
Biology → Quality of Instruction	0.020	0.020	0.005	3.877	<.001
Chemistry → Content Knowledge	−0.003	−0.003	0.002	1.797	.072
Chemistry → Quality of Instruction	-0.000	−0.000	0.000	1.608	.108
Content Knowledge → Quality of Instruction	0.020	0.020	0.005	3.877	.000
Earth Science → Content Knowledge	−0.001	−0.001	0.002	0.306	.760
Earth Science → Quality of Instruction	−0.000	−0.000	0.000	0.295	.768
Methodology → Quality of Instruction	0.189	0.188	0.019	10.095	<.001
Pedagogy → Quality of Instruction	0.371	0.370	0.022	16.793	<.001
Physics → Content Knowledge	−0.012	−0.012	0.002	7.306	<.001
Physics → Quality of Instruction	−0.000	−0.000	0.000	3.374	.001
Technology → Quality of Instruction	0.124	0.124	0.013	9.693	<.001

4.2. Research Question 2: Can teaching experience and professional development moderate the relationship between teachers' instructional knowledge and the quality of instructional delivery?

The answer to this research question reveals the moderating role of science teachers' professional development and experience on the relationship between instructional knowledge and the quality of instruction. The TIMSS Grade 8 data from the 2023 version measures professional experience in terms of years of teaching, making it a metric variable, while professional development is assessed through a series of yes or no (categorical) scale items. Figure 4 presents a graphical output illustrating the moderated relationship.

The results indicate that the moderated model (see Figure 4) explains a larger percentage of variance (R^2 = 0.374) in the quality of instruction compared to the ordinary causal model (R^2 = 0.346) shown in Figure 3. This implies a 2% increase (from 34.6% to 36.7%) in explanatory power for the moderated model. The slope analysis of the moderating effect is illustrated in Figures 5 and 6, showing the number of standard deviations below or above the mean quality of instruction when a construct is moderated by a metric variable. For a categorical moderator, it reflects changes in quality of instruction at zero and one standard deviation.

Figure 5 demonstrates the moderating effect of teaching experience, revealing that teaching experience more effectively moderates teachers' knowledge of teaching methodology in science, followed by technology, pedagogy, and then content knowledge. At one standard deviation, the slope of quality of instruction becomes steeper, indicating a wider deviation from the mean (red line).

Figure 4

Moderated relationship between Teachers' Instructional knowledge and quality of instruction

