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The Effects of Teachers' Technological Pedagogical Content Knowledge (TPACK) on Students' Scientific Competency

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Abstract

The integration of Technological Pedagogical Content Knowledge (TPACK) into instructional design is pivotal for teachers. This intricate knowledge framework encompasses the interplay between technology, pedagogy, and subject matter, profoundly impacting the multifaceted aspects of student learning, encompassing knowledge acquisition, skill development, and the cultivation of desirable attributes. This research at hand adopts an exploratory approach, examining two sample groups: 1) Science teachers from secondary schools under the Northeastern Region of Thailand during the academic year 2565–2566, totaling 124 individuals, and 2) Secondary school students receiving instruction in science-related subjects from the aforementioned teachers, with a minimum of one classroom involved. Data collection tools include a survey on TPACK, a scientific competency assessment, and semi-structured interviews. Statistical analysis employs mean, standard deviation, and content analysis. Testing of hypothesis uses One-Way Analysis of Variance (One-Way ANOVA). The study reveals that students taught by science teachers with varying levels of TPACK exhibit statistically significant differences in scientific competency at a 0.05 significance level. When comparing scientific competency with TPACK levels of teachers, statistically significant differences at the 0.05 level are found in two pairs: 1) the Adapting level and the Advancing level and 2) the Exploring level and the Advancing level.

Keywords: teacher knowledge, teacher education, professional development, scientific competency

1. Introduction

Scientific competency stands as a cornerstone in the intellectual and practical development of individuals, playing a pivotal role in shaping informed and critical thinkers who can navigate the complexities of our modern world (OECD, 2023). The significance of scientific competency extends far beyond the realms of laboratory experiments and theoretical knowledge (OECD, 2019). It empowers individuals to comprehend, question, and contribute meaningfully to the scientific advancements that drive progress in diverse fields. Based on PISA 2015 framework, there are 3 aspects in scientific framework: Explain phenomena scientifically, Evaluate and design scientific enquiry, and Interpret evidence and data scientifically. Explain phenomena scientifically means ability to perceive, generate, apply, and assess explanations and problem-solving approaches for natural and technological phenomena, demonstrates competencies such as: 1) Applying scientific knowledge appropriately; 2) Using various formats to represent knowledge and interpreting the meaning of such information; 3) Creating and verifying the accuracy of scientific predictions and problem-solving methods; 4) Identifying, constructing, and assessing models; 5) Perceiving and generating explanatory hypotheses for various phenomena and 6) Describing the potential of applying scientific knowledge for societal benefit. Evaluate and design scientific enquiry involves the ability to design and assess inquiry processes. This includes methods for formulating scientifically oriented questions and interpreting data. The competencies are as follows: 1) Formulating questions in scientific studies as specified; 2) Designing appropriate experiments to address questions; 3 Evaluating whether the designed experiments are the most suitable for answering the questions; and 4) Interpreting presented data in various formats, drawing appropriate conclusions, and assessing the relevance of the information provided. The last one is Research, evaluate and use scientific information for decision making and action. It is the competency in studying, researching, evaluating, and using scientific data for decision-making and action involves the ability to investigate, evaluate, and communicate information, scientific statements, and disputes presented in various formats and contexts., showcasing proficiency in the following skills: 1) Researching, evaluating, and communicating the relevance of information from various sources (scientific, social, economic, and ethical) that may be significant or valuable for making decisions on science-related issues, supporting arguments, or suggesting problem-solving approaches; 2) Distinguishing between scientifically supported statements and statements from experts, compared to those from non-experts or the general public, and providing reasoning for such distinctions; 3) Generating arguments to support scientifically appropriate conclusions from a set of data; 4) Critiquing common flaws in disputes related to science, utilizing knowledge of the acquisition and processing of information, such as poorly formulated hypotheses, causal relationships, inaccurate explanations, and limited conclusions from available data; 5) Making decisions using scientific disputes, either individually or collectively, contributing to addressing current issues or supporting sustainable development (OECD, 2015). The landscape of scientific competency development is undergoing a transformative shift, propelled by advancements in technology, evolving educational paradigms, and an ever-growing awareness of the importance of scientific literacy in a rapidly changing world. As we navigate the 21st century, the traditional approaches to cultivating scientific competency are being redefined to meet the demands of a dynamic and interconnected global society. This introduction delves into the changing dynamics of scientific competency development, exploring the factors influencing this evolution and the implications for individuals, education systems, and the broader socio-economic fabric. From personalized learning experiences to interdisciplinary approaches, the contemporary journey towards scientific competency reflects a commitment to equipping learners with the skills needed to thrive in an era defined by innovation and scientific discovery. Scientific competency, a cornerstone of informed citizenship and societal progress, grapples with a myriad of challenges in its developmental journey. This introduction delves into the critical issues that pose obstacles to the effective cultivation of scientific competency. From disparities in educational access to persistent gender and diversity gaps in STEM fields, these challenges not only impact individual learning journeys but also have broader implications for the scientific community and society at large. The integration of technology in education has ushered in a paradigm shift, emphasizing the pivotal role of teachers in facilitating effective learning experiences for students. The Technological Pedagogical Content Knowledge (TPACK) framework has emerged as a valuable model, guiding educators in seamlessly blending technology, pedagogy, and content knowledge (Koehler, 2013). According to by Niess et al. (2006), there are 5 levels of TPACK include 1) the level of Advancing; eagerly considers using TPACK in a variety of ways in building concepts—encourages student hands-on explorations and experimentation, incorporates TPACK in student assessment, 2) the level of Exploring; examines different ways of teaching mathematics content—willing to demonstrate new ways of thinking about concepts with TPACK, able to manage the classroom and carefully guide students toward gaining the concept. 3) the level of Adapting; tries ideas for incorporating TPACK in teaching—but in teaching students, at best has students use drill and practice of the ideas with the TPACK. 4) the level of Accepting; practices using with different capabilities of teacher knowledge but not a consistent thought, and 5) the level of Recognizing; Recognizes all seven aspects of TPACK but rarely thinks about incorporating this knowledge. In the context of students' scientific competency, teachers equipped with a robust understanding of TPACK play a crucial role in fostering a dynamic and enriched learning environment. This introduction delves into the interconnectedness of teachers, TPACK, and students' scientific competency, exploring how a well-balanced amalgamation of technological expertise, pedagogical strategies, and content knowledge empowers educators to nurture the next generation of scientifically literate individuals.

