Evaluating the Role of Technological Pedagogical Content Knowledge in ICT-Enhanced Science Education

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Manuscript received August 9, 2024; revised September 11, 2024; accepted October 24, 2024; published January 13, 2025

***Abstract*—This study investigates the critical factors influencing the integration of Information and Communication Technologies (ICT) in science education, focusing on Technological Pedagogical Content Knowledge (TPCK), ICT teaching self-efficacy, enjoyment, control appraisal, and value appraisal among pre-service and in-service science teachers. Utilizing structural equation modelling, the findings highlight that ICT teaching self-efficacy, enjoyment, and control appraisal significantly predict value appraisal, demonstrating their crucial roles in teachers' perceptions of ICT value. TPCK also emerged as a significant predictor, emphasizing the importance of integrated knowledge for effective ICT use in teaching. The strong prediction relevance of the study confirms the model's effectiveness. These findings align with the TPCK framework and imply that in-service programs must include greater emphasis on practical workshops, online courses as well and group activities to enhance teachers' ICT self-efficacy and TPCK. In this way, it is possible to know how best to integrate ICT in teaching science, resulting in actionable ways to improve teaching practices and student learning outcomes.**

***Keywords*—Information and Communication Technologies (ICT) integration, science education, Technological Pedagogical Content Knowledge (TPCK), teacher self-efficacy, affective factors, pre-service teachers, in-service teachers, educational technology**

I. Introduction

The landscape of science education is changing greatly as teachers work to prepare students to live in a technology-driven world. The use of ICT in teaching science has become a global concern championed by both policymakers and teachers [1]. As such, teachers must have a special combination of expertise called Technological Pedagogical Content Knowledge (TPCK), which enables them to integrate technology with pedagogy and science content effectively [2].

Research suggests that pre-service teachers need to acquire knowledge in integrating technology since teacher education institutions are required to assist their students in connecting knowledge of technology, teaching methods, and academic content [3] Many researchers, according to Voogt *et al.* [4], make inadequate links between the preparation of pre-service teachers to use ICT and pedagogical issues. Pre-service teachers chose techniques that aligned with their beliefs and prior experience [5]. Pedagogical knowledge is enhanced by technological knowledge and academic content knowledge [6].

The use of information technologies has become unavoidable in teaching science. It is followed generally by the teaching process, and more specifically by teaching science with the increasing interest of teachers and officials in employing information technology in teaching [7]. In this regard, Darwish [8] recommends that there is a need to impress upon teachers the importance of the TPCK model, benefiting from it in the educational process by enrolling programs in pre-service and in-service teacher preparation programs to enhance knowledge of technological pedagogical content. As also noted by Sabry [9], there is a need to stress the importance and necessity of the TPCK model. According to Hassanein [10], most teachers do not have the requisite knowledge and skills to enable them to make use of technology in education, nor adequate training in the use of technology, which is one of the goals of the teacher training programs, whether pre-service or in-service, focusing on the technology itself.

The ability of ICT has been judged of paramount importance and has formed the basis of many theoretical frameworks for scholars worldwide [11, 12]. ICT has significantly influenced the teaching and learning process, enhancing both the quantity and quality of education [13]. According to research, the beliefs and emotions of the teachers act as key factors for or against the use of ICT [14, 15]. Furthermore, several models emphasize the role of teachers' affective-motivational factors in explaining classroom ICT use. For instance, the will, skill, and tool model [16], determines not only shared constructs [17], but the affective-motivational factors of the teacher's skills and aptitude [18], which in combination may account for up to 90% of the variation in the use of ICT in school. The application of ICT in schools varies by subject and is shaped by the specific content of each subject [19].

Moreover, emotional experience is a decisive characteristic of ICT tools. The Ministry of Education in Palestine recognized the need to keep pace with global trends. Technological advancements have been integrated into school systems in many countries. To facilitate this, a plan was created to develop curricula that enable teachers to incorporate technological resources to enhance student learning. Consequently, the Ministry tasked its Curriculum Development Center with creating this new curriculum. The Center quickly gained momentum and successfully completed the curriculum by July 2016, distributing it to schools [20]. Recent curriculum planners responsible for designing new textbooks have recognized the importance of aligning educational materials with these technological advancements, ensuring that they effectively support the updated curriculum and foster student engagement. The planners may have had a curriculum in mind with segments provided by computerized

doi: 10.18178/ijiet.2025.15.1.2224

auxiliaries, but the assumption behind the project was that the most enjoyable learning is that which creates an illusion of knowledge, to make the activity a more pleasurable experience with very little traditional content and much more participation [20]. This highlights a very critical problem at the junction between TPCK, ICT teaching self-efficacy, enjoyment, control appraisal, and value appraisal associated with preservice and in-service science education [21].