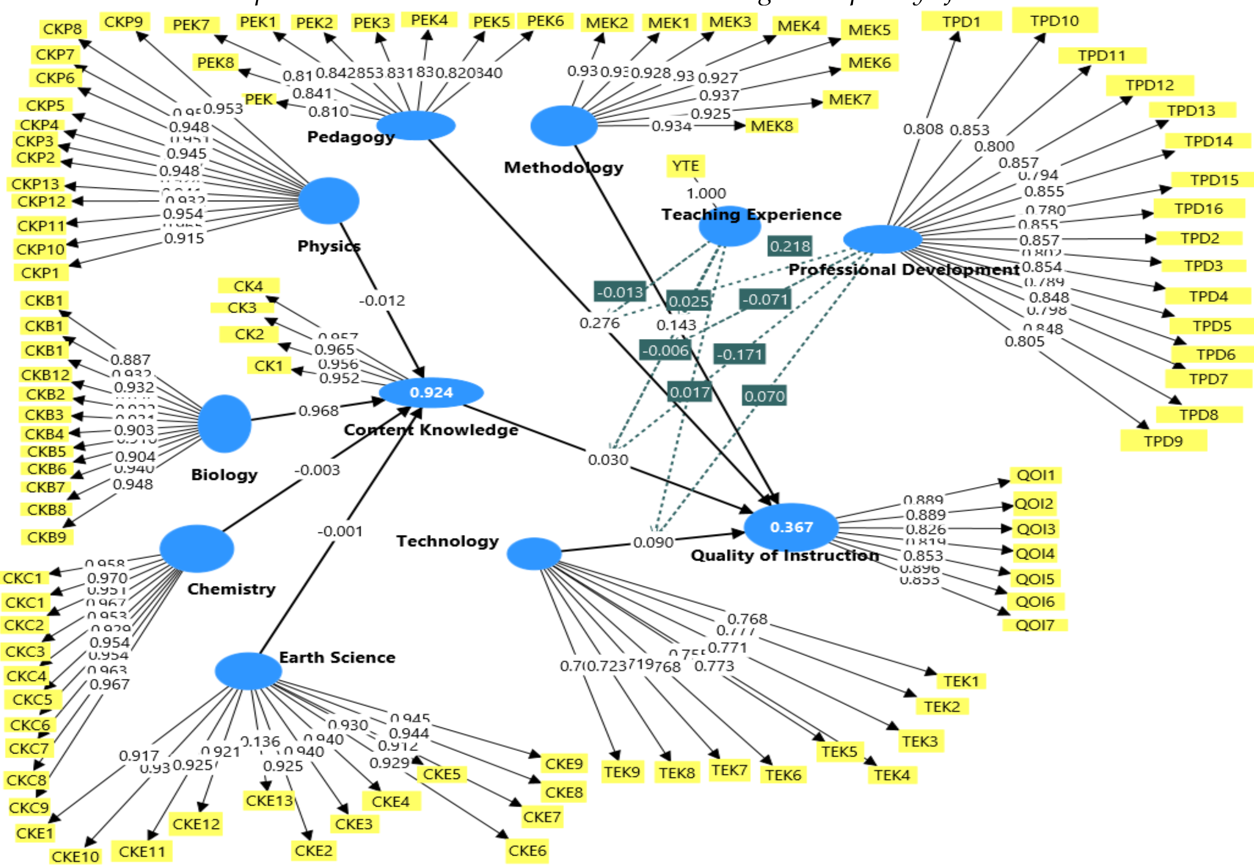
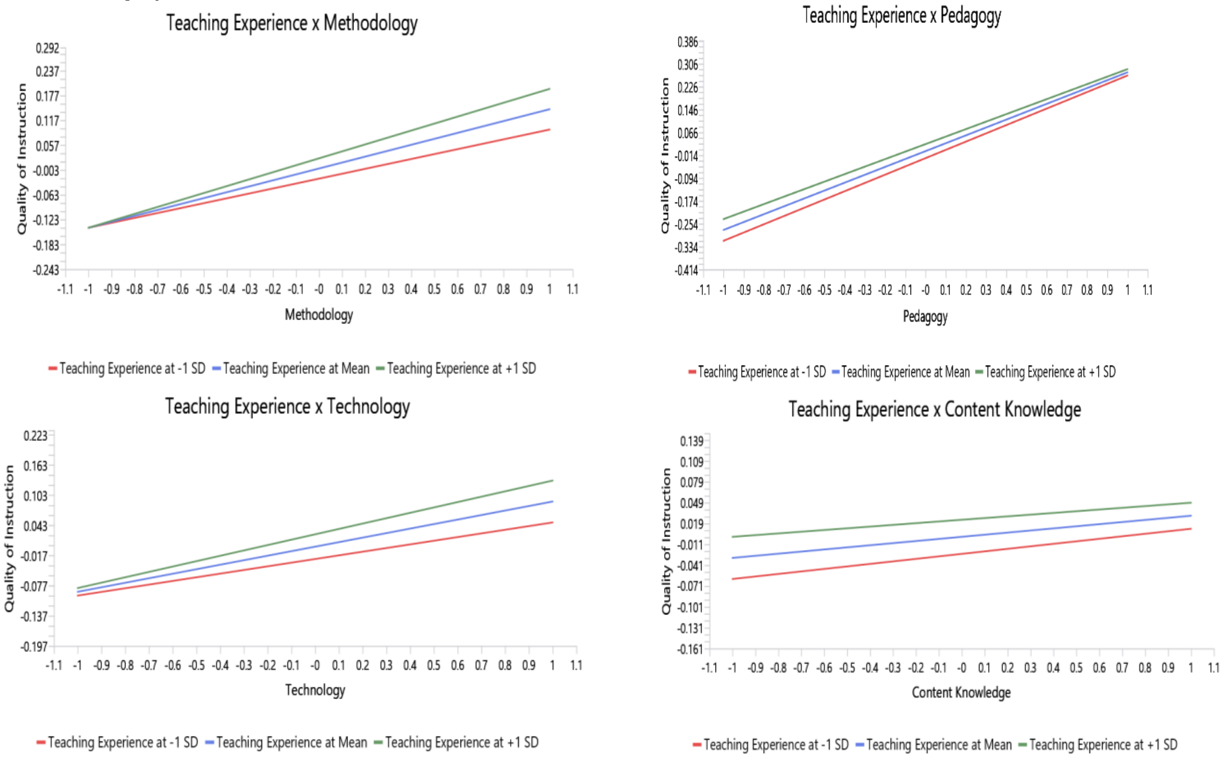


