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ASSESSING PRE-SERVICE SCIENCE TEACHERS' TECHNOLOGICAL PEDAGOGICAL CONTENT KNOWLEDGE (TPACK) IN THE HYBRID LEARNING ENVIRONMENT

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ABSTRACT

The integration of hybrid learning in science education presents both opportunities and challenges for pre-service teachers, particularly in balancing technological, pedagogical, and content knowledge (TPACK) while embedding 21st-century skills. This study examines pre-service science teachers' perceptions of their TPACK competencies and ability to integrate critical thinking, creativity, communication, and collaboration in hybrid learning environments. Semi-structured interviews were conducted with twelve purposefully selected pre-service teachers using a basic interpretive qualitative approach. Thematic analysis identified one theme - Teaching in a Hybrid Environment, with two sub-themes: delivering science lessons and integrating 21st-century skills. The participants demonstrated adaptability in using digital tools for instruction; however, inconsistencies in technological proficiency and challenges in pedagogical application suggested more structured training. The findings highlight the importance of professional development programmes that provide targeted support, hands-on digital tool training, and instructional strategies tailored to hybrid science education. This study contributes to educational research on TPACK implementation and enlightens teacher preparation programmes with evidence-based recommendations by addressing these gaps. Aligning with the United Nations Sustainable Development Goal (SDG) 4: Quality Education, it underscores the urgency of equipping future educators with the digital competencies and pedagogical expertise required for evolving teaching environments.

Keywords: TPACK; pre-service science teachers; 21st-century skills; teacher training; hybrid learning

INTRODUCTION

The integration of technology and 21st-century skills in education has significantly reshaped teaching methodologies, particularly in science education, where digital tools enhance conceptual understanding and student engagement. Aligning with Sustainable Development Goal (SDG) 4: Quality Education, which promotes inclusive and equitable learning opportunities, preparing pre-service teachers for hybrid learning environments is important. However, despite the comprehensive initiatives for technology-enhanced education, gaps remain in teacher readiness, particularly in the effective integration of Technological Pedagogical Content Knowledge (TPACK) and the development of critical thinking, communication, collaboration, and creativity (4Cs) in hybrid science instruction.

In Malaysia, the shift towards hybrid learning - combining in-person and online instruction - has introduced pedagogical opportunities

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and challenges (Kazu & Yalçın, 2022; Raes, 2022; Essa, 2023). While this instructional model fosters flexibility and interactivity, its success depends on educators' ability to integrate technology, pedagogy, and content knowledge seamlessly (Raes et al., 2020; Essa, 2023). The COVID-19 pandemic accelerated this transition, underscoring the need for strong digital competencies to support student learning (Sheng et al., 2023). However, many educators still struggle to effectively incorporate technology into pedagogical content knowledge (PCK) (Aktaş & Özmen, 2020; Guzmán & Vesga, 2023). This challenge is particularly evident among pre-service teachers, who require structured training to develop the competencies necessary for technology-driven and student-centred learning environments (Tondeur et al., 2017; Redmond & Lock, 2019; Eshelman & Hogue, 2023).

Pre-service teachers play a pivotal role in shaping future classrooms, and their perceptions, attitudes, and technological competencies directly influence instructional quality (Diamah et al., 2022; Ergogo et al., 2023). However, research highlights a critical gap in technological competencies, as many pre-service teachers fail to integrate technology with pedagogical content knowledge effectively (Suryawati et al., 2017; Bashir & Jimmy, 2023). Irwanto et al. (2022) further emphasise that while pre-service teachers demonstrate high confidence in pedagogical knowledge (PK), they often struggle with technological knowledge (TK), revealing the need for holistic TPACK training. Without structured development, teachers risk treating these domains in isolation rather than as an interdependent framework necessary for hybrid instruction.

The Technological Pedagogical Content Knowledge (TPACK) framework, developed by Mishra & Koehler (2006), provides a comprehensive model for integrating technology into teaching effectively. Koehler et al. (2015) assert that effective teaching requires an intersection of technological, pedagogical, and content knowledge, ensuring that digital tools are not merely used for their novelty but meaningfully incorporated into instruction. Zulkipli et al. (2023) found that pre-service science teachers often exhibit greater familiarity with pedagogical content knowledge (PCK) but lack proficiency in TPACK, underscoring the need for structured digital pedagogy training (Batane & Ngwako, 2017; Yildiz, 2021).

Despite increased research on TPACK, a significant gap remains in understanding how it is operationalised in hybrid science education. While studies highlight TPACK's relevance in teacher preparation, limited empirical evidence explores how pre-service teachers effectively apply these competencies in hybrid classrooms (Wulandari & Inggitajna, 2023; Abdullah & Mahmud, 2024). Science instruction relies on experiments, data analysis, and conceptual visualisation, necessitating specific pedagogical strategies to meaningfully integrate technology (Salleh et al., 2023; Zulkipli et al., 2023; Cojorn & Sonsupap, 2024). The absence of research on how pre-service teachers manage these challenges raises concerns about their preparedness for evolving educational demands.