The research gap lies in understanding the connection between these two critical components of education. While TPACK has been studied in various contexts (Kumala, Ghufron, & Pujiastuti, 2022; Flores & Sabado, 2023; Kotoka & Kriek, 2023), the specific influence of a science teacher's TPACK on students' development of scientific competency remains largely unexplored. Closing this gap is essential for shaping more effective science education practices and fostering deeper understanding and proficiency in scientific concepts among students. Delineating the relationship between science teachers' TPACK and students' scientific competency represents a critical pursuit in the optimization of science education. The Programme for International Student Assessment (PISA) revealed a concerning trend in Thai students' scientific performance (OECD, 2023), prompting a closer examination of educational factors. Understanding the relationship between teachers' proficiency in integrating technology, pedagogy, and content knowledge and students' scientific competency is critical. A comprehensive study, involving assessments of teachers' TPACK levels and students' scientific skills, could unveil insights into the weaknesses in current teaching practices. By elucidating this correlation, we gain valuable insights into the efficacy with which teachers leverage technology, pedagogy, and content knowledge in concert to foster deeper learning experiences. Such findings can inform targeted professional development initiatives, equipping educators with the tools to implement innovative and demonstrably impactful instructional strategies. Furthermore, establishing a positive association between TPACK and student performance would underscore the pivotal role of this framework in cultivating scientific prowess, potentially influencing curriculum design and instructional approaches across the field. Ultimately, this research holds the potential to yield significant contributions to the ongoing endeavor of enhancing science education, ensuring that educators are equipped with the necessary knowledge and skills to nurture students' proficiency and kindle their curiosity within the realm of scientific exploration.

2. Research Methodology

This investigation entails a survey-based research approach, employing questionnaires for science teachers and assessments to evaluate students' scientific competency.