There is evidence that technical knowledge alone is not enough for the successful integration of ICT. Some studies have identified a variety of affective factors influencing teachers' use of technology, including but not limited to emotions, beliefs, and self-efficacy attitudes [2, 12, 22, 23]. Such factors influence the extent of a teacher's willingness or ability to utilize ICT for teaching effectively. Control-value theory (CVT) helps explain this connection [24]. It states that attitudes and emotions in classrooms regarding the use of computers can be predicted by control appraisals (perceived ability to use ICT) or value appraisals (perceived relevance and importance of technology utilization), leading to increased technology incorporation in instruction [25]. Furthermore, enjoyment plays a vital role because when teachers experience positive feelings, they are more inclined to use technological devices [23].

However, there is still a critical gap in understanding the way these factors manifest themselves differently between pre-service and in-service science teachers. Although these variables have been studied separately [26], no research has combined them to explore their influence on each other and variations among different levels of teaching experience [21].

To address this gap, the study asks: "What are the interactions and disparities of TPCK, self-efficacy, enjoyment control appraisal, and value appraisal for pre-service and in-service science teachers?" Therefore, by looking at how these factors interact we can offer useful insights on better strategies for preparing both pre- and in-service teachers to successfully integrate ICT into science education.

The following hypotheses were created to examine how TPCK, ICT teaching self-efficacy, enjoyment, control appraisal, and value appraisal play out in different contexts of science education. These hypotheses seek to discover how these crucial factors relate to one another and determine if there are differences between novice teacher training programs versus those directed toward practitioners. Understanding these dynamics is essential for developing effective strategies for ICT integration in science classrooms. The hypotheses are as follows:

H1: There is a significant positive effect of TPCK, ICT teaching self-efficacy, enjoyment, and control appraisal on value appraisal.

H2: There is a significant positive effect of TPCK, ICT teaching self-efficacy, enjoyment, and value appraisal on control appraisal.

H3: There is a significant positive effect of TPCK, ICT teaching self-efficacy, value appraisal, and control appraisal on enjoyment.

H4: There is a significant positive effect of TPCK, value appraisal, enjoyment, and control appraisal on ICT teaching self-efficacy.

H5: There is a significant positive effect of ICT teaching self-efficacy, enjoyment, value appraisal, and control appraisal on TPCK.

H6: There is a significant difference in the responses of sample individuals towards control appraisal, enjoyment, ICT teaching self-efficacy, TPCK, and value appraisal based on pre-service and in-service status.

These hypotheses will guide our investigation into the factors influencing ICT integration in science education, providing insights that can inform pre-service and in-service teacher training programs.

The theoretical basis for the proposed hypotheses is strongly supported by empirical research and foundational theories such as CVT. For instance, the control appraisal is positively related to ICT teaching self-efficacy, which is treated as one of the most important constructs of the current study [27], providing ground supporting CVT which deals with how one's control appraisal affects emotion and motivation. In addition, it has been shown that both control appraisal and value appraisal lead to enjoyment [28, 29], which takes on an important role in enhancing one's ICT teaching self-efficacy [30]. More specifically, enjoyment is a positive predictor of ICT teaching self-efficacy in pre-service ICT teachers [26, 31], thus confirming enjoyment-self-efficacy associations. Therefore, the inclusion of constructs such as control appraisal, value appraisal, and enjoyment in relation to self-efficacy is well-grounded in existing theoretical frameworks and empirical findings, addressing the critique of insufficient theoretical support for the hypotheses.

II. Literature Review

The general teaching-learning environment in the sciences is gradually changing as teachers attempt to prepare students to face life challenges in a complex society driven by technology [1]. This integration is viewed as a way of making students more interested in class content, enabling them to have a better understanding of the technological requirements of today's world.

The TPCK model offered by Mishra and Koehler [32], is a model that lies at the center of the integration of ICT in education. It assumes three distinct areas of knowledge: technological knowledge, pedagogical knowledge, and content knowledge. TPCK stresses all three concepts, and the author has postulated that teachers must have ways of understanding technology in context with teaching and content knowledge. This approach emphasizes the importance of not only making teachers aware of how to use technology, but also ensuring that they know how to effectively integrate it into the curriculum to enhance learning in specific content areas.

The second conceptual framework that can be used for understanding the process of ICT integration is CVT, suggested by Pekrun [24]. Accordingly, CVT avers that emotions in learning contexts are determined by control appraisals and value appraisals. Control appraisal is the perceived ability to use ICT while value appraisal concerns the perceived significance of ICT in teaching. These appraisals affect the teacher's mood which, in turn, determines how they implement the use of technology in their teaching [25]. Thus, this theory provides insight into how teachers' enactive and allocentric self-regulation of learning is mediated by cognitive and affective processes.

Despite the theoretical support for ICT integration, empirical research highlights significant challenges in preparing pre-service teachers for this task. Studies by Mouza *et al*. [3] and Sun *et al.* [33], suggest that pre-service teachers often lack comprehensive training in integrating technology. These researchers highlight the need for teacher education programs to bridge the gap between technological knowledge, teaching methods, and content knowledge. This aligns with findings by Voogt *et al*. [4], who argue that many teacher preparation programs fail to adequately link ICT training with pedagogical practices. This disconnect often results in pre-service teachers selecting techniques that align with their prior experiences and beliefs rather than innovative pedagogical strategies [5].

