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Reframing Teaching Effectiveness in Metaverse-Enhanced TVET: The Mediating Role of Teacher Engagement Within an i-TPACK Framework

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Abstract. The rapid growth of metaverse technologies is transforming teaching practices in technical and vocational education and training (TVET), and posing new challenges for teachers' pedagogical and technological skills. Although institutional investments have been rising, limited research exists on how teacher development is translated into teaching effectiveness using both psychological and behavioral processes. This study analyses the mediating effect of teacher engagement in professional development, pedagogical training, metaverse tools engagement, teacher readiness, and teaching effectiveness through the metaverse. The data were gathered through judgmental sampling of 214 Malaysian TVET teachers with relevant experience in metaverse teaching. The analysis was conducted using two-step covariance-based structural equation modelling. The findings indicate that professional development, pedagogical training, and engagement with metaverse tools significantly predict teaching effectiveness, with their effects partially mediated by teacher engagement. Teacher engagement emerged as the strongest determinant, functioning both directly and indirectly, in enhancing teaching effectiveness through the metaverse. The study advances the immersive technological pedagogical content knowledge (i-TPACK) framework by positioning teachers' engagement as a central mechanism that activates teacher development in metaverse TVET environments.

Keywords: i-TPACK; TVET; metaverse; pedagogical training; teacher readiness; teacher engagement

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1. Introduction

1.1 Background of Study

The rapid development of extended reality technologies has transformed the educational environment, leading to the emergence of the metaverse. In technical and vocational education and training (TVET), experiential practice, contextual realism, and applied learning present unique opportunities in the metaverse. As industrial environments are recreated in metaverse environments, they allow students to learn actively, collaboratively, safely and risk-free (Nicolosi et al., 2024). Therefore, TVET institutions worldwide are investing in digital infrastructure, virtual labs, and simulated pedagogies to transform teaching and training for future workplaces and equip students with the skills they need.

Despite this prospect, the existing body of knowledge has primarily focused on students, examining metaverse technologies for their potential to enhance students' motivation, engagement, and conceptual comprehension. Among the advantages of the metaverse in TVET education are better spatial reasoning, increased immersion, and greater satisfaction (Uribe et al., 2024). Nevertheless, these viewpoints do not adequately address the teacher's role as the primary agent in transforming technological potential into valuable learning outcomes. Without knowledge of the mechanisms by which teachers' developmental contributions are translated into effective practice, the promise of metaverse education may not be fulfilled.

Past scholars (Latepi & Madar, 2025; Wang & Li, 2024) have shown that teachers' readiness, pedagogical competence, and tool literacy are sufficient to achieve positive outcomes when technologies are provided. However, counter-evidence shows that even after investments in training and resources, outcomes remain unequal (Preminger et al., 2024; Shimu & Haolader). Metaverse tools might seem attractive and interesting to teachers, yet without the long-term commitment and dedication of the psychological resource, they tend to be applied shallowly or, at best, incomprehensively. This implies that teachers' development is insufficient, and that teachers' involvement can turn development inputs into stable and effective teaching practices.

While teacher engagement has been the subject of numerous studies in educational technology, it is often treated as an outcome variable or a secondary correlation. Not many empirical studies have rigorously tested its mediating capacity, clarifying the effects of professional development (PD), pedagogical training (PT), metaverse tool engagement (MTE), and teacher readiness (TR) on teaching efficacy in an metaverse-based setting (Li et al., 2022). This oversight is risky because it can lead to poor policy and institutional planning, as investments can focus on the inputs, which include equipment and courses, without the psychological and behavioral mechanisms that eventually result in such inputs being effective.

1.2 Research Objectives

RO1: To examine the teacher development dimension (e.g., PD, MTE, PT, TR) that affects teaching effectiveness through the metaverse (TETM).

RO2: To examine the mediating effect of teacher engagement (TE) between the teacher development dimension (e.g., PD, MTE, PT, TR) and teaching effectiveness through the metaverse (TETM).

RO3: To examine teachers' engagement towards teaching effectiveness through the metaverse (TETM).

1.3 Significance of Study

The study is novel in three respects. First, it combines several aspects of teachers' growth into a single structural framework, allowing a clear picture of how they affect one another. Second, it does not frame TE as a peripheral element but as the core that transforms the inputs of teacher development dimension into positive teaching outcomes. Third, it contributes to conceptualizing TE as an activating mediating mechanism that links knowledge, readiness, and pedagogical competence to TETM settings within the immersive technological pedagogical content knowledge (i-TPACK) framework. Collectively, these contributions offer new theoretical insights and practical principles for TVET institutions and policymakers to realize the transformative potential of the metaverse in TVET education.

2. Literature Review

2.1 Theoretical Perspective

The theoretical approach of this study is based on the TPACK model suggested by Mishra and Koehler (2006), which underlines the interdependence of TPACK in instruction. The TPACK model can help teachers gain insights into how to incorporate metaverse tools into TVET teaching, while maintaining rigor in the subject matter. As the introduction of metaverse learning environments is accelerating rapidly, this framework needs to be extended to embrace the affordances the metaverse offers. Therefore, this study presents the "immersive-TPACK" (i-TPACK) framework (Figure 1), which includes PD, MTE, PT, TR, and TE as instrumental facilitators of teaching performance.

The classic center of content knowledge, pedagogical knowledge, and technological knowledge is the main aspect, but the model is extended to the i-TPACK, by adding TR and PD as core inputs. Teacher engagement is assumed to be one of the mediating variables that initiate and transform the aforementioned inputs into TETM conditions. The framework also highlights that TE is not a byproduct but a dynamic process that connects teachers' PD, pedagogical mastery, and technological integration to successful teaching practices in the metaverse and experiential learning environment. In contrast to the conventional TPACK, i-TPACK views TE as a mediating mechanism that activates the transformational power of teacher professional growth, pedagogical teaching, and technology acceptance.

In this context, TE is positioned as the dynamic force that transforms teacher development involvement into effective teaching outcomes in both virtual and experiential settings. This study recognizes the interactive and affective nature of teaching in the metaverse by extending TPACK to i-TPACK, arguing that aligning pedagogical competence with technological affordances, readiness, and sustained participation is essential.