The integration of 21st-century skills, particularly the 4Cs (critical thinking, creativity, communication, and collaboration), remains a major concern in teacher education (Ibrahim et al., 2019). While these skills are essential for student success, research indicates that pre-service teachers struggle to embed them meaningfully into hybrid science instruction (Valli et al., 2014; Valtonen et al., 2017, 2021). Kim et al. (2019) emphasise that classrooms serve as the primary environment where students observe and practice these skills, making teacher preparation essential in fostering effective instruction. Although some educators use technology to encourage creativity and collaboration, promoting critical thinking and problem-solving remains underdeveloped (Stehle & Peters-Burton, 2019). Salleh et al. (2022) highlight that novice science teachers often struggle to tailor their instructional strategies, further complicating their ability to effectively integrate technology and 21st-century skills into hybrid learning.

Research has identified persistent barriers to effective TPACK implementation, including limited technological access, inadequate training, and entrenched traditional teaching methods (Selialia & Kurata, 2023; Li, 2024). While these challenges are well-documented in general education, more research is needed to explore their impact on hybrid science instruction, where educators must balance digital and in-person teaching strategies. Without addressing these systemic challenges, teacher education programmes risk producing underprepared graduates for modern science classrooms (Ibrahim et al., 2019; Mourlam et al., 2021).

Additionally, Cojorn and Sonsupap (2024) highlight that science teachers' TPACK proficiency significantly influences students' critical thinking, problem-solving, and creative abilities, reinforcing the importance of strengthening TPACK integration in teacher education. Zulyusri et al. (2022) further support this, noting that educators' lack of technological readiness significantly limits the effective use of hybrid learning models. Jituafua (2024) proposes a structured framework for enhancing TPACK competencies among pre-service science teachers, identifying seven best practices, including expert-guided lesson planning, microteaching, self-reflection, and iterative feedback. These approaches strengthen TPACK integration and ensure that technology is incorporated and effectively leveraged in hybrid science education.

By aligning with the 2023 Malaysia Education Digital Policy and SDG 4: Quality Education, this research underscores the urgent need for integrating digital pedagogy into teacher training. It offers novel insights into how structured training, targeted interventions, and instructional strategies can enhance pre-service teachers' digital competencies, ensuring they are prepared to implement hybrid learning while fostering 21st-century skills in science education.

Research Questions

This study investigates pre-service teachers' perceptions of their TPACK competencies and ability to integrate 21st-century skills in hybrid science education. Specifically, this study aims to:

1. Examine pre-service teachers' perceptions of their Technological Pedagogical Content Knowledge (TPACK) in hybrid science education.

2. Explore how pre-service teachers integrate 21st-century skills (Critical Thinking, Creative Thinking, Communication, and Collaboration) into hybrid science instruction.

By addressing these objectives, this study extends existing research by providing empirical insights into how hybrid learning environments influence pre-service teachers' pedagogical and technological practices (Wulandari & Inggitajna, 2023; Abdullah & Mahmud, 2024). Additionally, this study has the potential to challenge existing research on TPACK assessment by emphasising the need for more comprehensive evaluation tools beyond self-reported measures (Hofer & Grandgenett, 2012; Mourlam et al., 2021). Furthermore, this study contributes to the scientific advancement of teacher education by offering practical recommendations for integrating 21st-century skills into hybrid science instruction, an area that remains underexplored in the current literature (Setiawan et al., 2019; Daud & Mahamod, 2021; Massari et al., 2021; Putri et al., 2022).

METHODS

By the end of 2021, as Malaysia entered the endemic phase with widespread COVID-19 vaccinations among adults, schools reopened, but hybrid learning remained necessary due to large class sizes and the need for physical distancing. To mitigate transmission risks, classes operated on a rotational basis, with half of the students attending in person while the other half participated virtually. Combining face-to-face instruction with online distance learning (ODL), this concurrent teaching approach became the standard hybrid learning model. As part of this transition, pre-service teachers resumed their teaching practicum in government schools starting in March 2022, marking their first exposure to asynchronous and hybrid teaching environments. Each pre-service teacher was assigned 10 to 12 teaching periods per week, covering general science for lower and upper secondary levels and Biology, Physics, or Chemistry for Form 4 students, depending on their specialisation.

This study employs a basic interpretive qualitative design to explore pre-service teachers' perceptions in one of the teacher training institutes in Malaysia of their TPACK for teaching science in a hybrid learning environment and to investigate the integration of 21st-century skills, specifically the 4Cs, into such environments. This design allows for an in-depth understanding of how these future educators perceive their technological and pedagogical competencies and their perspectives on integrating essential 21st-century skills, as qualitative research is particularly suited to exploring complex phenomena and providing nuanced interpretations of participants' experiences (Creswell & Poth, 2016).

Twelve pre-service science teachers were purposively selected based on specific criteria: (1) completion of their teaching practicum, (2) experienced teaching in a hybrid learning environment during the COVID-19 pandemic, and (3) representation across science majors (Biology, Chemistry, and Physics) to capture diverse instructional experiences. Initially, twenty-one pre-service teachers met these criteria. To refine the selection, participants completed an open-ended survey, reflecting on their hybrid teaching experiences. The final twelve participants were chosen based on their ability to articulate and critically reflect on their practicum experiences. This screening approach helped mitigate selection bias, ensuring that the data collected provided rich, meaningful insights into hybrid science teaching. Muhaimin et al. (2023) emphasised that purposive sampling is a technique for collecting data that is not random, allowing for unique characteristics to be determined according to the research objectives. Details of the participants are outlined in Table 1.