2.1 Participant

The study encompassed science teachers in secondary schools throughout the academic year 2022–2023 across 20 provinces in the northeastern region of Thailand, comprising a total of 458 schools. The sample size was determined utilizing Taro Yamane's formula, taking into account a 95% confidence level with an approximate margin of error of ± 5% (Yamane, 1967). Following the random selection of schools, a convenient sampling strategy was utilized to collect data from science teachers, involving the acquisition of information from 124 teachers in 76 schools. Additionally, a purposive sampling technique was applied to select a subset of students studying science under the selected science teachers.

2.2 Research Instruments

1) The TPACK Questionnaire, adapted from Schmid et al. (2020), was developed using a 5-point rating scale. This survey assesses all seven aspects of TPACK, covering Technological Knowledge (TK), Content Knowledge (CK), Pedagogical Knowledge (PK), Pedagogical Content Knowledge (PCK), Technology Content Knowledge (TCK), Technology Pedagogical Knowledge (TPK), and Technology Pedagogical Content Knowledge (TPACK). Each dimension consists of four items. The questionnaire received content validity confirmation from experts, with a score of 0.95, and item appropriateness scores ranging from 4.88 to 5.00.

2) The Scientific Competency Assessment is formulated as a two-tier multiple-choice test, wherein respondents are prompted to select answers and provide explanations. This assessment framework was crafted in accordance with the conceptual framework outlined in PISA 2015 (OECD, 2015). It encompassed competencies across three domains: ① Explain phenomena scientifically, ② Construct and evaluate designs for scientific enquiry and interpret scientific data and evidence critically, and ③ Research, evaluate and use scientific information for decision making and action. The congruence index between the questions and the observed behaviors was 1.00. Item discrimination ranged from 0.33 to 0.67, and the difficulty level varied from 0.29 to 0.75. The reliability coefficient standed at 0.76.

3) The semi-structured interview related to the teaching practices of the science teachers. The assessment of the instrument's quality involved consulting with five experts to evaluate the content validity of the interview items. The experts determined the content validity to be 1.00, with item appropriateness scores ranging from 4.80 to 5.00.

2.3 Data Collection

The researchers conducted a meeting with the collaborating teachers to provide an overview of the study and secure their consent. Following their approval, data collection occurred through a TPACK questionnaire administered via Google Form. The acquisition of student data will be overseen by the collaborating teachers, who will elucidate the research intricacies and afford students the autonomy to decide on their participation. Data gathering will commence subsequent to the submission of their signed consent forms. Confidentiality and anonymity measures will be strictly adhered to throughout the entirety of the data collection process. Upon the conclusion of the data collection phase, the researchers proceed to analyze the amassed data to categorize the TPACK levels of the teachers. Following this, coordination efforts are undertaken to schedule interviews, segmented by TPACK levels within each group.

2.4 Data Analysis

The data acquired from the questionnaire aimed at evaluating the TPACK level of science teachers underwent analysis through the computation of mean and standard deviation (S.D.). Subsequently, these statistical measures were interpreted in accordance with the framework outlined by Niess et al. (2007), as follows:

4.21–5.00 means the level of Advancing,

3.41–4.20 means the level of Exploring,

2.61–3.40 means the level of Adapting.

1.81–2.60 means the level of Accepting, and

1.00–1.80 means the level of Recognizing.

Concerning the examination of data derived from scientific competency assessments, the researchers meticulously scored and subjected the results to analysis utilizing analysis of variance (ANOVA) statistics to compare means between TPACK level. Moreover, the examination of data obtained through interviews, the researcher organized and categorized the responses prior to conducting content analysis. The findings of this analysis were subsequently presented using a descriptive format.