Figure 5

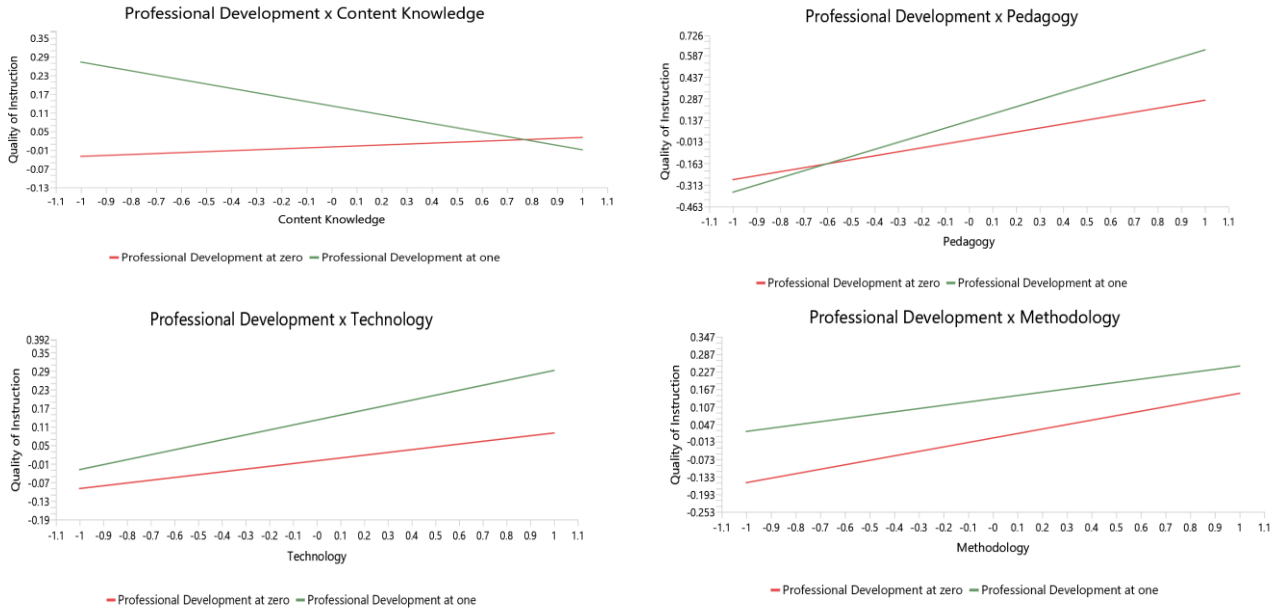
Slope Analysis of Moderating effect of teaching experience on relationship between instructional knowledge and Quality of Instruction



The results from Figure 6 reveal changes in the quality of instruction after the effects of various instructional knowledge are moderated. It can be observed that the relationship between technology knowledge and quality of instruction is perfectly moderated. The effect of professional development on the relationship between knowledge of science teaching methodology and quality of instruction is more pronounced compared to knowledge of pedagogy. In contrast, the moderating effect of professional development on the relationship between content knowledge in science and quality of instruction is negative. Furthermore, the results indicate that professional development and teaching experience have little to no effect on science teachers' content knowledge.

Figure 6

Slope Analysis of moderated relationship between instruction Knowledge and Quality of instruction by Professional Development



Therefore, we can infer that teachers' technological knowledge significantly enhances the quality of instruction in science subjects, especially after gaining more professional experience and development. However, average levels of professional development and teaching experience are sufficient to improve science teachers' knowledge of pedagogy and teaching methodology, thereby enhancing the quality of instruction.

5. Discussion

The study hypothesized that the quality of instruction in sciences could be explained by the level of teachers' instructional knowledge, moderated by years of teaching experience and associated professional development. The results revealed that teachers' knowledge of teaching methods, pedagogy, content, and technology significantly influences the quality of instruction in sciences. This may be attributed to the unique nature of science teaching, which emphasizes methods aimed at enhancing student discovery and accommodating innovations such as technology integration across various concepts and topics. These findings align with Aditomo and Klieme (2019) and Teig and Nilsen (2022), who demonstrated that explicit teaching of the nature of science using high-quality instructional methodologies, such as inquiry-based learning, enhances student learning outcomes. Additionally, Tsybulsky (2018) reported that instructional methods are crucial for students' understanding of the nature of science.