Table 1. Details of the Participants

Participant	Gender	Major
1	Female	Biology
2	Female	
3	Male	
4	Female	
5	Male	Chemistry
6	Male	
7	Female	
8	Female	
9	Male	Physics
10	Male	
11	Female	
12	Male	

Although the sample size in this study is small, this is common in qualitative research, where the goal is depth over breadth (Creswell & Poth, 2018). Unlike quantitative studies, qualitative research does not seek generalisability but aims for analytic generalisation, where findings are transferable to similar populations (Yin, 2018). The selected participants represent pre-service science teachers and teacher training institutions facing comparable challenges, making the insights highly relevant (Merriam & Tisdell, 2016). Patton (2015) argues that information-rich cases enhance understanding of complex phenomena and stresses credibility over sample size in ensuring rigorous qualitative inquiry. This study maximises data richness by focusing on experienced participants, offering valuable implications for teacher training and digital pedagogy.

Semi-structured interviews were chosen for data collection purposes. A set of validated interview protocols prepared by the researchers were used. The semi-structured format of the interviews allowed for a flexible yet focused exploration of participants' experiences and perspectives (Patton, 2015). Additionally, Creswell (2009) highlighted that semi-structured interviews allow progressive refinements to gain an in-depth understanding of a research question.

During the data collection process, the researchers conducted interviews employing a flexible yet structured approach to explore their experiences with TPACK integration in hybrid learning. The researchers used open-ended questioning techniques to elicit detailed responses while applying probing strategies to uncover deeper insights. Ethical protocols were strictly adhered to, including informed consent, confidentiality, and participant comfort. Each semi-structured interview was conducted between 20 and 30 minutes. The interviews were audio-recorded, transcribed verbatim, and then reviewed by the researchers to ensure accuracy. Participants were identified and labelled from 1 to 12 to facilitate data management and analysis.

The researchers conducted data analysis by using thematic analysis, a technique suited for identifying and interpreting patterns or themes within qualitative data (Braun & Clarke, 2006). The analysis involved several key steps:

(1) Familiarisation with data: The researchers did initial readings of interview transcripts to become familiar with the content and identify preliminary themes;

(2) Generating initial Codes: Data were coded manually by the researchers by going through each line in the transcripts, with codes representing key concepts related to TPACK, 21st-century skills, and science teaching (e.g., PK, PCK, Technological literacy, Tools, Media, Integration, and Skills);

(3) Formation of categories: The codes obtained from the first transcript were organised into potential categories, focusing on patterns related to pre-service teachers' perceptions and their integration of 21st-century skills in hybrid learning environments. The coding of the subsequent transcripts followed the same procedure. The process requires researchers to go back and forth between

the codes that emerged, and the initial categories constructed to make sure the categorisation of the codes and recurrence of the codes support the existence of the categories; and

(4) Formation of Themes: The themes were reviewed and refined to ensure they accurately represented the data and were relevant to the research questions.

This rigorous approach ensured a comprehensive and systematic qualitative data analysis, providing valuable insights into pre-service teachers' perceptions and experiences in hybrid learning environments. Consistency checks were conducted by having three researchers independently code the same interview transcripts to enhance trustworthiness.

Any inconsistencies in the analyses were discussed among the team to reach a consensus, as recommended by Lincoln and Guba (2016) for improving reliability in qualitative research. Additionally, the study employed peer debriefing, with three experts in science education and instructional technology reviewing and commenting on the themes, categories, and aspects developed during the analysis.

RESULTS AND DISCUSSION

The findings of the study will be reported under one main theme, which is 'Teaching in the Hybrid Learning Environment'. This theme emerged based on the context of the study, which focuses on hybrid learning. The findings from research questions 1 and 2 were collectively placed under this theme to ensure the reporting is seamless with no repetitive points. Under this main theme, the two sub-themes will answer the research questions posed for the study. The sub-themes constructed are: (i) delivering science lessons, and (ii) integrating 21st-century skills, as shown in Table 2. The subsequent sub-headings will detail findings from each sub-theme and offer a relevant discussion that contributes to understanding the underlying phenomena.

Table 2. Findings

Theme	Sub-Theme	Aspects
Teaching in a Hybrid Learning Environment	Delivering Science Lesson	Perceived competency Common strategies Personal reflection
	Integrating 21^{st}-Century Skills	Focus Elements Integration of Level and Approaches

The sub-theme "Delivering Science Lessons" reflects the pre-service science teachers' perceptions of their TPACK when teaching science in a hybrid learning environment. Participants were asked to elaborate on their experiences during their teaching practicum when teaching and learning were conducted through hybrid methods. Based on their responses, the researchers observed significant variations in how participants perceived their TPACK and how it influenced their competence in using technology for hybrid lessons.