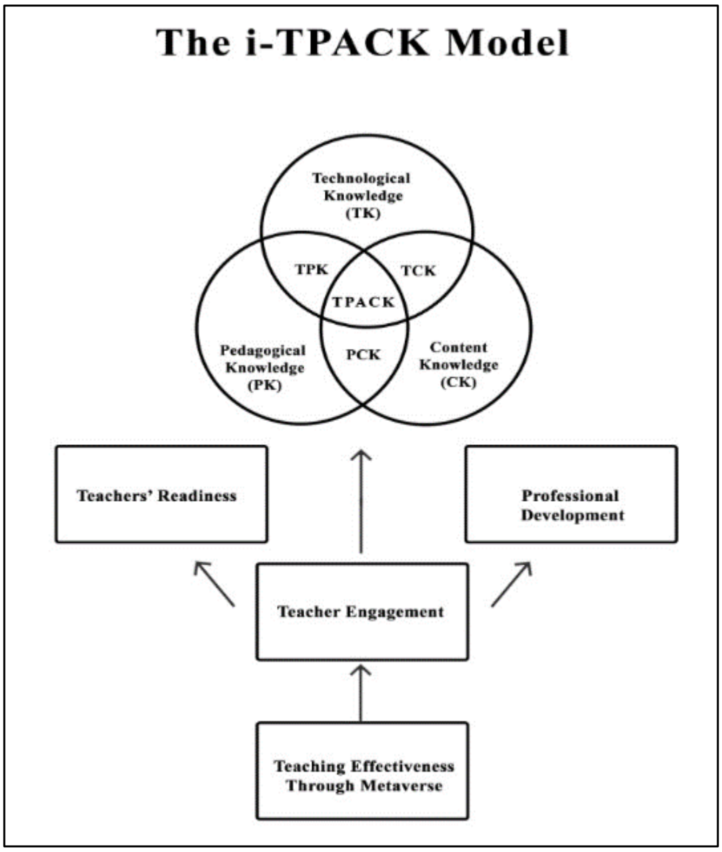

Figure 1: The i-TPACK Model

2.2 Hypothesis Development

2.2.1 Professional development and teaching effectiveness

Professional development has been shown to enhance teachers' teaching abilities and, consequently, their learning abilities (Bowman et al., 2022; Sims & Fletcher-Wood, 2021). In instances in which the development was specifically oriented towards the use of metaverse tools, it not only teaches technical knowledge but also demonstrates pedagogical applications of the metaverse's affordances. While evidence indicates that PD enhances teachers' ability to design metaverse virtual reality/augmented reality simulations, this assumption may be overly optimistic in practice, as not all teachers respond equally to PD initiatives, particularly when interventions are standardized rather than tailored to individual technological self-efficacy levels or subject contexts (Mystakidis et al., 2021). Thus, based on that argument, the following hypothesis was posited for empirical investigation:

H_1: PD has a direct positive effect on TETM.

2.2.2 Metaverse tools engagement and teaching effectiveness
In general, MTE is frequent, reflective, and pedagogically focused, as it allows teachers to consider affordances (e.g., embodied practice, safe failure, scenario replay) that directly impact skills acquisition in TVET areas. Recent studies, such as those by Garg et al. (2025) and Tene et al. (2024), indicate that metaverse technologies (virtual reality/augmented reality) expand the possibilities for focused practice and active evaluation, which have become central to teaching performance. Conversely, Pandey et al. (2024) and Rawat and Hagos (2024) cautioned that the MTE alone cannot ensure teaching effectiveness, as inappropriate instructional design or shallow implementation may yield novelty effects without subsequent benefits. Thus, based on the that discussion, the following hypothesis was posited for empirical exploration:

H_2: MTE has a direct positive effect on TETM.

2.2.3 Pedagogical training and teaching effectiveness through the metaverse
Metaverse environment-specific PT provides teachers with the means to transform virtual affordances into powerful learning patterns that construct scaffolded simulations, formative feedback cycles, and collaborative activities, which are designed to reflect workplace needs. Recent studies report that virtual reality-based TR improves teachers' instructional design capabilities and classroom performance, especially when training focuses on practice-based design and assessment in the virtual environment (Dai et al., 2023; Edinger, 2020). However, critics such as Andoh et al. (2022) argued that TR should be accompanied by support (materials, time, and assessment coordination), otherwise trained methods will be hard to maintain, and this would mean the PT would be practice-based, discipline-based, and institutionally supported. Thus, the following hypothesis was posited for empirical exploration:

H_3: PT has a direct positive effect on TETM.

2.2.4 Teachers' readiness and teaching effectiveness
The TR, in the form of technical proficiency, personnel orientation, and logistical readiness, provides the foundation for successful metaverse education. Research by Bower et al. (2020) and Li et al. (2023) on metaverse adoption indicated that TR predicts readiness to use metaverse platforms and initial instructional competence as TR increases, and that, as TR increases, trustworthiness of implementation and better teaching outcomes are achieved. However, TR on its own may not be sufficient, as institutional pressures (bandwidth, time, and institutional incentives) may affect the translation of TR into teaching effectiveness. Thus, the following hypothesis was hypothesized for empirical investigation:

H_4: TR has a direct positive effect on TETM.

2.2.5 Teacher engagement and teaching effectiveness
The behavioral, cognitive, and emotional investment in teaching as a proximal predictor of instruction quality is evident in TE. According to Hutchins and Biswas (2024), when teachers are more involved in the pedagogical content and tools (such as co-designing experiences and iterating simulations), students'

learning and classroom dynamics can be significantly improved (Sunday et al., 2025). TE maintains looping refinement, student responsiveness, and innovative pedagogical applications that underpin teaching success in the metaverse. However, counterarguments highlight that both the workload and fatigue may pose long-term threats to TE in designing incentives and teaching practices that can help sustain TE. Thus, the following hypothesis was posited for empirical exploration:

H_5: TE has a direct positive effect on TETM.