Consequently, for in-service teachers, receiving continuous Professional Development (PD) is important in improving TPCK. Both Darwish [8] and Sabry [9] have pointed out the necessity of training in the form of PD which should be ongoing and encompass the practical implementation of ICT in classroom learning. Others have posited that the purpose of continuous PD programs should be the enhancement of the teachers' capacity to use ICT tools in their teaching practices appropriately. However, challenges such as lack of skills and information remain significant factors. In his article, Hassanein [10] explains that ICT readiness in education is suboptimal because teachers themselves often do not know how to properly apply this technology. Another assignment adversely affects ICT use by making training programs focus on mere technology instead of how it can be professionally incorporated into the teaching process.

Several studies show that the abovementioned criteria impact teachers' readiness and capacity to use ICTs positively [22, 15]. Teachers' affective states in general and their perceived self-competency specifically are positively correlated to the frequency and efficacy of ICT use. The Will-Skill-Tool model that was developed by Velázquez [16] also supports the idea of teachers' motivational factors. In essence

This is also evident in the application of ICT as far as teaching is concerned because the adoption of ICT also changes with the subject being taught. Siddiq *et al.* [19] noted that ICT is general where some functions are general, while others point to discipline-specific instructions. Such a situation complicates the issue of handling knowledge, indicating that it is imperative to approach the use of ICT tools and strategies as they pertain to specific subject areas. That is why it is crucial to analyze these subtleties, which will help form the proper ICT integration model relative to the discipline.

There is evidence that Education policies and curriculum development processes worldwide acknowledge the need to include ICT in educational systems. An example of national efforts to integrate technology into curricula is given by Abualrob [20]. The attempt to construct a new curriculum that provides for the integration of the ministry's technological resources is an indication that the education systems of the world are slowly moving toward the adoption of ICT in teaching. That is why many similar initiatives are being discussed as signals of a growing understanding of the need to equip students for the technologically advanced world and help teachers adapt technology to their work.

Despite the advancements and initiatives in ICT integration, significant research gaps remain. Jenßen *et al*. [26] note a lack of comprehensive studies that consider TPCK, ICT self-efficacy, enjoyment, control appraisal, and value appraisal simultaneously. There is also a need for research comparing pre-service and in-service teachers regarding these constructs. Understanding the differences and similarities between these groups can provide valuable insights into how to better prepare and support teachers for successful ICT integration in science education.

III. Methodology

This study employs a descriptive approach to examine the interplay of TPCK, ICT Teaching Self-Efficacy, Enjoyment, Control Appraisal, and Value Appraisal in pre-service and in-service science education. A descriptive approach is chosen due to its effectiveness in capturing detailed information about the current state of these constructs and their interrelationships within the target populations.

The data was analyzed using Structural Equations Methodology (SEM) with the Smart-PLS4 program, and divided into two stages: The first two formulations relate to two other kinds of nuclear model analysis known as Standard Model Analysis and Structural Model Analysis. Thus, SEM is chosen for its ability to estimate intricate associations between manifest and latent constructs, allowing it to assess the relationships among the examined factors. The Standard Model Analysis comprised the measurement model's reliability and validity while the Structural Model Analysis evaluated the relationships between the constructs as postulated.

The study population is divided into two groups: in-service school teachers and pre-service teachers. This division helps the study to examine the variations in the ICT competencies, self-efficacy, and ICT integration of pre-service and in-service teachers. Pre-service teachers are still in the process of formal schooling and thus do not have vast teaching experience; on the other hand, in-service teachers have pertinent teaching experience but need to adapt themselves to new trends in ICT. It also helps draw specific conclusions towards the betterment of both these programs, taking into consideration the given inequalities.

The first group consists of 819 in-service teachers teaching third to sixth grades in the Jenin, Qabatiya, and Tubas districts in the northern part of West Bank, Palestine. The second group consists of 96 pre-service teachers who are enrolled for the field experience practicum at Arab American University in 2024. These sites and samples are selected because they could be regarded as typical of the broad sphere of education in Palestine. Additionally, vital records provided by the Ministry of Education are available.

In-service teachers included 210 participants, and 25% of schools from each directorate were randomly selected and participation was stratified. In this sense, the adoption of the stratified sampling approach intended to cover diverse respondents' backgrounds and teaching experiences. The electronic questionnaire was distributed to in-service teachers, and 172 participants responded. For the pre-service group, the questionnaire was administered to 96 students enrolled in the field experience practicum course, with 68 completed questionnaires returned. This resulted in a response rate of 81.9% for in-service teachers and 70% for pre-service teachers.

Sample sizes were determined using power analysis to ensure sufficient statistical power for testing the hypothesized relationships. The questionnaire was distributed electronically for ease of access, although this method presents some limitations, such as restricted internet access for certain participants. The questionnaire items were piloted, tested, and refined to ensure the reliability and suitability of the constructs being measured.