The interview analysis did not reveal issues related to content knowledge. However, it identified factors related to pedagogical and technological knowledge that shaped their teaching practices. For instance, in terms of pedagogical knowledge and skills, Participants 2, 4, 5, 6, 8, 9, 10, and 11 perceived themselves as proficient. They expressed confidence in teaching their assigned subjects and were able to choose appropriate approaches, methods, and strategies to implement their lessons with minimal supervision. This is evident from responses like those of P4 and P10:

"During the practicum, I had so much fun planning and implementing my biology class. I tried different strategies since I had two different groups of students during class [physical and online]. I enjoyed teaching them and received good feedback from them, too." (P4)

"I think teaching my physics class via ODL and face-to-face in the class took much of my time deciding what was best for both groups. I knew I did well at that time; they [the students] were able to follow the lesson despite the constraints." (P10)

Conversely, Participants 1, 3, 7, and 12 perceived themselves as less proficient or competent in selecting appropriate strategies for teaching. Their responses indicated uncertainty in decision-making, fear of ineffective lesson delivery, frequent frustration after lessons, and a consistent need for guidance from mentors or supervisors.

As P7 described:

"I personally think I lost my confidence during the practicum. Most of the time, I needed someone to validate my lesson planning—whether my approach or activities were effective. Sometimes, I felt frustrated when I couldn't help the students grasp the lesson well. I found it challenging to adjust to teaching students in different modes at the same time." (P7)

It became clear that perceived competence in pedagogical skills was closely tied to the ability to effectively use technology in teaching specific content (TPACK). Further analysis revealed that P1, P3, P7, and P12 described themselves as having only moderate technological literacy and skills compared to other participants. These participants reported relying primarily on basic tools, such as PowerPoint slides, to teach students in class and those joining through Google Meet. They noted that their initial engagement with technology in a hybrid mode was challenging, as they had to learn from others or explore the technology independently before gaining the confidence to use it during teaching. They often feared that technological issues might disrupt their lessons. For instances as P1 and P12 shared:

"I tend to panic when the technology I'm using doesn't work as planned." (P1)

"I invested a lot of time learning new apps or tools to avoid any mishaps during lessons, but it drains my energy and distracts my focus" (P12)

On the other hand, the majority of participants did not report any difficulties integrating a variety of platforms and tools into their teaching. For instance, some participants seamlessly combined Google Meet, Google Classroom, and Quizizz with in-person classroom activities. They also used technological tools like iPads or tablets for teaching while simultaneously jotting down notes, drawing on slides, and presenting edited videos to students physically and online. An example of this was provided by P6, who described using multiple technologies to manage students in both modes effectively:

"When I taught them [the students] about elements across Period 3 in the periodic table, for example, I provided my recorded lecture via the Telegram group and asked those joining online to watch it in advance. During the lesson, I started with a Google Form to assess students' understanding and gave them time to respond. Meanwhile, I taught the topic physically in class and gave a hard copy of the same question in the Google Form to students in class. I went back to the online students to check their answers and addressed any questions they had about the elements and their properties. I had to plan all of this [managing students in different modes], but to me, it was doable." (P6)

The next aspect, 'common strategies,' focuses on the findings related to strategies used by participants in teaching science through hybrid learning modes, as well as the tools and platforms frequently employed in their lessons. When asked how they managed to teach two sets of students simultaneously in different learning environments, most participants highlighted the importance of aligning pedagogical strategies with technology and ensuring that the planned activities and assessments suited physical and online classrooms. Notably, this alignment was absent in interviews with P1, P4, and P7.

For instance, when selecting online content such as videos from platforms like YouTube, participants expressed concern about the clarity, curriculum alignment, and appropriateness of the material for their students. They often preferred videos created by local teachers in the Malay language to enhance understanding. If suitable resources were unavailable, many opted to record their teaching videos (e.g., P1, P5, P6, P8, and P10). This approach ensured that the content was curriculum-appropriate and reduced the likelihood of student confusion. Accompanying the videos, teachers typically provided both physical and digital handouts via platforms like Google Classroom or shared Word documents through WhatsApp or Telegram, which students could use in class after watching the videos. This approach is evident in the following excerpt:

"I'll make sure any teaching methods or technologies I use in class support the attainment of learning outcomes. For instance, when teaching about microorganisms, I used many videos and pictures to help students visualise different types of microorganisms. To aid their memory, I also create mind maps showing their characteristics" (P2).

Another prevalent strategy was to avoid overly sophisticated technology, which could overwhelm teachers and students. Participants noted that minimal technology use, while easy to manage, was often ineffective in maintaining student engagement, whether online or in person. Participants emphasised the need for a balanced use of technology, which could engage students and simultaneously assess their understanding. Several participants affirmed that technology should be neither too basic nor too complex.

"As time passed, I figured out what worked best in the hybrid classroom. Technology is essential, but I don't need to use anything too complex. Instead, I make use of different apps and vary how I integrate technology, whether for communication, information retrieval, or activities that assess student understanding" (P5)

"I think teachers need to consider what kind of technology helps students stay focused. You can't just deliver lectures using slides and then get the students to complete exercises as we do in a typical physical class. You need to get students involved. For example, I used PhET, a simple simulation platform, to demonstrate a concept, and then let students explore it further" (P11)

The findings revealed that, regarding learning platforms and tools used during hybrid instruction, most participants preferred Google Meet for communicating with students engaged in online learning (ODL). Google Meet offers free access and can easily be integrated with Google Classroom, making it a convenient choice. Another commonly used video conferencing tool was Zoom, which participants appreciated for its breakout room feature, enabling small group discussions and consultations. Some participants also utilised additional devices, such as tablets or iPads, to project slides in their physical classrooms while using laptops for online interactions.