3. Results

Through an assessment of the scientific competency of students instructed by science teachers exhibiting distinct TPACK levels, discernible variations in scientific competency scores were identified. The particulars are delineated as follows:

Table 1. Students' scientific competency categorized based on the TPACK levels of science teachers

Scientific Competency	Level of TPACK	n	**Full score**	$\bar{X}$	SD	df	F	P
Explain phenomena scientifically	Recognizing	1981	10	3.91	0.34	4	2.919*	0.024
	Accepting			4.01	0.21			
	Adapting			3.97	0.21			
	Exploring			3.98	0.28			
	Advancing			4.17	0.36			
Construct and evaluate designs for scientific enquiry and interpret scientific data and evidence critically	Recognizing	1981	10	3.61	0.32	4	2.263	0.066
	Accepting			3.36	0.21			
	Adapting			3.56	0.74			
	Exploring			3.47	0.67			
	Advancing			3.86	0.64			
Research, evaluate and use scientific information for decision making and action	Recognizing	1981	10	1.85	0.21	4	5.442*	0.000
	Accepting			1.56	0.35			
	Adapting			1.81	0.59			
	Exploring			1.83	0.64			
	Advancing			2.70	1.46			
Scientific Competency	Recognizing	1981	30	8.75	0.42	4	5.084*	0.001
	Accepting			8.65	0.21			
	Adapting			9.17	1.46			
	Exploring			9.30	1.32			
	Advancing			10.44	1.63			

Note. *p < 0.05.

The outcomes derived from the Analysis of Variance (ANOVA) underscore that students, under the guidance of science teachers characterized by distinct levels of TPACK, manifest statistically significant divergences in their scientific competency at a 0.05 significance level. Delving into the granularities of this analysis, it becomed evident that, within the realms of explain phenomena scientifically and research, evaluate and use scientific information for decision making and action, pronounced statistically significant disparities were discernible at the 0.05 significance level. Intriguingly, in the sphere of construct and evaluate designs for scientific enquiry and interpret scientific data and evidence critically, no statistically significant disparities were observed.

Subsequent to this, a pairwise comparative analysis was undertaken to scrutinize the specific TPACK levels that exhibit discernible differences concerning each facet of scientific competency. The particulars were elucidated as follows:

3.1 Explain Phenomena Scientifically

After the initial analysis of variance (ANOVA) demonstrated a notable impact of teacher TPACK levels on student explaining phenomena scientifically competency, a subsequent pairwise comparison study was executed. This investigation delves into the distinctions in the aspect of "Explaining phenomena scientifically" among students categorized based on their respective teachers' TPACK levels. The detailed outcomes of this analysis were meticulously outlined in Table 2.

Table 2. Comparing the "Explaining phenomena scientifically" scores of students categorized according to the TPACK levels of science teachers when classified into pairs

Level of TPACK	$\bar{X}$	Recognizing	Accepting	Adapting	Exploring	Advancing
Recognizing	3.91	-	-0.100	-0.061	-0.076	-0.265
Accepting	4.01			0.038	0.023	-0.165
Adapting	3.97				-0.015	-0.204*
Exploring	3.98					-0.189*
Advancing	4.17					-

Note. *p < 0.05.

Derived from Table 2, the comparative analysis of students' "Explaining phenomena scientifically", stratified by their teachers' TPACK levels, revealed statistically significant distinctions in "Explaining phenomena scientifically" at a 0.05 significance level. Notably, two pairs exhibited statistically significant differences: 1) the Adapting level group and Advancing level group and 2) the Exploring level group associated Advancing level group.

3.2 Research, Evaluate and Use Scientific Information for Decision Making and Action

In the initial examination of the ANOVA data, it was noted that distinct levels of TPACK among teachers exert differing influences on students' ability to "Research, evaluate, and use scientific information for decision making and action". Subsequently, a comparative investigation was carried out to evaluate this particular aspect of students' competencies. The categorization was based on the TPACK levels of their respective teachers in a pairwise manner. The analytical outcomes correspond with the results outlined in Table 3.

Table 3. Comparing the "Research, evaluate, and use scientific information for decision making and action" scores of students categorized according to the TPACK levels of science teachers when classified into pairs

Level of TPACK	$\bar{X}$	Recognizing	Accepting	Adapting	Exploring	Advancing
Recognizing	1.85	-	0.285	0.035	0.011	-0.862
Accepting	1.56			-0.249	-0.273	-1.147
Adapting	1.81				-0.025	-0.897*
Exploring	1.83					-0.873*
Advancing	2.70					-

Note. *p < 0.05.

When comparing students' "Research, evaluate, and use scientific information for decision making and action" categorize by the TPACK levels of their teachers, it was found that students exhibit different abilities in systems thinking. This was statistically significant at the 0.05 significance level, with a total of 2 pairs, namely: 1) the Adapting level and the Advancing level group, and 2) the Exploring level and Advancing level group.