The questionnaire was structured around five dimensions: Technological Pedagogical Content Knowledge (TPCK), ICT Teaching Self-Efficacy, Enjoyment, Control Appraisal and Value Appraisal. Each construct was measured through specific items based on validated scales from prior research, ensuring alignment with the theoretical models discussed. For example, the TPCK items were adapted from the framework proposed by Misher and Koehler [32], while the ICT self-efficacy items were informed by the work of Venkatesh *et al.* [34].

These dimensions were consistently utilized to evaluate both groups of subjects (pre-service and in-service teachers) allowing comparison in terms of the competencies and attitudes of the two groups towards the integration of ICT. By using the same instrument for both categories, the study ensures that the constructs are measured uniformly, providing a reliable basis for comparison. In this study, composite reliability and factor loadings were utilized to assess the internal consistency and construct validity of the measurement model.

A. Composite Reliability

The high composite reliability values (>0.70) indicate that the constructs (e.g., Technological Pedagogical and Content Knowledge, ICT in Teaching Self-Efficacy, Enjoyment, Control Appraisal, and Value Appraisal) are consistently measured across different items. This reliability suggests that the constructs are stable and dependable, providing a solid foundation for further analysis.

B. Factor Loadings

Factor analysis calculates the variation among connected variables and factors. The degree to which a construct is related to a particular factor is measured by the factor loading of the variable. In essence, factor loading represents the correlation between a factor and a construct. It indicates how much variance in that specific factor is accounted for by the construct. A common guideline in Structural Equation Modeling (SEM) is that a factor should elicit a sufficient amount of variance from the observed construct to be considered significant. Typically, a factor loading of 0.5 or higher is often deemed acceptable [35], pointing to a connection between the factor and its variable, thereby indicating that the factor effectively captures the underlying constructs being measured.

IV. FINDINGS

In this section, we report the results of our statistical analysis, including the evaluation of factor loadings, composite reliability, and the relationships between the key constructs. These findings provide insights into how Technological Pedagogical Content Knowledge (TPCK), ICT teaching self-efficacy, enjoyment, control appraisal, and value appraisal interact in the context of ICT integration in science education.

Table 1 shows that all constructs are higher than 0.50, the excepted criteria as per Hair *et al.* [35]. The exact results for each construct are presented in Table 1.

Table 1. Factor loadings for different constructs

Constructs	Code	M	SD	Factor Loading	VIF	α	CR	AVE
Technological, Pedagogical, and Content Knowledge	A01	4.09	0.541	0.807	2.129	0.794	0.862	0.539
	A02	4.01	0.468	0.837	2.229			
	A03	4.20	0.598	0.759	2.489			
	A04	4.15	0.566	0.843	2.515			
	A05	4.05	0.554	0.804	2.280			
ICT in Teaching Self-Efficacy	B01	4.16	0.617	0.677	1.352	0.751	0.858	0.668
	B02	3.55	0.859	0.730	1.774			
	B03	3.84	0.748	0.577	1.413			
	B04	4.07	0.640	0.825	2.301			
Enjoyment	C01	4.13	0.686	0.783	1.415	0.764	0.798	0.501
	C02	3.96	0.703	0.855	1.695			
	C03	3.78	0.739	0.812	1.884			
Control Appraisal	D01	3.66	0.805	0.663	1.006	0.869	0.905	0.657
	D02	4.30	0.510	0.736	1.528			
	D03	3.90	0.759	0.578	1.205			
Value Appraisal	E01	4.27	0.676	0.819	1.618	0.774	0.854	0.594
	E02	4.06	0.616	0.729	1.423			
	E03	4.27	0.586	0.825	1.718			
	E04	4.10	0.742	0.703	1.488			

Table 1 shows factor loadings for different constructs, such as Technological Pedagogical and Content Knowledge, ICT in Teaching Self-Efficacy, Enjoyment, Control Appraisal, and Value Appraisal. The factor loadings are all above 0.50, confirming the reliability of the constructs. High factor loadings indicate that the items are good indicators of the underlying constructs. This strong relationship ensures that the constructs are accurately represented by the items.

These findings support the overall research objective by confirming that the key factors influencing ICT integration in science education are being measured accurately. As a result, the study can confidently explore the relationships between these constructs and recommend educational strategies, such as teacher training programs, that focus on enhancing TPCK and self-efficacy, with the assurance that these factors are reliably represented.

A. Constructing Reliability and Validity

Like Cronbach's Alpha, the Composite reliability test checks the internal consistency of scale items contained, and if an "index of the commonality of the observed constructs is used as an indicator of a latent construct". On the other hand, Average Variance Extracted (AVE) is a measure used to compare the amount of variance explained by the construct with the number of variance indexes measurement error. This means that it is used in determining the convergent validity; it is calculated by summing up the products of the correlations of two constructs with the corresponding constructs.