Access to additional devices proved advantageous for teachers. In many cases, participants employed flipped learning strategies to mitigate the limitations of limited devices. This involved providing all necessary materials in advance via WhatsApp or Telegram. As highlighted by P6, while online students were engaged in exercises or discussions, teachers used this time to focus on their physical students, alternating between the two groups. Moreover, participants also used platforms like ClassDojo, Quizziz, Kahoot! and Wordwall to create collaborative activities and simple assessments, fostering interactivity and gauging students' comprehension in physical and virtual classrooms.

"To make my class engaging, I use Quizziz, as it offers both online and paper modes. Students in class answer questions online, and I can scan their answers. It's interesting and manageable. I can then review their performance" (P6)

"Wordwall is great. I can use existing templates to design activities or worksheets. For example, I created a word search to help students recall key concepts about linear motion or designed an activity where they matched situations to concepts like inertia, momentum, or free fall" (P9)

Additionally, the use of Canva was noted as more predominant than PowerPoint among participants, as Canva's features allow for creating more visually appealing teaching materials, including slides, videos, and posters. Most participants claimed they were able to master Canva's features through self-learning and YouTube tutorials, as mentioned by P2, 4, 5, 6, 8, and 9.

Another finding under this theme concerns how participants implemented experiments in their science teaching. Most reported conducting fewer experiments during hybrid learning compared to traditional in-person instruction. The hybrid learning mode's pacing often did not allow sufficient time for practical activities, with more time needed to spend on theoretical content. However, when experiments were conducted, participants ensured that both online and physical students could perform them at different times. This approach doubled the usual class time required for experiments.

Some experiments were modified to allow ODL students to participate synchronously. Teachers would set up a recording device in the physical classroom, such as a smartphone or laptop, enabling online students to observe their peers' conducting experiments. Additionally, participants used materials that could be easily obtained at home for experiments. For instance, when teaching about solubility, students at home used salt, sugar, and effervescent tablets to conduct the experiments. If experiments could not be performed, participants opted for YouTube videos or PhET simulators to discuss the theoretical concepts.

"For experiments, YouTube is my preferred option to help students visualise concepts. I browse, select the best videos, and discuss them with the students. I can do this simultaneously in class and online. Another strategy is to use simulation apps like PhET. There are many experiments available, but the challenge is that not all of them align with our syllabus" (P8)

The last aspect under this sub-theme is 'personal reflection,' which captures the participants' views after re-examining their experiences implementing hybrid learning during their practicum. The reflections revealed two common codes: adaptability and self-efficacy. Adaptability, in this context, refers to the participant's ability to adjust to the new teaching and learning environment, while self-efficacy describes their beliefs in their capacity to fulfil their roles as practicum teachers.

Across the twelve pre-service science teachers involved in the study, these two codes - adaptability and self-efficacy - were consistently identified in their reflections. Most participants acknowledged the initial challenges of managing online and in-person instruction but also emphasised their growing ability to navigate these dual demands. P6 and P12, for instance, shared:

"Initially, it was difficult to manage both in-person and online students, but as I gained more experience with the tools, it became second nature." (P6)

"I believe that facing the new situation of hybrid learning required me to adapt by applying the knowledge of technology and skills [pedagogy and technology] I already had. I managed to navigate it by making numerous adjustments, experiencing failures, and learning to improve afterwards" (P12)

This sentiment, echoed by several others, illustrates how the participants' adaptability improved over time as they gained more hands-on experience with hybrid teaching. Self-efficacy also emerged as a critical factor in their reflections. Many participants reported feeling unsure of their ability to teach effectively in a hybrid environment at the beginning of their practicum. However, their confidence grew as they became more proficient with the technological tools and teaching strategies required for hybrid learning. One pre-service teacher reflected, "At first, I was not sure I could manage the technology or engage students effectively in a hybrid class, but over time, I felt more confident in my teaching abilities" (P4). The increase in self-efficacy was commonly expressed, as participants noted that the belief in their ability to manage the complexities of hybrid teaching strengthened with practice. Another participant remarked, "Seeing my students respond positively to my lessons, whether online or in-person, made me realise I could handle this type of teaching confidently" (P9).

The participants' reflections reveal a shared growth experience, as their adaptability and self-efficacy developed throughout the practicum. Many concluded that hybrid teaching required technological proficiency and the ability to remain flexible and confident in the face of challenges. As P2 summarised, "The hybrid environment pushed me to be more adaptable and confident, which I now realise are crucial traits for any future teacher." (P2).