Additionally, the results revealed that both professional development and teachers' teaching experience can moderate the relationship between instructional knowledge and the quality of science instruction. However, teaching experience did not consistently moderate the relationship between instructional content knowledge and quality of instruction. This may be due to the fact that instructional content in sciences remains relatively stable and can be mastered within a few years of teaching.

These findings align with existing literature. Ko and Chung (2015) suggest that continuous professional development and engagement in professional learning activities are crucial for maintaining and enhancing teaching quality, regardless of experience level. Similarly, Graham et al. (2020) and Podolsky (2019) reported that while teaching experience generally enhances the quality of instruction and student satisfaction, this effect may decline after prolonged years of experience. Professional development is beneficial for all teachers, indicating that the regression effect of teaching experience on quality of instruction is particularly relevant in the area of content knowledge, which may become archaic without ongoing professional development.

Furthermore, the results demonstrate the significant influence of content, pedagogy, technology, and teaching method knowledge. This implies that instructional knowledge in sciences extends beyond traditional technological pedagogical content knowledge, as reported by Puentedura (2006) and Mishra and Koehler (2006). The findings reveal that knowledge of science instruction content (Gess-Newsome et al., 2019; Ojetunde & Ramnarain, 2023b; Sutherland et al., 2022), technology (Rosyidi et al., 2024; Zheng et al., 2023), pedagogy (Fauth et al., 2019; König et al., 2021), and methodology (Mukagihana, 2021; Ramnarain & Schuster, 2014) are reliable predictors of quality instruction and can be moderated by professional development and teaching experience.

6. Theoretical Implication

The findings of the study imply that knowledge of content, pedagogy, and technology alone is insufficient for the successful integration of technology in teaching and learning sciences; teachers' knowledge of methodology is also essential for effective technology integration. Moreover, when designing a research study that involves a teaching method (such as experimental or scaffolding) integrated with computer programming to facilitate learning, the extended TPACK model [MTPACK] is appropriate. This integration may require an innovative combination of the General Methodological Knowledge [GMK] with other instructional knowledge or modifications of either (e.g., MTK), both [MTPK], or all components. For instance, in a virtual laboratory setting, a modified methodology, modified pedagogy, and modified technology can be combined with existing content knowledge. Similarly, in an Intelligent Tutoring System [ITS], all components of MTPACK were adjusted. In this context, scaffolding (teaching methodology) was utilized based on data generated from learners regarding their academic abilities and interaction patterns. This data-informed approach was used to modify both the content of instruction and the associated pedagogy.

7. Conclusion

The study represents a significant effort to explore the various instructional knowledge necessary for high-quality science teaching and the factors that influence it. It concludes that knowledge of teaching methodology is as crucial as other instructional knowledge areas, such as content and pedagogy, when integrating technology into science education. Additionally, it finds that teachers' professional development can moderate the relationship between their instructional knowledge and the quality of science instruction. While teaching experience also plays a role, there may be a regression effect over time concerning science teachers' content knowledge. Therefore, incorporating teaching methodology into the TPACK model of technology adoption will provide a comprehensive understanding not only of technology integration but also of the potential combinations of instructional knowledge that science teachers need to effectively adopt advanced learning technologies in STEM education.

8. Recommendations

The study's findings emphasize the importance of various types of instructional knowledge for teachers and the effective combinations necessary for successful technology integration. This underscores the need for science teachers to continuously enhance their instructional knowledge to improve their teaching effectiveness. Additionally, the findings suggest that educational stakeholders, such as government and school administrators, should prioritize professional development for science teachers to ensure they remain updated on the latest advancements in instructional knowledge. Furthermore, researchers are encouraged to adopt a holistic instructional knowledge model, such as MTPACK, in studies on technology integration, which encompasses teaching methods alongside content, pedagogy, and technology knowledge.

9. Limitations and Suggestions

This study has several limitations, especially concerning its design and the data used. The cross-sectional approach prevents the establishment of causal relationships among the constructs, which could be achieved with an experimental design. Additionally, the reliance on secondary data restricts the researchers' control over the variables and the data collection process. Moreover, since data was gathered exclusively from eighth-grade science teachers, this may reduce the external validity of the findings. Therefore, it is recommended that future researchers adopt an experimental approach and utilize primary data when conducting similar investigations.

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Data availability: Data used for this study is available in public domain (https://timss2023.org/data/).

Ethical statement: Ethical approval is not required for this study because it is a non-interventional study that utilizes secondary data from the publicly available TIMSS database.

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