3.3 Scientific Competency

Following a statistically significant ANOVA result indicating that teacher TPACK levels had an impact on student scientific competency, a pairwise comparison study was conducted to further explore these group differences. This subsequent analysis examined variations in scientific competency scores among students categorized by their teachers' TPACK levels. The findings from this analysis are presented in Table 4.

Table 4. Comparing the scientific competency scores of students categorized according to the TPACK levels of science teachers when classified into pairs

Level of TPACK	$\bar{X}$	Recognizing	Accepting	Adapting	Exploring	Advancing
Recognizing	8.75	-	-0.100	-0.423	-0.554	-1.697
Accepting	8.65			-0.524	-0.654	-1.797
Adapting	9.17				-0.130	-1.273*
Exploring	9.30					-1.143*
Advancing	10.44					-

Note. *p < 0.05.

When comparing students' scientific competency categorize by the TPACK levels of their teachers, it was found that students possess different abilities in scientific competency. This difference was statistically significant at the 0.05 significance level, with a total of 2 pairs, namely: 1) the Adapting level and the Advancing level group, and 2) the Exploring level and the Advancing level group.

From the discourse among science teachers regarding instructional design and the integration of Technological Pedagogical Content Knowledge (TPACK) to enhance students' scientific competency, the ensuing salient aspects can be methodically examined and succinctly summarized:

1) The design of instructional activities involves the utilization of real-life situations to facilitate a deeper comprehension among students.This is evident from the following dialogue excerpt:

> "Science is the embodiment of the surrounding world, and often, when explaining concepts, emphasis is placed on integrating everyday life situations into the content. For instance, when teaching about frictional force, there might be a discussion about soccer shoes, providing examples to help students visualize the concept." Teacher 1: Recognizing Level

> "Normally, everyday life situations are used to introduce lessons in order to get students interested. Then, during the conclusion, the situations are explained again so that students can gain a deeper understanding." Teacher 2: Adapting Level

> "To stimulate interest, real-life phenomena or situations are often employed, which can take the form of images or video clips. Subsequently, questions are posed to encourage students to independently seek answers. During the summary, a return is made to reiterate and interconnect the knowledge once again." Teacher 3: Adapting Level

> "Efforts are directed towards fostering students' recognition that the principles they are studying are applicable in diverse real-life situations. Primarily, video clips are employed, and during the expansion phase, endeavors are made to stimulate students to independently articulate explanations for the observed phenomena, aiming to gauge the depth of their comprehension." Teacher 4: Advancing Level

2) Conducting experiential science activities is aimed at instigating scientific processes in learners and enabling them to engage in meaningful interpretation of information. However, there are constraints in terms of time, content coverage, and inadequacy of scientific equipment. This is apparent from the provided excerpt of the conversation:

> "The learning activities are predominantly lecture-based. There may be some opportunities for students to conduct simple experiments using available materials, although this might be infrequent due to time constraints. Nonetheless, there is an effort to encourage students to actively participate in hands-on activities to practice scientific process skills." Teacher 2: Recognizing Level

> "Personally, I believe that conducting experimental activities is crucial in science teaching. However, due to the extensive content, time constraints, and limited availability of equipment, these activities cannot be conducted frequently. Nevertheless, if implemented, students tend to enjoy and have fun with the hands-on experiences." Teacher 4: Accepting Level

> "In my perspective, science and experimentation are integral components that should go hand in hand. Personally, I find value in facilitating student experiments as it provides a tangible illustration of concepts and allows students to hone a spectrum of skills, including teamwork, data collection, organizational proficiency, data interpretation, and presentation abilities. This approach ensures that students acquire both knowledge and skills in a cohesive manner." Teacher 3: Exploring Level

> "The school faces challenges, particularly in terms of experimental equipment, especially in the physics department. This poses a significant obstacle. However, efforts are made to encourage students to engage in experiments as it is believed to enhance their critical thinking skills. The utilization of virtual labs, such as PhET simulations, has been explored, which proves to be beneficial. Nonetheless, there are occasional issues related to internet connectivity." Teacher 1: Advancing Level