2.2.6 Mediation relationship of TE between PD, MTE, PT, and TR towards TETM
Teacher engagement is suggested as a necessary mediating factor between the teacher development dimensions and teaching performance in metaverse-enhanced TVET, based on previous empirical research (Alifah et al., 2025; Bowman et al., 2022; Onu et al., 2024). PD boosts teachers' mastery, confidence, and perceived relevance, which subsequently boosts TE and converts developmental contributions into measurable instructional gains (Rui-qi & Man, 2026). Equally, meaningful MTE promotes learning through exploration and pedagogical experimentation, but its impact becomes most real when teachers are cognitively and emotionally involved in responding to instructional objectives by adapting MTE (Beck et al., 2023).

Practice-based, collaborative PT builds instructional confidence and long-term TE, thereby enabling the successful delivery of metaverse teachings. Similarly, TR eliminates technical obstacles and builds confidence, enabling deeper involvement that converts TR into student-driven, repetitive actions (Sato & Loewen, 2022). In this regard, the following hypotheses postulated that TE will mediate the correlations among the variables PD, MTE, PT, and TR toward TETM:

H_6: TE mediates the relationship between PD and TETM.

H_7: TE mediates the relationship between MTE and TETM.

H_8: TE mediates the relationship between PT and TETM.

H_9: TE mediates the relationship between TR and TETM.

3. Methodology

The current study employed a quantitative research design to empirically test the hypothesized relationships among variables (H_1–H_9). As TVET teachers are heterogeneous and may vary significantly in their knowledge and areas of specialization, judgmental sampling was employed to ensure that the sample includes respondents with experience and knowledge relevant to the study's goals.

3.1 Data Collection

The questionnaire was sent online, and the link was provided via Google Drive. A total of 294 questionnaires were distributed, and 214 respondents returned them, yielding a response rate of more than 70%. The response was deemed comprehensive in educational research and adequate for covariance-based structural equation analyses, in which, as a rule, larger sample sizes are necessary to obtain a stable estimate of the parameter (Lund, 2023). The questionnaire method was selected because it enabled large-scale data collection, response standardization, and statistical modelling using covariance-based structural equations. Compared to interviews or case studies, it allowed the mediating relationships and latent constructs to be assessed with reliability and validity.

Before proceeding with primary data collection, the questionnaire was pretested with five TVET teachers. These five teachers verified the requirements for the questions and the consistency of the easily understandable measures, which resulted in optimism about the respondents' answers. Initial evaluations of the scale questions minimized discrepancies between the survey and the measures being assessed. The questions were revised after the pre-test to ensure their validity and the respondent's comprehension of the questionnaire's criteria.

A total of 30 TVET teachers piloted the questionnaire for this study. Six variables were considered when determining the internal accuracy of a measuring instrument using Cronbach's alpha coefficient. All six of the study's variables had Cronbach's alpha values greater than 0.7. Furthermore, to ensure construct validity and reliability, all constructs and assessment items were generated from prior studies and personalized to the context of this study. The items were measured on a five-point Likert scale ranging from 'strongly disagree' to 'strongly agree.'

3.2 Study Instrument

In addition to the 11 demographic questions in Section A of the questionnaire (refer to Appendix 1), 36 items were used to measure the six variables in the study. Section B contained six questions, adapted from Darling-Hammond et al. (2019), that assessed the concept of 'PD'. Section C contained six questions, which were modified based on research by Kye et al. (2021), to measure MTE. In Section D, six questions were adapted from Darling-Hammond et al. (2019) to assess the concept of PT. In Section E, six questions from Clarke and Hollingsworth (2002) were used to evaluate TR, whereas in Section F, six questions from Schaufeli et al. (2002) were used to assess TE. Lastly, the TETM dependent variable was assessed in Section G using six questions based on Bandura's (1997) framework.

The single-factor statistical test conducted by Harman was done to estimate common method bias. The results showed that none of the variables accounted for a majority of the variance. The initial factor strength accounts for less than 40% of the total variance, well below the 50% required. This implies that common method bias did not pose a significant threat to validity.

Lastly, ethical permission for this study was granted by the Universiti Tunku Abdul Rahman Research Ethics Committee (Approval No.: IPSR/RMC/UTARRF/2023-C2/A03). Before the survey, an information statement was issued to respondents outlining the study's purpose, voluntary participation, and assurances of confidentiality and anonymity.

Electronically informed consent was obtained, and respondents were given the opportunity to complete the questionnaire. No sample was gathered that might be personally identifiable, and all answers were gathered to serve purely academic research purposes

4. Findings

Descriptive analysis was performed with SPSS version 29 and analysis of moment structures version 29 was tested with the help of two-step structural equation modelling method (Anderson & Gerbing, 1988). First, the confirmatory factor analysis was employed to measure the reliability and validity of the measurement model. Second, the relationships among the five elements of this study were explored using structural equation structural modelling. The recommendations of Hu and Bentler (1999) were used to identify and evaluate certain model indicators. This includes χ^2 statistics, root mean square error of approximation, composite fit index, normed fit index, and the ratio χ^2/degree of freedom (Ramírez et al., 2025).

4.1 Demographic Analysis

The demographic analysis of 214 TVET teachers revealed a diverse, balanced sample, ensuring the study captured multiple perspectives on metaverse adoption in education. Gender distribution was relatively even, with males (53.3%) slightly outnumbering females (46.7%).

Age variation was notable, with the largest groups being those aged under 25 (22.9%) and 36 to 45 years (22.9%). Teachers aged 60 years and older accounted for 22%, while those aged 46 to 60 years accounted for 16.4%. This spread highlights the representation of both younger teachers, often more digitally adept, and senior teachers with extensive pedagogical experience, thereby allowing examination of generational differences in technology adoption.

Educational attainment was generally high, reflecting the professionalization of TVET. Master's degree holders represented the largest group (29.4%), followed by equal proportions of PhD and bachelor's degree holders (24.8% each), and 21% with diplomas. This suggests that most respondents held advanced qualifications, thereby reinforcing the credibility of the insights into PD and training.