Based on the high values of Cronbach's alpha and Composite Reliability (CR), the items loaded under each construct show a high degree of internal consistency, so that they measure the same construct adequately. AVEvalues, which read 0.50 for most constructs, mean that a lot of the variance is explained by the constructs being measured rather than associated with measurement error. Taken together these results imply that the constructs applied in the study reflect dependability and validity.

B. Discriminant Validity

In their discussion on assessing test validity, Campbell and Fiske [36] introduced the concept of discriminant validity. They stressed the importance of using both discriminant and convergent validation methods when evaluating new tests. A satisfactory assessment of discriminant validity indicates that a test measuring a specific concept is not strongly correlated with tests aimed at assessing theoretically distinct concepts. While there is not a fixed threshold for discriminant validity, correlation results below 0.70 suggests the presence of discriminant validity between the two measures. Conversely, a result above 0.70 implies a considerable overlap between the concepts, indicating that they may be measuring the same underlying construct, and thus, discriminant validity cannot be established [36]. The following Table 2 illustrates the discriminant validity between the study constructs.

Table 2. Correlations and measures of validity among constructs

Constructs	TPCK	ICT in Teaching Self-Efficacy	Enjoyment	Control Appraisal	Value Appraisal
TPCK	0.555				
ICT in Teaching Self-Efficacy	0.498	0.473			
Enjoyment	0.471	0.468	0.461		
Control Appraisal	0.457	0.449	0.400	0.349	
Value Appraisal	0.450	0.437	0.431	0.320	0.319

Discriminant validity is the inverse of convergent validity which is established if correlations between constructs are much lower than 0.70, showing that the constructs are dissimilar and do not all assess the same idea. Alphas, as in Table 2, present correlations; each of the constructs has discriminant validity, and each refers to a distinct facet of integrating ICT [37].

This ensures that the constructs represent unique aspects of ICT integration, contributing to the research objective of examining the interplay between multiple factors in shaping teachers' ICT use. By establishing the distinctiveness of these factors, the study highlights that improving one area (e.g., self-efficacy) won't necessarily improve others (like TPCK) without targeted interventions. This finding reinforces the need for a holistic approach to teacher preparation programs, addressing each factor individually to foster more effective and comprehensive ICT integration in science education.

C. HTMT

The Heterotrait-Monotrait Ratio (HTMT) is used to assess whether constructs are distinct from each other. The HTMT ratio should be below a certain threshold (commonly 0.85 or 0.90) to confirm that the constructs have discriminant validity.

All HTMT values as in Table 3 are below the threshold of 0.85 (or 0.90 if a more lenient criterion is used), indicating that the constructs in the study have good discriminant validity. This means that each construct measures a unique aspect of the integration of ICT in science education and is not redundant.

Table 3. HTMT ratios

Constructs	HTMT Ratios
TPCK	0.703
ICT in Teaching Self-Efficacy	0.803
Enjoyment	0.278
Control Appraisal	0.599
Value Appraisal	0.688

These results support the distinctiveness of the constructs used in the study, providing confidence that the measurement model is correctly specified and that the constructs are accurately capturing different dimensions of the research.

D. Structural Model

The structural model (Fig. 1) was assessed using Partial Least Squares Structural Equation Modeling (PLS-SEM) with SmartPLS 4.0. The study assesses the structural model's outcomes after accepting the conclusions of the measurement model's convergent validity. Studying the model's propensity for prediction as well as the relationships between the research constructs is necessary for this. The structural model should be assessed using a set of criteria that have been put to the test.

E. Effect Size (f^2)

Table 4 shows the effect size of the study constructs, the results show that there is a high effect size.

Table 4. Effect size f^2

Constructs	f^2
Control Appraisal	0.428
Enjoyment	0.344
ICT in Teaching Sel-Efficacy	0.574
TPCK	0.220
value Appraisal	0.180

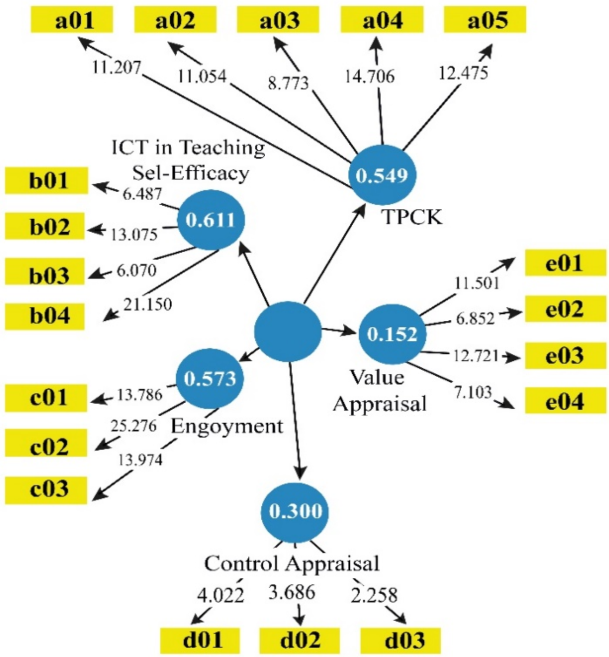

Fig. 1. Structural model.