3) The utilization of models in instructional activities is geared towards fostering a deep comprehension of scientific phenomena among students. However, the existing methodology does not place a strong emphasis on prompting students to autonomously generate conceptual models. This is evident from the following dialogue excerpt:

> "There are instructional media in the form of models to help students visualize and facilitate a deeper understanding more easily." Teacher 3: Accepting Level

> "Utilizing models as instructional tools, exemplified by employing an Earth rotation model, serves to enrich

teaching activities. This approach facilitates the observation of diverse phenomena, fostering a comprehensive underst anding among students." Teacher 4: Adapting Level

"In the pedagogical context, the utilization of models serves a dual purpose – as palpable teaching aids and as stimuli for students to formulate mental models derived from their observations or experimental endeavors. Nevertheless, it is noteworthy that the application of this methodology entails a temporal investment, and students frequently encounter challenges in its execution, leading to its comparatively limited adoption." Teacher 2: Advancing Level

"In the pedagogical approach, models serve as prevalent tools for elucidating various scientific phenomena. However, there is a notable lack of emphasis on fostering students' ability to independently formulate their own models. For instance, activities involving the use of clay to simulate the structure and function of animal cells exemplify this practice." Teacher 5: Advancing Level

4) The organization of teaching and learning activities that involve practical exercises entails guiding students to perform activities according to the steps outlined in the textbooks or work sheets provided by the instructing teacher. This is apparent from the ensuing excerpt of the dialogue:

"In teaching, work sheets with clear step-by-step instructions are commonly used. In most cases, students are expected to follow these instructions. The teacher typically explains the steps, poses questions to assess understanding, and then instructs students to carry out the activity on their own". Teacher 2: Accepting Level

"Typically, students are directed to adhere to the step-by-step instructions outlined in the instructional materials, whether from the textbook or provided in explicit activity guidelines." Teacher 3: Adapting Level

"Generally, students are instructed to follow the specified steps provided by the teacher in the work sheet or instructional materials. Occasionally, there might be projects assigned, allowing students to design their own projects, typically on a term basis." Teacher 2: Advancing Level

5) Generating conclusions from experiments is a task that often challenges students to align their summaries with scientific perspectives. In many cases, students may not fully encapsulate the scientific mindset in their conclusions, relying on the instructing educator to aggregate and articulate the overarching scientific ideas. This becomes apparent from the excerpt of the ensuing dialogue:

"In teaching activities or experiments, upon completion, students are often required to present reports summarizing the experimental results. In some instances, students may face challenges in preparing these summaries, leading teachers to take a more active role in summarizing the outcomes." Teacher 2: Adapting Level

"Typically, during activities, students are expected to present the outcomes, accompanied by a summary. Nonetheless, a considerable number of students tend to provide inaccurate summaries. Consequently, it is often the responsibility of the teacher to re-summarize the findings." Teacher 4: Exploring Level

"Conceptual summaries may not always align precisely with the intended concepts. As a result, teachers find it imperative to pose targeted questions, guiding students to revisit and refine their summaries, thereby fostering a more nuanced and thorough comprehension of the subject matter." Teacher 3: Exploring Level

6) Activities promoting student exploration, examination, and comparison of their own conclusions with peers from different groups using diverse learning techniques, such as the Gallery Walk, KWDL, and Think Aloud are somewhat infrequent due to time constraints. This is apparent from the provided excerpt of the conversation:

"Typically, when students complete their explanations, they often overlook the credibility of the information or the supporting evidence for those explanations. Summarizing collaboratively as a class is more advisable." Teacher 1: Accepting Level

"In the facilitation of instructional activities, the strategic utilization of the gallery walk technique is implemented. This method encourages students to independently explore and evaluate their comprehension, fostering a comparative analysis with the summaries provided by their peers. This structured approach often leads to the identification of divergent perspectives, subsequently contributing to informed and substantive discussions." Teacher 2: Exploring Level

"The KWDL and think-aloud techniques are employed to facilitate collaborative exploration and examination among students. Upon completion, students engage in collective discussions, particularly focusing on areas where their perspectives may diverge. This process aims to foster a shared understanding, leading to a collective reevaluation and synthesis of conclusions." Teacher 2: Advancing Level