Furthermore, teaching experience was also widely distributed: 22% had taught for 1–3 years, 21.5% had taught for 4–6 years, and 21% had taught for 7–10 years. A further 17.3% had less than 1 year of experience, while 17.8% had more than 1 decade of experience, reflecting perspectives from novice, mid-career, and senior teachers. In general, the demographic analysis indicates that the respondent population was heterogeneous with respect to gender, age, qualifications, teaching areas, and technological literacy.

4.2 Descriptive Analysis

Table 1 presents descriptive results indicating high mean scores for PD, MTE, PT, TR, and TE toward TETM, with averages exceeding 20 on their respective scales. These findings indicate that the respondents tend to have a favorable attitude towards their development experiences, participation, and efficacy in metaverse teaching situations. The standard deviations (between 1.43 and 1.70) were small, suggesting a high level of consensus among participants, and the skewness and kurtosis values were close to zero, indicating that the data were normally distributed and thus met the conditions for further covariance-based structural equation modeling analysis. This result is consistent with the study's requirements, underscoring the need to test TE as a mediating variable.

Table 1: Descriptive statistics of variables

	Mean	Std. Deviation	Skewness	Kurtosis
PD	21.0896	1.62720	-.091	-.362
MTE	21.3583	1.48586	.031	.240
PT	20.9977	1.70247	.114	-.445
TR	21.1550	1.43808	-.042	-.490
TE	21.1838	1.51414	.020	-.103
TETM	21.2827	1.57946	-.093	.094

Note: PD = Professional development, MTE = Metaverse tools engagement, PT = Pedagogical training, TR = Teachers' readiness, TE = Teacher engagement, TETM = Teaching effectiveness through metaverse

4.3 Confirmatory Factor Analysis

The confirmatory factor analysis results presented in Table 2 indicate that the measurement model met acceptable validity and reliability thresholds across all constructs. Factor loadings for the majority of items exceeded the recommended cut-off value of 0.70 (Hair et al., 2019), with only a few slightly below this benchmark (e.g., PD3 at 0.677, MTE3 at 0.562, TR6 at 0.647). These exceptions are still within a tolerable range, particularly since the overall average variance extracted (AVE) values for each construct remain above the 0.50 threshold, confirming adequate convergent validity.

This indicates that each construct explains more than half of the variance in its indicators, thereby supporting the measurement model's internal consistency. The high CR values for all constructs (0.84–0.875) indicate internal consistency, and AVE values above 0.50 confirm convergent validity. The low scores on the weaker loadings do provide valuable data, indicating that there are still opportunities to improve in areas such as the creative use of metaverse tools or the flexibility of new metaverse practices by teachers. Notably, these findings provided a solid foundation for measurement, on which future structural modeling can meaningfully test the hypothesized relationships.

Table 2: Confirmatory factor analysis

Items/Indicators	Factor Loading	AVE	CR
PD1	0.739	0.532	0.872
PD2	0.745		
PD3	0.677		
PD4	0.711		
PD5	0.737	0.576	0.840
PD6	0.764		
MTE1	0.886		
MTE2	0.910		
MTE3	0.562		
MTE5	0.617		
PT1	0.728	0.515	0.865
PT2	0.678		
PT3	0.722		
PT4	0.715		
PT5	0.727		
PT6	0.734		
TR1	0.721	0.505	0.859
TR2	0.732		
TR3	0.692		
TR4	0.749		
TR5	0.718		
TR6	0.647		
TE1	0.719	0.539	0.875
TE2	0.751		
TE3	0.739		
TE4	0.724		
TE5	0.740		
TE6	0.732		
TETM1	0.733	0.536	0.874
TETM2	0.762		
TETM3	0.725		
TETM4	0.775		
TETM5	0.710		
TETM6	0.684		

Note: PD = Professional development, MTE = Metaverse tools engagement, PT = Pedagogical training, TR = Teachers' readiness, TE = Teacher engagement, TETM = Teaching effectiveness through metaverse

4.4 Measurement Model

The measurement model in Figure 2 was assessed using confirmatory factor analysis to evaluate construct adequacy and overall fit. Although the chi-square statistic was significant (χ^2 = 597.231, df = 215, p < .001), the relative chi-square (χ^2/df = 2.778) fell within the acceptable range (< 5.0), indicating reasonable fit. Further supporting this supposition, the composite fit index = 0.917, incremental fit index = 0.918, and Tucker-Lewis index = 0.903, all exceeding the 0.90 threshold. While the normed fit index = 0.878, the goodness-of-fit index = 0.872, and the adjusted goodness-of-fit index = 0.836 were slightly below benchmark values, they remain acceptable for complex models. Furthermore, the root mean square error of approximation = 0.070 also fell below 0.08, indicating a satisfactory model fit to the observed data. Collectively, these indices demonstrate that the measurement model provides a reliable representation of the hypothesized constructs.