The effect sizes indicate substantial impacts of control appraisal (0.428), enjoyment (0.344), ICT teaching self-efficacy (0.574), TPCK (0.220), and value appraisal (0.180). The high effect size for ICT teaching self-efficacy suggests that educators who feel capable of leveraging ICT tools effectively are more likely to perceive greater value in their teaching practices.

Very high statistical significance was achieved regarding ICT in Teaching Self-Efficacy ($f^2 = 0.574$). This suggests that how effective educators are in using ICT in practice enhances the ability of educators to incorporate ICT in teaching. This supports research done in the past that emphasized self-efficacy concerning the use of educational technology. For instance, Sun, Strobel, and Newby [33] showed that pre-service teachers who possess higher levels of self-efficiency used technologies in teaching practices. This conclusion supports the studies by Wang and Zhao [38], as well as Bwalya and Rutegwa [39], stating that people with positive self-efficacy for performing tasks will undertake those activities and persevere despite the difficulties.

More specifically, control appraisal ($f^2 = 0.428$) in teachers' views of control regarding the use of ICT tools enables the identification of the impact of the measure on the implementation of the technology in class. This fact supports the literature [24, 15, 40] attesting to the importance of perceived control in the context of new technologies adoption.

When tested through the f^2 with the level 0.344, enjoyment suggests positive findings which means teachers who are satisfied with the use of ICT are those who will incorporate it in their teaching. This chimes with the notion that if people are to remain engaged with technology, enjoyment, as a form of intrinsic motivation, is indispensable [26].

The statistical measure of the significance of the impact of TPCK is even more pronounced with an $f^2 = 0.220$ for the study's sample size. The above is in tandem with the studies done on TPCK where Mishra and Koehler [32], and Heine *et al.* [18], have highlighted the need for this integrated knowledge that is required for intensive ICT use in education.

In addition, the effect size of value appraisal ($f^2 = 0.180$) indicates that teachers' perceptions of the value and benefits of using ICT in teaching contribute to their decision to integrate technology. This finding supports the idea that perceived value is a significant predictor of technology adoption [40, 23].

F. Predictive Relevance Q^2

The Predictive Relevance Q^2 value, also known as the "Stone-Q^2 Geisser's value", indicates the model's prediction relevance whereas the R square values indicate predictive accuracy [35]. The path model's predictive relevance for the construct is indicated by Q^2 values greater than zero for a particular reflective endogenous variable [41]. As shown in Table 5, when we ran the blindfolding method with an omission distance (D) value of 7, we obtained Q^2 values greater than zero, demonstrating the excellent predictive significance of our path model.

Table 5. Predictive relevance Q^2(construct cross validated redundancy) for key constructs, including control appraisal, enjoyment, ICT teaching self-efficacy, TPCK, and value appraisal

Constructs	RMSE	MAE	Q^2
Control Appraisal	0.894	0.627	0.210
Enjoyment	0.696	0.514	0.542
ICT in Teaching Sel-Efficacy	0.665	0.472	0.577
TPCK	0.776	0.452	0.543
value Appraisal	0.959	0.721	0.119

Q^2 values above zero for control appraisal (0.210), enjoyment (0.542), ICT teaching self-efficacy (0.577), TPCK (0.543), and value appraisal (0.119) indicate strong predictive relevance of the path model. These predictive values underscore the model's ability to forecast the impact of TPCK, ICT teaching self-efficacy, and related constructs on perceived instructional value in science education. This supports the argument that enhancing these factors can lead to more effective teaching practices and improved student outcomes.

G. Findings for the Research Question

The research question of this study asks: **"What are the interactions and disparities of TPCK, self-efficacy, enjoyment, control appraisal, and value appraisal for pre-service and in-service science teachers?"** This question is explored through the six hypotheses (H1–H6), each of which examines the relationships between these constructs.

Fig. 1 visualizes the structural relationships between key constructs in the study, including TPCK, ICT teaching self-efficacy, enjoyment, control appraisal, and value appraisal. These constructs were modeled to assess their direct and indirect impacts on teachers' ICT integration behaviors. The structural model shows how these categories interact, with ICT teaching self-efficacy, control appraisal, and enjoyment emerging as strong predictors of value appraisal. This relationship highlights that teachers who feel confident in their ability to use ICT, perceive control over its usage, and find enjoyment in incorporating technology are more likely to recognize its value in science education. In turn, this heightened value appraisal positively influences their overall integration of ICT into teaching practices.

In the following section, we present a comprehensive analysis of each hypothesis, which directly answers the research question.

The Q^2 values for all constructs in Table 6 are significantly positive, reaffirming the predictive relevance of the model. For example, the R^2 value for the path from TPCK, ICT teaching self-efficacy, enjoyment, and control appraisal to value appraisal is 0.152, explaining 15.2% of the variance in value appraisal, which is statistically significant ($p < 0.05$).