The findings under this sub-theme demonstrate a wide spectrum of technological proficiency among pre-service teachers, shaping student engagement and learning outcomes in hybrid classrooms. Many participants displayed confidence in integrating digital tools, utilising platforms such as Google Meet, YouTube, and Canva to design engaging lessons. This aligns with research highlighting the positive impact of multimedia tools and collaborative teacher networks in enhancing instructional effectiveness (Timotheou et al., 2023). Studies indicate that well-designed digital learning experiences can increase student motivation and comprehension (Aktaş & Özmen, 2020). However, not all participants shared this confidence - P1 and P7, for example, expressed frustration and anxiety when dealing with technology, revealing gaps in their digital literacy and preparedness. These disparities reinforce the need for targeted professional development to ensure equitable technological readiness among pre-service teachers (Redmond & Lock, 2019; Eshelman & Hogue, 2023).

The influence of hybrid learning on student engagement varies, depending on the ability of teachers to integrate technology effectively. Participants who strategically used interactive tools such as Quizizz, Kahoot! and Wordwall reported higher student participation and attentiveness levels. These platforms provided immediate feedback and gamified learning experiences, increasing student motivation and concept retention (Witchel et al., 2018). Conversely, participants who relied solely on basic lecture-style delivery through PowerPoint slides or Google Meet struggled to maintain student engagement, with some noting a lack of interaction and reduced student responsiveness. This contrast underscores the importance of pedagogical adaptability in hybrid settings, as passive online learning environments can lead to cognitive disengagement and lower academic performance (Naidu, 2017; Zulyusri et al., 2022).

One of the most significant pedagogical challenges in hybrid science education was delivering practical lessons, particularly hands-on experiments (Natale et al., 2021; Mojica & Upmacis, 2022). Some pre-service teachers creatively adapted by leveraging digital simulations such as PhET and incorporating pre-recorded video demonstrations. These approaches effectively provided students with conceptual understanding, aligning with studies suggesting that simulations can enhance science learning by offering interactive, visual representations of abstract concepts (Fluck & Dowden, 2013; Agustini et al., 2019). However, several participants raised concerns that digital alternatives failed to replicate the depth of hands-on experimentation, limiting students' opportunities for inquiry-based learning and skill development. This limitation is well-documented in science education research, which stresses that while technology can supplement learning, it cannot fully replace physical laboratory experiences (Babinčáková & Bernard, 2020; Forbes et al., 2023).

The findings also expose critical gaps in the application of the TPACK framework, which emphasises the integration of content, pedagogy, and technology for effective instruction (Mishra & Koehler, 2006; Koehler et al., 2015). While some pre-service teachers demonstrated a strong grasp of technological and pedagogical knowledge, others struggled to cohesively integrate these elements. This issue was particularly evident in their difficulties balancing student engagement across physical and virtual settings, as well as in their selection of digital tools to support content mastery. The inconsistent application of TPACK across participants suggests systemic weaknesses in teacher training programmes, which often provide limited opportunities for authentic, technology-integrated teaching practice (Voogt & McKenney, 2017; Tondeur et al., 2020).

Despite these pedagogical and technological challenges, the hybrid learning experience acted as a catalyst for professional growth, fostering adaptability and self-efficacy among pre-service teachers. Those actively engaged in trial and error, reflective teaching, and peer collaboration developed greater confidence in navigating hybrid classrooms. This aligns with findings that exposure to diverse instructional strategies and digital tools enhances teachers' ability to manage complex learning environments (Suzan et al., 2021; Putri et al., 2022). However, this growth was not uniform across participants—some teachers remained reliant on mentor guidance and reported persistent anxiety in managing hybrid instruction. This suggests that structured support mechanisms, such as scaffolded professional development and hands-on technology workshops, are essential to ensure that all pre-service teachers develop the necessary competencies (Ebersole, 2019; Lee & Davis, 2023).

Ultimately, these findings highlight that hybrid learning presents opportunities and challenges for pre-service science teachers. While it promotes innovation, digital fluency, and flexibility, it also demands a high level of pedagogical and technological integration. The contrasting experiences among participants underscore the need for teacher education programmes to move beyond general technology training and focus on practical applications of TPACK - particularly in science education, where hands-on learning remains essential. To address this gap, several strategic approaches can be considered: enhancing digital literacy workshops that train pre-service teachers to adapt or repurpose online resources; encouraging collaboration between pre-service and in-service teachers to co-develop localised, context-relevant content; and advocating for institutional support to provide curriculum-aligned digital tools. These measures could strengthen pre-service teachers' readiness to teach effectively in hybrid settings while fostering meaningful integration of technology and pedagogy.

The sub-theme "Integrating 21st-Century Skills" suggests the pre-service science teachers' perceptions of their TPACK when integrating 21st-century skills in teaching science in a hybrid learning environment. This sub-theme is comprised of two aspects, namely focus elements and integration level and approaches.

In discussing the first part of this sub-theme, the focus elements refer to the hierarchy the participants placed on the four main skills of the 21st-century. Overall, the responses given by all the participants reflect their positive views towards the importance of integrating 21st-century skills in teaching. Participants consistently stress that integrating the 4Cs is not only relevant but essential for students' academic success and preparing students for real-world scenarios.