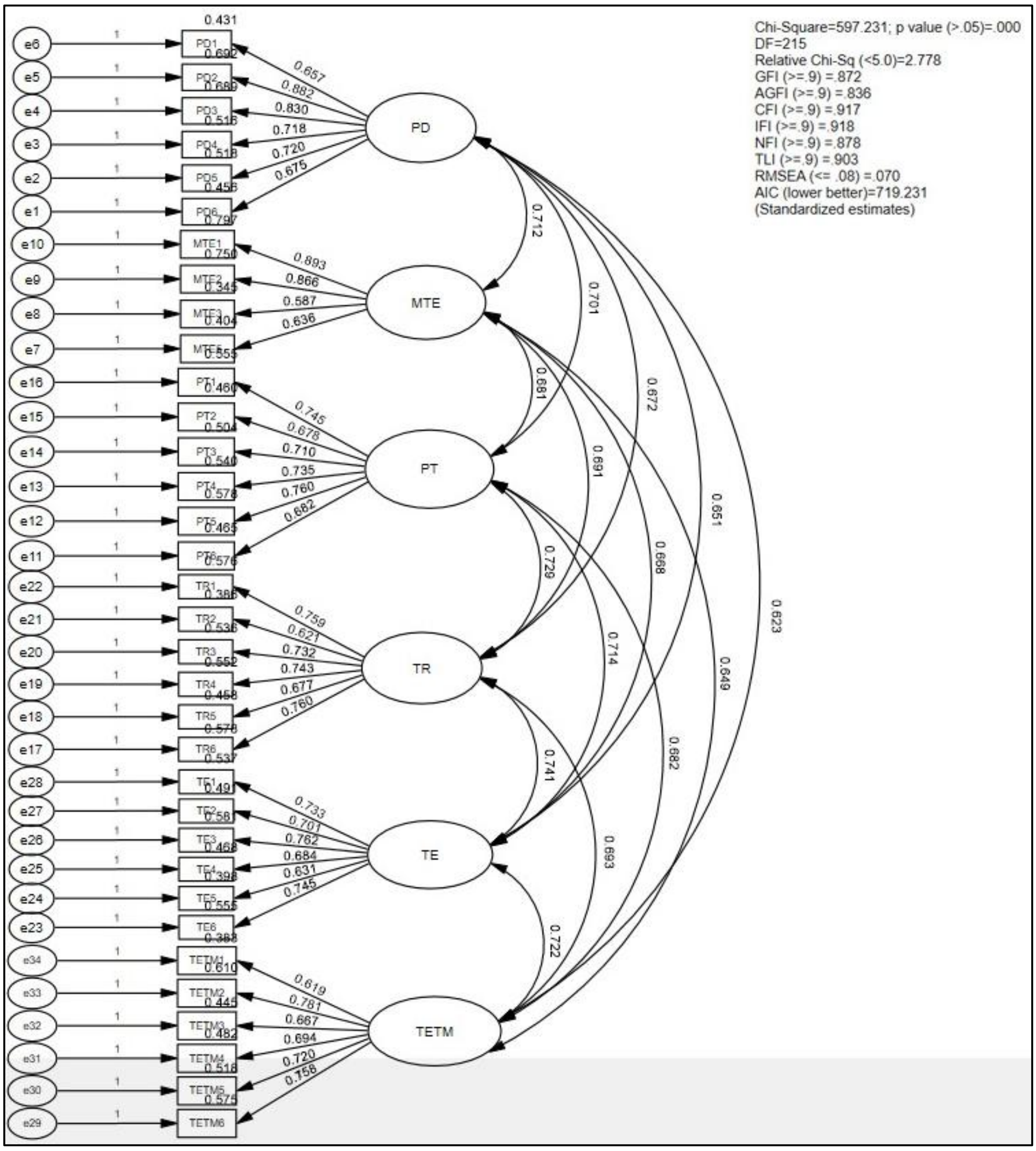

Figure 2: Measurement model

4.5 Construct Validity and Reliability

Table 3 has demonstrated the construct validity and reliability of the measurement model. The constructs all have CR values beyond the recommended 0.70, ranging from 0.844 to 0.885, and all exhibit good internal consistency. AVE values were also diagonally indicated and supported convergent validity, with the majority of constructs having values greater than or close to the 0.50 threshold and exceeding it, indicating that the constructs accounted for more than half of the variance of the items they measured. Although TETM (0.502) and TR (0.514) were only slightly above the cut-off, they were tolerable, particularly given their high CR scores.

Moreover, the squared inter-construct correlations were always less than the AVE values, thereby confirming discriminant validity. These inconsistencies indicate that, although the constructs were connected, they reflected distinct conceptual areas and provided a robust basis for testing the hypothesized mediating role of TE in the relationship between the dimensions of teacher development and TETM.

Table 3: Construct validity and reliability

Constructs	CR	PD	MTE	PT	TR	TE	TETM
PD	0.885	0.565					
MTE	0.844	0.507	0.583				
PT	0.865	0.491	0.464	0.517			
TR	0.863	0.452	0.477	0.531	0.514		
TE	0.859	0.424	0.446	0.51	0.549	0.505	
TETM	0.857	0.388	0.421	0.465	0.48	0.521	0.502

Note: PD = Professional development, MTE = Metaverse tools engagement, PT = Pedagogical training, TR = Teachers' readiness, TE = Teacher engagement, TETM = Teaching effectiveness through metaverse

4.6 Structural Model

The structural model in Figure 3 demonstrates the relationships among PD, MTE, PT, TR, TE, and TETM. Model fit indices indicate acceptable representation of the data (χ^2 = 597.231, df = 215, $p < 0.001$; composite fit index = 0.917; incremental fit index = 0.918; Tucker-Lewis index = 0.903; root mean square error of approximation = 0.070). The findings revealed that PD (β = 0.301), MTE (β = 0.368), and PT (β = 0.173) significantly and positively influence TE, suggesting that continuous professional learning, technological engagement, and structured PT collectively enhance teachers' instructional effectiveness. Nevertheless, TR had a weak impact on TETM (β = 0.073), indicating that readiness alone is insufficient and requires tangible skills and practice in exploiting metaverse technologies.