> "In certain experimental scenarios, hypotheses are introduced, and students are encouraged to assess the congruence of the conclusions with these hypotheses. This practice is accompanied by collaborative discussions and knowledge-sharing among students to collectively derive conclusions. Nonetheless, this comprehensive approach is often limited due to time constraints." Teacher 5: Advancing Level

4. Discussion

The results obtained from the Analysis of Variance (ANOVA) in this study bring to light a compelling connection between the levels of TPACK exhibited by science teachers and the scientific competency of their students. The findings underscore a statistically significant relationship between these variables, providing valuable insights into the role of teacher expertise in influencing student outcomes in the realm of science education. The emphasis on TPACK as the distinguishing factor among science teachers is noteworthy. TPACK represents a unique blend of technological knowledge, pedagogical skills, and content expertise. This choice suggests a recognition of the multifaceted nature of effective science teaching, acknowledging that successful science teachers must possess a combination of technological proficiency, pedagogical strategies, and deep content understanding. There is a notable association between the knowledge of TPACK and the development of students' learning and innovation skills (Sulistyarini et al, 2022). Align with Irmita and Atum (2018), the TPACK approach had a significant effect on both scientific literacy and social skills of students.

The comparative analysis of students' ability to "Explaining phenomena scientifically" stratified by their teachers' TPACK levels provides a nuanced perspective on the influence of teacher expertise on a specific aspect of scientific understanding. The result highlights the relevance of considering TPACK in the context of students' proficiency in explaining scientific phenomena. The observed distinction between the Adapting and Advancing level groups implies that students under teachers characterized by a higher level of TPACK (Advancing level) demonstrate a more advanced ability to explain scientific phenomena compared to those with teachers at the Adapting level. This could signify that a deeper integration of technological, pedagogical, and content knowledge enhances the quality of students' scientific explanations. Similarly, the significant difference between the Exploring level group and Advancing level group implies that students under teachers with a greater TPACK proficiency (Advancing level) outperform their peers whose teachers are at the Exploring level in explaining scientific phenomena. This indicates the potential impact of advanced TPACK on fostering students' scientific reasoning and communication skills. The result of the comparative analysis of students' ability to "Research, evaluate, and use scientific information for decision making and action" stratified by their teachers' TPACK levels reveals noteworthy distinctions in students' aptitude for scientific competency. The observed difference between the Adapting and Advancing level groups implies that students with teachers exhibiting higher TPACK levels (Advancing level) are more adept at applying systems thinking in the context of scientific decision-making and action compared to those with teachers at the Adapting level. This may indicate that a more advanced integration of technology, pedagogy, and content knowledge contributes to students' capacity for holistic and interconnected thinking when dealing with scientific information. Likewise, the significant difference between the Exploring level and Advancing level groups indicates that students under teachers with greater TPACK proficiency (Advancing level) outperform their peers whose teachers are at the Exploring level in utilizing scientific information for decision-making and action. This emphasizes the role of advanced TPACK in fostering students' ability to engage in thoughtful and strategic decision-making processes informed by scientific knowledge. The result of comparing students' scientific competency based on the TPACK levels of their teachers yields valuable insights into the intricate relationship between teacher expertise and student outcomes. The statistical significance of these differences at the 0.05 level emphasizes the importance of considering the integration of technology, pedagogy, and content knowledge when examining students' proficiency in scientific competency. The identification of two pairs with statistically significant differences, specifically between the Adapting level and Advancing level groups, as well as between the Exploring level and Advancing level groups, contributes to a nuanced understanding of the impact of teacher TPACK levels on students' scientific competency. The observed difference between the Adapting and Advancing level groups suggests that students under teachers characterized by higher TPACK levels (Advancing level) demonstrate a more advanced scientific competency compared to those with teachers at the Adapting level. This finding underscores the crucial role of a more sophisticated integration of technology, pedagogy, and content knowledge in fostering students' overall scientific understanding and competence. Besides, the significant difference between the Exploring level and Advancing level groups indicates that students under teachers with greater TPACK proficiency (Advancing level) outperform their peers whose teachers are at the Exploring level in terms of scientific competency. This emphasizes the positive impact of advanced TPACK on shaping students' abilities to apply scientific knowledge, skills, and reasoning in a comprehensive manner. Çoklar and Özbek (2017) state that teachers who are more innovative in their use of technology are more confident in their ability to integrate technology into their teaching practices.