The findings revealed that collaboration and communication emerged as the dominant 21st-century skills prioritised by pre-service science teachers in lesson planning and implementation. Participants reported that activities requiring these skills were the easiest to design and integrate into hybrid learning environments. In contrast, critical thinking received moderate emphasis, while creative thinking was identified as the most challenging skill to address. For example, P2 and P4 emphasised that in designing their lessons, collaboration and communication skills can always be incorporated as compared to critical and creative thinking skills:

"In my lessons, I often included group tasks where students from both in-class and online settings collaborated. This made it easier to focus on communication and teamwork compared to critical or creative thinking activities." (P2)

"Designing activities for collaboration and communication felt more practical in the hybrid setting as they were simpler to design for both in-person and online students" (P4)

Most participants noted that hybrid learning, involving engaging students in physical and virtual settings, necessitated strategies fostering collaboration and communication. Designing lessons that allowed interaction between these two groups helped maintain student engagement. An illustrative case from P3's interview further underscores this approach: "I leveraged the hybrid class setting by assigning a task where both in-class and online students collaborated. For a lesson on the interdependence between living organisms, form 2 students watched videos on different habitats and their resident species. Based on their observations, they were then grouped (4–5 members per group) to construct food chains and food webs. Each member focused on one habitat, and the groups compared the similarities and differences in primary, secondary, and tertiary consumers across habitats. This activity encouraged collaboration and communication to complete the task." (P3)

Another notable example came from P8, who designed an integrated activity that explicitly aimed to address all four 21st-century skills in one of her form four science classes.

"I asked my students to work in groups to propose an innovation to reduce plastic waste in their communities. They were required to research existing solutions, and creatively design a new product or campaign. Each group then presented their proposal through an online pitch using slides and a short video. This task encouraged them to think critically about environmental issues, communicate ideas clearly, collaborate across settings, and apply creativity in problem-solving." (P8)

This example demonstrates a meaningful attempt by a participant to implement a task that fostered creativity, critical thinking, collaboration, and communication in a balanced way.

In terms of the integration aspects, critical and creative thinking integration was limited in hybrid learning due to the challenges posed by the dual settings of in-person and online students. Participants highlighted that their primary focus was ensuring students in both environments gained fundamental knowledge and skills to complete the syllabus. Despite these constraints, elements of critical thinking were embedded in activities that required problem-solving, analysis, and evaluation. Creative thinking was occasionally fostered through open-ended questions, encouraging students to generate ideas, establish relationships, make predictions, and generalise based on assigned tasks.

However, participants acknowledged that monitoring discussions and facilitating these higher-order thinking activities across the hybrid format was demanding. Time constraints often led to teachers supplementing incomplete answers with their explanations. P6 and P7 provided further insight into these challenges in their interviews:

"I asked students to evaluate the impact of human activities on the environment, but monitoring discussions between in-class and online groups was difficult. I had to summarise their ideas to ensure understanding." (P6) "When brainstorming, students offered good ideas, but the hybrid format caused uneven participation. I had to guide the discussion to keep it on track." (P7)

Despite these challenges, participants emphasised their efforts to address critical and creative thinking skills as outlined in the learning standards. They strived to ensure that hybrid teaching achieved the intended outcomes. However, they acknowledged that students' mastery of these skills in most lessons was not yet excellent.

An important aspect highlighted under this sub-theme is participants approach to integrate 21st-century skills into their lessons during hybrid learning. This refers to the methods employed to foster skills such as collaboration and communication among students. Most participants adopted 21st-century learning approaches that emphasised student-centred learning. Specifically, cooperative, and collaborative learning were the most applied strategies, enabling students to work together effectively in physical and online classes. For example, P11 noted, "Group work allowed my students to share ideas and interact, even when some were online and others were in the classroom."

To facilitate collaboration, participants frequently organised students into small groups or pairs. A consistent practice observed was grouping students based on their learning environments. However, due to technical limitations, such as the use of a single device during lessons, it was rare to see students from physical and online settings combined in the same group. Participants encouraged discussions during group activities and required students to present their assigned tasks or answers to promote communication skills. As P9 explained, "Asking students to present their solutions helps them build confidence and communicate better with their peers." Additionally, participants moderated interactions by ensuring students in both settings took turns sharing ideas before proceeding with discussions, ensuring inclusivity and active participation.

In order to integrate critical and creative thinking, the researchers noted that the participants mostly adopted problem-based, inquiry-based, and project-based learning, focusing more on the first two approaches. The use of problem-based learning was found to be commonly practised. As mentioned, the participants will usually pose more complex problems to be solved by the students cooperatively or individually to gauge their ability to solve problems by applying the basic knowledge they have learned. Inquiry-based learning was commonly conducted when involving practical activities or demonstrations during the lesson. Due to time constraints, the participants mostly practised confirmatory and structured inquiry, which helped them promote the thinking process within a controlled class environment. As the processes were more structured, the participants could ensure that the students' thinking skills could be promoted while adhering to the time limit.

This approach is rarely implemented for project-based learning as it demands longer time for students to complete the project and suitable topic as proposed in the curriculum specification documents. According to some of the participants, in order to promote critical and creative thinking through project-based learning, they will give at least two weeks for students to discuss during and after the class at their convenience. The progress will be monitored individually, and they are required to present the project during class through physical or virtual presentation. To complete the project, the students must show high commitment and work collaboratively outside of the classroom. This is one of the main challenges faced by the participants as some of the projects presented did not achieve the standard, and they also received complaints regarding unsatisfactory commitment from the group members. Excerpts from the interviews conducted with P3, P5 and P11 described the approaches mentioned.