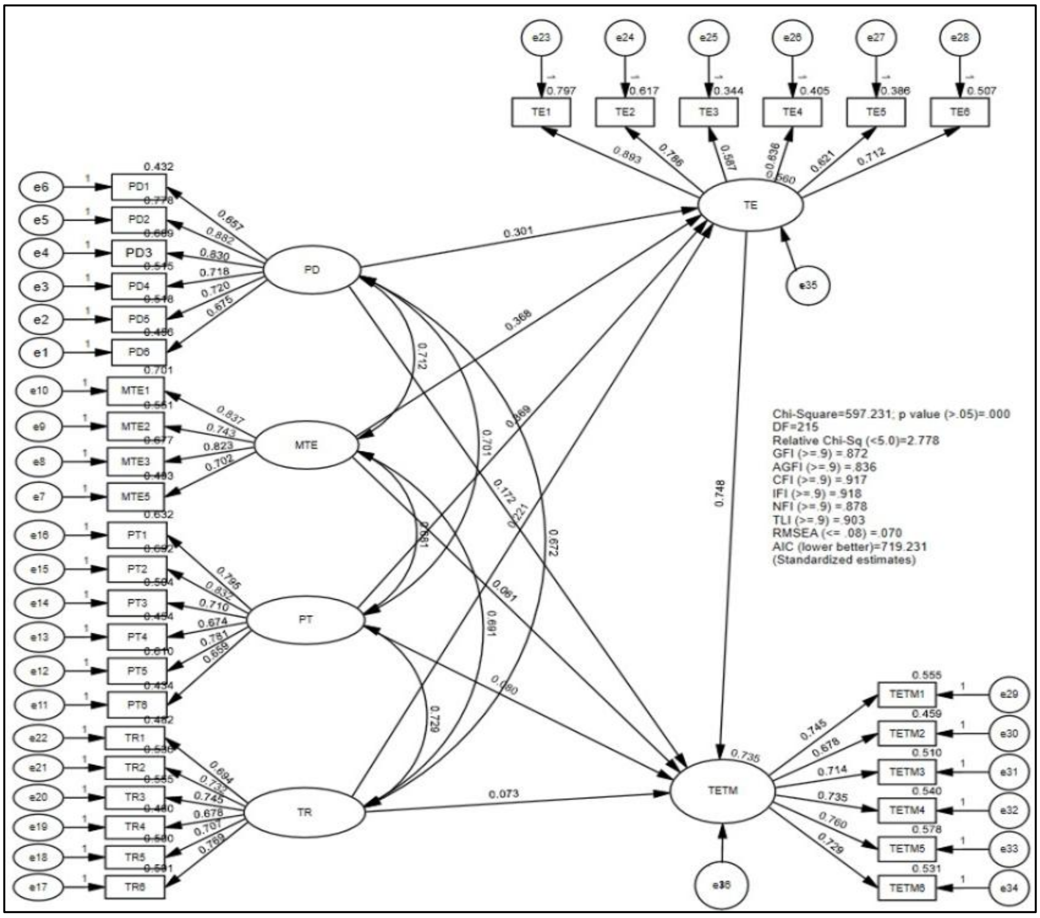

Figure 3: Structural model

In practice, teachers who perform well in traditional teaching are better positioned to transfer and implement such strategies in metaverse learning settings. This highlights the importance of TVET institutions focusing on continuous professional growth, specific training, and experience with metaverse tools, rather than basing it solely on teachers' perceived readiness. The structural model, therefore, provided strong support for the hypothesized model, with most direct and mediated relationships supported and, hence, strengthening the framework.

4.7 Path Coefficient of the Direct Research Model

The direct hypothesis testing revealed mixed results across the teacher development dimensions. As presented in Table 4, PD significantly influenced TETM (β = 0.140, CR = 2.857, p = 0.004). Although modest in strength, this result highlights the importance of structured learning initiatives and professional growth in shaping outcomes. Similarly, MTE demonstrated a significant and slightly stronger impact (β = 0.149, CR = 3.170, p = 0.002), suggesting that experiential familiarity with metaverse tools directly contributes to instructional success. PT emerged as the most influential institutional factor (β = 0.190, CR = 3.653, p < 0.001), confirming that pedagogical preparedness is central to integrating metaverse technologies effectively.

In contrast, TR did not show a significant direct effect (β = 0.073, CR = 1.304, p = 0.192), indicating that preparedness alone does not guarantee teaching effectiveness in metaverse environments. However, TE was the most dominant predictor (β = 0.735, CR = 13.898, p < 0.001), underscoring its pivotal role as the psychological and behavioral driver of effective teaching in the metaverse.

Table 4: Direct hypotheses testing results

Hypothesis	Path	β	CR	p-value	Result
H1	PD → TETM	0.140	2.857	0.004	Supported
H2	MTE → TETM	0.149	3.170	0.002	Supported
H3	PT → TETM	0.190	3.653	0.000**	Supported
H4	TR → TETM	0.073	1.304	0.192	Not Supported
H5	TE → TETM	0.735	13.898	0.000**	Supported

Note: PD = Professional development, MTE = Metaverse tools engagement, PT = Pedagogical training, TR = Teachers' readiness, TE = Teacher engagement, TETM = Teaching effectiveness through metaverse

4.8 Results of the Mediating Effect Test

The mediation analysis offered further insights into the mechanisms underlying these relationships. As shown in Table 5, TE partially mediated the effects of PD, MTE, and PT on TETM. For PD, the direct effect (0.140) was complemented by a stronger indirect effect (0.221), producing a total effect of 0.361. Similarly, MTE yielded a direct effect of 0.149 and an even larger indirect effect of 0.270, yielding the strongest total effect of 0.419. Pedagogical training displayed both direct (0.190) and indirect (0.126) effects, generating a total of 0.316, demonstrating that training is impactful both directly and through TE. Conversely, TR again failed to exert significant mediated effects, with a total effect of only 0.141, highlighting its limited role in the framework.

Table 5: Direct, indirect, and total effects (mediation analysis)

Predictor	Direct Effect	Indirect Effect	Total Effect	Mediation Result
PD	0.14	0.221	0.361	Partial Mediation
MTE	0.149	0.27	0.419	Partial Mediation
PT	0.19	0.126	0.316	Partial Mediation
TR	0.073	0.068	0.141	No Mediation

Note: PD = Professional development, MTE = Metaverse tools engagement, PT = Pedagogical training, TR = Teachers' readiness, TE = Teacher engagement, TETM = Teaching effectiveness through metaverse

The dominance of TE is particularly prominent. With a direct coefficient of 0.735 (p < 0.001), it was by far the strongest path in the model. This finding underscored that, while institutional support such as PD and PT are essential, their impact is significantly amplified only when teachers are engaged. This empirical evidence positions engagement as the crucial mechanism through which innovation is realized in metaverse-enhanced TVET.