The test results show that T-value (4.124) is significant at p-value (0.000≤0.05) with a path coefficient of (0.390) and R^2 of (0.152). This supports the hypothesis which states that there is a significant positive effect of TPCK, ICT teaching self-efficacy, enjoyment, and control appraisal on value appraisal. The analysis confirms that the path coefficient (0.390) is significant ($p < 0.05$), with an R^2 of 0.152, indicating that these variables collectively explain 15.2% of the variance in value appraisal.

This is similar to the findings of Mishra and Koehler [32] and Heine *et al.* [18], who have established how teachers' use of technology in pedagogy and content knowledge has the potential to increase the perceived value of the practices. Overall ICT teaching self-efficacy was positively influenced, supporting the notion of the necessity of teachers' confidence in using technologies to improve learning achievements among students.

The last H6 was tested using an independent sample T-test as in Table 7.

Table 6. Hypotheses testing results

Hypotheses	Path coefficient	Sample Mean	R^2	T-Value	P-Value
TPCK, ICT teaching self-efficacy, Enjoyment, Control appraisal → Value appraisal	0.390	0.403	0.15	4.124	0.000
TPCK, ICT teaching self-efficacy, Enjoyment, Value appraisal → Control appraisal.	0.440	0.471	0.19	4.758	0.000
TPCK, ICT teaching self-efficacy, Value appraisal, Control appraisal → Enjoyment	0.579	0.585	0.33	8.178	0.000
TPCK, Value appraisal, Enjoyment, Control appraisal → ICT teaching self-efficacy	0.492	0.512	0.24	6.494	0.000
ICT teaching self-efficacy, Enjoyment, Value appraisal, Control appraisal → TPCK	0.380	0.419	0.14	2.718	0.000

Table 7. Independent sample T-test

Constructs	Group	Mean	SD	df	T-value	*P*-Value
Control Appraisal	Pre-service	3.90	0.50	122	−0.81	0.444
	In-service	3.97	0.44			
Enjoyment	Pre-service	4.04	0.47	122	1.11	0.269
	In-service	3.91	0.61			
ICT in Teaching Sel-Efficacy	Pre-service	3.88	0.48	122	−0.34	0.731
	In-service	3.91	0.51			
TPCK	Pre-service	3.96	0.52	122	−2.21	0.029
	In-service	4.15	0.38			
Value Appraisal	Pre-service	4.17	0.35	122	−0.03	0.973
	In-service	4.17	0.55			

Table 7 shows that there is a significant difference (p = 0.029) between the participants pre-service and in-service, with participants in-service having a higher mean (4.15) compared to participants pre-service. This suggests that practical teaching experience enhances TPCK. However, no significant differences were observed in control appraisal, enjoyment, ICT teaching self-efficacy, or value appraisal between the two groups. These results highlight the importance of further developing TPCK among pre-service teachers before they enter the classroom.

In response to the research question, the findings confirm that TPCK, self-efficacy, and related constructs significantly influence teachers' ICT value appraisal, with notable differences between pre-service and in-service teachers regarding TPCK. These findings are consistent with previous literature emphasizing the importance of TPCK, self-efficacy, and affective factors in the effective integration of ICT in education. Studies have shown that teachers' beliefs in their technological capabilities (ICT teaching self-efficacy) and their perceptions of the value and enjoyment derived from using ICT significantly influence their teaching practices and student outcomes.

These results align with earlier studies, such as [18, 32] which suggested that TPCK and ICT self-efficacy significantly influence teaching practices. The observed predictive relevance of control appraisal, enjoyment, and value appraisal echoes findings by Pekrun [24], underscoring how teachers' beliefs about ICT control and enjoyment can drive successful technology integration in classrooms.

By comprehending these predictive relevance values, stakeholders in education, especially in teachers' training institutions, can have a clear understanding of what aspects to concentrate on more to improve the use of ICT in science education. This can result in the identification of focused strategies, which increase teachers' perceived competence and practical application of ICT, thereby raising educational performance.

H. Practical Implications of the Research Findings

The findings of this study provide valuable insights into how Technological Pedagogical Content Knowledge (TPCK), ICT teaching self-efficacy, enjoyment, control appraisal, and value appraisal interact to influence the integration of ICT in science education. These insights have several practical applications for educators, policymakers, and institutions aiming to enhance technology adoption in teaching:

- Teacher Training Programs: The strong relationship between TPCK, ICT self-efficacy, and value appraisal suggests that teacher training programs need to prioritise developing teachers' technological skills and also their pedagogical understanding of how to integrate technology into subject-specific teaching. This can be achieved through practical, hands-on workshops, where teachers are guided on how to effectively use ICT tools in science classrooms.