In order to design learning activity, all teachers made references to the incorporation of real-life situations, actual laboratory equipments, or subjects pertinent to students' daily experiences. Notably, teachers positioned at the adapting and advanced levels of TPACK explicitly cited the utilization of visual aids, such as images or video clips, as a means to stimulate heightened elucidation of phenomena by students. Issues related to time constraints, extensive content, and inadequate laboratory equipment are significant points of discussion. Consequently, a majority of teachers tend to opt for lecturing methods over conducting experiments. This inclination diminishes opportunities for the development of scientific competency, even though teachers acknowledge the importance of hands-on activities. In contrast, advanced-level teachers, despite facing similar challenges, leverage virtual laboratories as substitutes for practical experiments. Instead of transitioning to lecture-based teaching, this approach provides students with more opportunities for hands-on practice. This indicates that they go beyond simply using technology as a presentation tool and leverage it to create engaging, interactive learning experiences. To enhance scientific competency, it is recommended to embrace experiential learning—a dynamic process wherein learners construct knowledge by actively transforming their experiences—providing a valuable approach for tackling real-world challenges (Muñoz Martínez & Charro Huerga, 2023; Nguyen et al, 2023). The teacher believes that using models enhances students' understanding, but this tends to be a skill associated with passive learning. In this context, teachers use models primarily for explanation rather than engaging in active learning where students use models to generate knowledge from explaining phenomena. This inclination may stem from the teacher's lack of confidence in students' ability to perform such tasks. Additionally, it might be influenced by inadequate design of model-based learning activities, hindering students from independently constructing knowledge. Alternatively, this preference for passive learning approaches could be attributed to the teacher's attachment to familiar teaching methods. Activities that instruct students in a step-by-step manner constrain them by providing explicit directions, limiting the opportunity for them to develop scientific competency. Students are unable to engage in self-directed learning, leading teachers to adopt a guiding approach or have students rely on instructions from the teacher. This may stem from the teacher's concern that if students conduct independent research, they might not cover the curriculum content as per the prescribed guidelines. As a result, implementing active learning or designing learning experiences that emphasize the development of scientific competency becomes challenging. It is crucial for teachers to strike a balance between incorporating active learning methods, fostering hands-on experiences, and ensuring curriculum coverage. Professional development opportunities that empower teachers to design effective model-based learning activities and build confidence in facilitating active learning can contribute to overcoming these challenges. Soko and Samo (2023) state that both teaching and training experience were found to have a positive influence on teachers' TPACK. Additionally, a shift in mindset towards embracing innovative approaches and acknowledging the importance of student-driven inquiry is essential for creating a more enriching and effective science education experience. In order to promote students' future competency, Yu et al. (2022) underscore the significance of fostering science teachers with an open-minded approach to embrace future changes in education.

5. Conclusion

In summary, the study establishes a significant link between science teachers' TPACK levels and their students' scientific competency. The emphasis on TPACK as a vital factor in effective science teaching underscores its unique blend of technological, pedagogical, and content expertise. The findings reveal that students under teachers with higher TPACK levels demonstrate advanced scientific competency, emphasizing the importance of integrating technology, pedagogy, and content knowledge. Despite common challenges such as time constraints and limited resources, advanced-level teachers stand out by incorporating virtual laboratories for hands-on experiences. However, in order to enhance science education, it is crucial for teachers to balance active learning methods, hands-on experiences, and curriculum coverage. Professional development opportunities should empower teachers to design effective learning activities and embrace innovative approaches, fostering a more enriching science education experience.

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Authors' contributions

Dr. Kanyarat Cojorn and Dr. Kanyarat Sonsupap were responsible for study design, data collection, drafted the manuscript and revising. Dr. Somsong Sitti also offered consultancy regarding the study and assisted in revising the manuscript. All authors have read and approved the final manuscript.

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