5. Discussion

The current study's results contribute to teacher development and involvement in the formation of the TETM in TVET. The findings align with the three research objectives and draw out the interaction among TVET institutional supports, teacher motivation, and instructional outcomes. Regarding RO1, the study found that both PD and PT had a significant impact on teaching effectiveness, whereas TR did not. The PD's positive impact brings out the great significance of organized and sustained upskilling, especially in the fast-changing digital world. This observation is consistent with the results of Darling-Hammond et al. (2017), who noted that long-term PD is beneficial to instructional practices when it promotes collaboration and reflection.

Likewise, Preminger et al. (2024) demonstrated that PD promotes effective teaching, but it is associated with active engagement. Nevertheless, the present research refutes the arguments of Wang and Li (2024) that PD alone is sufficient, as the current study's findings indicate that the effect of this method is enhanced by TE. Apart from this, PT emerged as the most powerful direct predictor of the need to underpin meaningful technology integration, in line with Latepi and Madar (2025), who emphasized the need to anchor digital tools in pedagogy.

Considering RO2, the findings indicate that the more teachers actively and confidently engage with metaverse tools, the greater the effectiveness of teaching. It shows that the use of the tool is not only a technical issue but also depends on teachers' motivation and innovativeness in working with metaverse technologies (Yuanling et al., 2026). The mediating role of TE emphasizes that effective tool use is an attitudinal investment rather than mere familiarity. This aligns with Kye et al. (2021) and Li et al. (2022), who stated that the use of metaverse tools can yield better learning outcomes with motivated and creative teachers. However, the current results contradict Shimu and Haolader (2025)'s findings, who considered technological familiarity to be sufficient to make it effective. Rather, the current study indicates that competence has to be coupled with interest in developing creative and effective teaching activities.

Lastly, responding to RO3, the findings show that TE is the strongest predictor of TETM. The effects of PD, PT, and MTE were mediated by engagement and demonstrated the greatest direct impact on effectiveness. This observation supports Schaufeli et al. (2002), who theorized TE as a performance driver and applied their model to the emerging field of metaverse education. The findings also resonate with those of Li et al. (2022), who found that TE acted as a mediator in the adoption of digital technologies, but did not examine the metaverse context.

Compared with other studies (e.g., Wang & Li, 2024), this study underscores the importance of TE, suggesting that institutional inputs are sufficient; however, engagement converts these inputs into significant outcomes. For example, two teachers can obtain the same PD or have access to the same tools, but one may make their lesson more creative, student-centered, and practical, demonstrating that TE is the key to effective metaverse teaching. Taken together, these findings indicate that TVET teachers, including PD, PT, and MTE, are required enablers, but the effects of these programs are limited to TE, and readiness is insufficient.

5.1 Implications of the Study

5.1.1 Theoretical implications

The research contributes significantly to the theoretical understanding of the TPACK model by developing the i-TPACK model and applying it to an educative immersion setting. Although the original TPACK model has offered long-term insights into how teachers combine pedagogy, technology, and content, it has mostly been conceptualized as a body of knowledge. The results show that reconsidering the TPACK model as an engagement-activated model has empirical support, as TE was identified as the most powerful predictor of TETM, exerting both a direct impact and mediating the effects of PD, PT, and MTE. It is important to note that pedagogical and technological competence alone is not enough; these competencies must be brought to life through interaction to deliver meaningful results.

Ideally, the i-TPACK framework makes its contributions to the body of work in two aspects. First, it extends TPACK into the metaverse learning domain by integrating constructs that capture the affective and behavioral aspects of teaching in the metaverse. Second, it offers a systematic template (Figure 1) that integrates both institutional provisions (training, readiness, tool use) and psychological processes (engagement) to explain teaching effectiveness. The gap this novel extension bridges is that engagement has been seen as secondary and marginal to digital pedagogy scholarship. This offers scholars a sound theoretical view on how developmental influences translate into teaching success in the rapidly changing environment of vocational learning.

5.1.2 Policymaker implications

The i-TPACK framework makes a substantial contribution to policymakers when formulating digital transformation strategies in TVET education. One of the central conclusions is that TR does not significantly predict teacher performance, as policies that equate enthusiasm or willingness with performance are problematic. Policymakers should understand that investments in digital infrastructure and training cannot achieve the desired effect without a well-thought-out strategy that encourages TE as the key to success. To provide a concrete implementation, TE must be clearly integrated into national TVET systems and policy tools.

Indicatively, the evaluation criteria for teachers must not be restricted to technical skills or involvement in professional growth but must also reflect prolonged involvement in metaverse pedagogy. Furthermore, it should be promoted through policies that encourage shared PD models, mentoring systems, and innovation hubs that foster environments where engagement becomes institutionalized. The emphasis in funding programs must be on long-term, practice-based programs that combine pedagogical design with metaverse technology, rather than short-term workshops, which tend not to be sustained. Significantly, equity should also be considered in policies by making sure that the

PD opportunities are differentiated and modified so that digital-savvy and less proficient teachers do not have inequalities.

5.1.3 Teacher implications
For teachers, the study's findings are particularly instructive, as they shift the concept of engagement from a peripheral issue to a central factor in teaching performance in the context of metaverse education. The i-TPACK model emphasizes that PD, PT, and MTE are crucial, but they can work only when teachers are actually involved in the process. The teachers are then urged to adopt engagement as a professional position, to participate actively, be creative, and keep learning.

There are several implications for the practice of teachers. Initially, teachers need to shift their attitude toward compulsory training from a passive, compulsory involvement to a reflective, inquisitive mindset that will help maintain their participation in the long term. First, it may be accomplished through professional learning communities, designing metaverse teaching together with colleagues, and continuously modifying instruction as students' needs and workplace realities emerge.

Second, teachers should be aware that willingness or eagerness to embrace new technologies does not necessarily translate into effectiveness; rather, they need to actively work to turn readiness into classroom practice. Readiness translates into meaningful outcomes through engagement. Moreover, the study identifies the need for teachers to embed pedagogical underpinnings in the implementation of metaverse tools. Instead of treating metaverse applications as independent novelties, teachers need to incorporate them into instructional designs that foster student-centered, applied learning.