- Ongoing Professional Development: For in-service teachers, Continuous Professional Development (CPD) programs should focus on enhancing ICT self-efficacy by providing opportunities for teachers to experiment with ICT tools in a supportive environment. These CPD programs should include peer mentoring, collaborative projects, and reflective practice to help teachers build confidence in using technology.
- Curriculum Design and Support: Curriculum designers should integrate ICT as a core component across all science subjects, ensuring that the use of technology is not seen as an optional add-on but as a fundamental part of the learning process. The findings show that when teachers perceive value in ICT for teaching (value appraisal), they are more likely to use it. Therefore, curricula should explicitly include ICT-driven activities and learning outcomes, demonstrating its practical benefits in helping students grasp complex scientific concepts.
- Enhancing Teacher Motivation and Engagement: The positive correlation between enjoyment and ICT integration highlights the need for strategies that make the use of technology enjoyable for teachers. Schools and training institutions should create a culture where experimenting with new technologies is encouraged and celebrated.

In summary, these findings offer actionable steps for schools, training institutions, and policymakers to enhance ICT integration in education. By focusing on developing teachers' TPCK, improving their self-efficacy, and ensuring that they see the value and enjoyment in using technology, educational institutions can create more effective learning environments that leverage the full potential of ICT in science education.

V. Conclusion

The main finding of this research is the significant positive effect of TPCK, ICT teaching self-efficacy, enjoyment, and control appraisal on value appraisal in the context of science education. These findings are supported by the path model analysis, indicating strong relationships between these constructs. This study corroborates previous research suggesting that teachers' perceptions of value in technology-enhanced teaching are influenced by their confidence in using ICT tools.

The results of this research confirm all six hypotheses with strong evidence. With regard to the results, H1(that there is a positive TPCK, ICT teaching self-efficacy, enjoyment and control appraisal effects on value appraisal) was supported with a significant ($p < 0.05$) coefficient of the path. H2 analysis on the other hand confirmed that these same constructs also control appraisal significantly. In support of H3, TPCK, ICT teaching self-efficacy, value appraisal and control appraisal together determined enjoyment which underscored ICT in enhancing teacher satisfaction with its use.

In addition, H4 and H5 were also confirmed, implying that TPCK and ICT teaching self-efficacy are also significantly related. They indicate that teachers' ability to integrate ICT LP is enhanced by their self-belief in using ICT (ICT teaching self-efficacy) and the other way around. Finally, H6 was also validated in the sense that there were observable differences between their pre-test group and self-practice teachers, especially in their comments on TPCK, where the self-practice teachers scored higher than the pre-service teachers due to the field experience.

Our results confirm the TPCK framework. This framework suggests that effective teaching with technology requires a balance between technological, pedagogical, and content knowledge. The findings demonstrate how these components together shape teachers' perceptions of ICT's value in science education. This study extends the current understanding by highlighting the role of enjoyment and control appraisal in this context.

Educational policymakers and teacher educators should focus more on developing effective PD programs. These programs should aim to increase teachers' ICT teaching self-efficacy and TPCK. Specific strategies might include hands-on workshops and demonstration lessons, allowing teachers to experiment with effective applications of technologies in science learning. Also, online courses present easily accessible, online computer-based modules that are self-contained and deal with both the concept and the application of ICT. In addition, collaborative projects challenge the teachers to collaborate on activities that entail the incorporation of ICT in their teaching methodologies, and dissemination of knowledge. The use of the aforementioned strategies will lead to the establishment of conditions conducive to ICT use in the classroom by the educators.

Future studies may look at the consequences of ICT incorporation on the teaching practices in the given country and the learners' achievements. The second research question explores temporary contextual influences to extend knowledge on effective ICT adoption in various school environments concerning access to resources and teachers' perceptions. Secondly, the exploration of specific PD provisions on the enhancement of teachers' ICT skills and self-efficacy would also be useful. In addition, while the present study focuses on pre-service and in-service science teachers in general, future research could explore how different teaching grades or subject disciplines (e.g., math, physics) might affect ICT integration. Such analysis could yield more granular insights into ICT usage across diverse educational contexts

Therefore, it can be concluded that TPCK, ICT teaching self-efficacy, enjoyment, and control appraisal are the important factors influencing teachers' perception of the instructional value in science education. In connection with these findings that link theory to research evidence, this study makes a significant contribution toward advancing the knowledge of how the use of educational technology may best be leveraged in improving teaching practices and students' achievement in science learning environments.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Dr. Marwan M. A. Abualrob conducted the research problem hypothesis and data analysis. He also played a crucial role in interpreting the data and ensuring the statistical methods were appropriately applied and reported. Dr. Said Hamed Al-Saadi wrote the introduction, and the literature review and formulated the research question. He also discussed the study findings and prepared the final paper, ensuring that all sections were cohesively integrated and well-articulated. Both authors approved the research intent, discussed all parts of the final version, and collectively ensured the manuscript met the standards for academic publication, had approved the final version.

Acknowledgment

We extend our sincere gratitude to all the participants who contributed to the data collection phase of this research. We also wish to acknowledge the support from our institution and colleagues who provided guidance and resources throughout this project. Special thanks to Dr. Lucy Anne Perry from the English Language Department for her extensive English editing, which greatly enhanced the clarity and quality of this work.

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