6. Limitations and Future Research
This study contributes to knowledge of teacher development and involvement in metaverse-enhanced TVET, but several limitations should be noted. The study was conducted only with Malaysian TVET teachers, which limits the generalizability of the results. A broader coverage of cross-country settings, such as Finland with its strong digital pedagogy, and South Korea with its advanced metaverse adoption, may help demonstrate the influence of organizational and cultural settings on teacher interaction and teaching performance (Lanxin & Norizan, 2025).

Furthermore, the study included self-reported data, which may be subject to social desirability bias or false self-evaluation. Partially, this restriction might explain why the role of readiness was not significant in the results. This issue can be addressed in future studies by employing mixed-methods research designs, for example, combining surveys with classroom observations, interviews or digital analytics to triangulate the evidence and gain a more detailed insight into practice (Yuanling et al., 2026).

7. Conclusion

This study investigated the effect of teacher development dimensions, PD, PT, MTE, TR, on TETM, with TE as a mediating mechanism in the i TPACK model proposed. The findings offer firm evidence that, although teachers' development factors are important, they are only realized in full when prompted by TE. In practice, the study's implications underscore the value of continuous, practice-based PD that fosters sustained engagement. Overall, this study adds, both conceptually and empirically, to the discourse on digital pedagogy by showing that the success of metaverse education is not only dependent on access to technological devices or the professional competence of teachers, but also on the capacity to sustain TE as a mediating link. In the context of Malaysian TVET, where digital transformation is rapidly growing yet, at this stage, is underexplored, the findings offer a timely framework for theory, policy, and practice.

Conflict of Interest

The author declares that no competing interests or potential conflicts of interest are relevant to this study.

8. Generative AI statement

During the preparation of this study, we employed AI tools, including ChatGPT 4.0, to improve the article's readability, and Grammarly to ensure grammatical accuracy. Following the use of these tools, we carefully reviewed and validated the final version of the manuscript. As the authors, we assume full responsibility for the content of the published work.

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Appendices

Questionnaire (Appendix 1)

Demographic Profile

1. Gender
2. Age
3. Education Level
4. How many years of teaching experience do you have in TVET education?

Professional Development

1. I regularly participate in professional development programs to improve my engagement in Metaverse-enhanced teaching.
2. The professional development activities I engage in are specifically designed to address the integration of Metaverse tools in TVET education.
3. My institution provides sufficient encouragement and resources for professional development in Metaverse-based teaching strategies.
4. Professional development programs equip me with innovative techniques for using the Metaverse in vocational training.
5. Participating in professional development activities boosts my confidence in utilizing Metaverse tools to deliver subject-specific knowledge effectively.
6. Collaboration with peers during professional development sessions enhances my ability to integrate Metaverse tools into my teaching strategies.

Metaverse Tools Engagement

1. I am confident in my ability to effectively use Metaverse tools to create engaging and interactive lessons in TVET education.
2. The integration of Metaverse tools significantly enhances students' hands-on learning experiences in vocational training.
3. I find it straightforward to incorporate Metaverse-based simulations into my routine teaching practices.
4. The use of Metaverse tools in my lessons increases student motivation, participation, and engagement.
5. I frequently explore and experiment with new features of Metaverse tools to enhance my teaching strategies.
6. Training programs focused on Metaverse tools have strengthened my ability to effectively engage students in TVET education.

Pedagogical Training

1. The pedagogical training I received has enhanced my ability to plan effective lessons that integrate Metaverse tools in TVET education.
2. Pedagogical training has equipped me with the necessary skills to manage diverse student needs while using Metaverse-based teaching tools in vocational settings.
3. I regularly apply the teaching strategies learned through pedagogical training to effectively engage students in Metaverse-enhanced learning activities.
4. Pedagogical training has improved my ability to utilize modern teaching technologies, such as the Metaverse, to enhance student learning experiences in TVET education.
5. The pedagogical training I've received has increased my confidence in assessing student performance accurately using Metaverse-based assessments in vocational subjects.
6. My institution offers regular pedagogical training programs that help me stay updated on the latest Metaverse tools and teaching strategies for TVET education.

Teachers' Readiness

1. I feel confident in my ability to teach effectively in a Metaverse-enhanced TVET environment.
2. I am well-prepared to handle the diverse learning needs of TVET students using Metaverse tools and technologies.
3. I am proficient in using the digital tools and technologies, including the Metaverse, required for TVET teaching
4. I stay updated on industry trends and advancements in Metaverse technologies to enhance my teaching content in TVET education.
5. I am ready to integrate innovative teaching strategies, including Metaverse-based methods, into my lessons to improve student learning outcomes.
6. My institution provides sufficient support to ensure my readiness for teaching in a Metaverse-enhanced TVET education environment.

Teacher Engagement

1. I am fully engaged in planning and delivering Metaverse-enhanced lessons that meet the diverse needs of TVET students.
2. I actively participate in professional development programs focused on integrating Metaverse tools to improve my teaching effectiveness.
3. I collaborate with colleagues to share best practices and improve teaching strategies for integrating Metaverse technologies into TVET education.
4. I am motivated to go beyond the basic curriculum requirements by using Metaverse tools to support students' learning goals and foster deeper engagement.
5. My engagement in Metaverse-enhanced teaching activities positively impacts the overall classroom environment and student participation.
6. I dedicate time to assess and reflect on my use of Metaverse technologies in teaching, which helps improve student outcomes and my teaching practices.

Teaching Effectiveness Through Metaverse

1. Using the Metaverse in my teaching significantly improves students' understanding of complex vocational concepts and enhances my own engagement in the process.
2. The immersive nature of Metaverse tools enhances student engagement and participation in my TVET classes, making the learning experience more dynamic.
3. Metaverse-based teaching methods improve the practical skills of students in vocational training, which motivates me to stay engaged in the lessons.
4. I effectively utilize Metaverse technologies to create realistic simulations for hands-on learning, enhancing both student learning outcomes and my own teaching effectiveness.
5. Students show greater motivation to learn when Metaverse technologies are integrated into lessons, which increases my own enthusiasm to engage in their learning process.
6. The use of Metaverse tools in teaching improves overall student performance in vocational assessments and strengthens my confidence in using such tools.