"I typically assigned problems for students to discuss or solve individually, allowing me to assess their critical thinking and creativity. For instance, when teaching about substance movement across the plasma membrane, I asked them to explore real-life applications of the concept and explain the processes involved" (P3)

"During hybrid learning, I rarely assigned projects due to their time-consuming nature and the difficulty of monitoring progress. Instead, I preferred assigning problems for discussion and resolution during class or as homework" (P5)

"To evaluate students' critical thinking and creativity, I tasked them with designing a car equipped with safety features to reduce impulsive force. This activity was conducted during hybrid learning" (P11)

The findings under this sub-theme reveal the progress and persistent challenges pre-service science teachers face in integrating 21st-century skills, particularly the 4Cs, in hybrid learning environments (Sasaki et al., 2020; Yılmaz & Malone, 2020). While collaboration and communication were prioritised due to their relative ease of implementation, critical and creative thinking received significantly less attention. These disparities reflect broader trends identified by Valli et al. (2014) and Valtonen et al. (2017), who highlight pre-service teachers' struggles in embedding all four skills cohesively. Although technology facilitates creativity and teamwork, its role in fostering deeper cognitive engagement, such as analytical reasoning and problem-solving, remains insufficiently leveraged (Cojorn & Sonsupap, 2024; Lestari et al., 2021; Stehle & Peters-Burton, 2019).

Hybrid learning's dual-mode structure influenced how these skills were addressed. Most participants found it practical to integrate collaboration and communication through structured group activities that engaged both in-class and virtual students. Tasks like constructing food webs enabled students to interact across both modalities, fostering teamwork and real-time engagement (Bahtiar et al., 2023; Natale et al., 2021). However, this emphasis on social interaction often came at the expense of critical and creative thinking, which requires independent problem-solving and higher-order reasoning. Participants struggled to design and monitor cognitively demanding tasks across hybrid settings, leading to a reliance on confirmatory and structured inquiry rather than exploratory learning (Valtonen et al., 2021; Voogt & McKenney, 2017).

Notably, contrasting views emerged regarding the feasibility of integrating critical and creative thinking into hybrid learning. Some pre-service teachers reported success with structured problem-based learning and guided inquiry, facilitating analytical thinking through well-defined prompts. However, others found that managing student discussions and sustaining engagement across physical and online settings was overwhelming. Time constraints led to an over-reliance on teacher-directed explanations rather than open-ended exploration, restricting opportunities for independent student reasoning. Creative thinking, which demands extended processing time and originality, was the most neglected, as participants perceived it as difficult to facilitate within the rigid structure of hybrid instruction. Similar concerns have been raised in prior studies, which suggest that teachers tend to prioritise tangible, easily assessable skills over those requiring more nuanced instructional scaffolding (Valtonen et al., 2017, 2021).

Despite these challenges, research consistently emphasises the necessity of embedding the 4Cs into education to enhance student preparedness for complex problem-solving and interdisciplinary learning (Kim et al., 2019; Alzahrani, 2024; Marlyn et al., 2024). Alifah and Sukartono (2023) demonstrated that intentional integration of 21st-century skills improves student engagement and cognitive development. Project-based learning, for instance, has been widely advocated as an effective approach to fostering these competencies (Ibrahim et al., 2024). However, in this study, pre-service teachers largely avoided project-based instruction due to its time-consuming nature and difficulties in monitoring students' contributions—echoing Valtonen et al. (2020, 2021), who found logistical constraints as a major barrier to implementing complex, student-driven learning activities.

The findings suggest an urgent need for structured professional development beyond basic training in digital tools. Herlinawati et al. (2024) argued that teacher training should focus on equipping educators with pedagogical strategies that integrate the 4Cs meaningfully rather than treating them as supplementary. Pre-service teachers require targeted guidance on lesson planning, formative assessment techniques, and adaptive instructional approaches to balance engagement, technology use, and cognitive skill development (Salleh et al., 2020). Marlyn et al. (2024) further stress that gaps in pedagogical proficiency hinder teachers' ability to foster 21st-century skills effectively, making ongoing support and mentorship essential for successful implementation. In this regard, training modules should be designed collaboratively with teacher educators to develop practical strategies and context-specific models for enhancing these skills in hybrid teaching.

Overall, the findings emphasise the importance of embedding these skills systematically into curricula, supported by targeted teacher training to overcome existing challenges. Aligning with the work of Valtonen et al. (2017), Kim et al. (2019), and Alifah and Sukartono (2023), the study underscores the need for robust strategies to ensure that pre-service teachers are well-equipped to prepare students for the demands of a complex and rapidly evolving world.

CONCLUSION

This study highlights the potential of hybrid learning in science education while exposing critical gaps in pre-service teachers' technological and pedagogical readiness. While participants demonstrated adaptability in using digital tools for student engagement, inconsistencies in the TPACK application reveal the need for more structured training to bridge the gap between technological knowledge and effective pedagogy. Integrating technology in science instruction requires balancing interactive, student-centred learning with hands-on, practical experiences - a challenge many pre-service teachers struggle to navigate. Hence, to maximise the benefits of hybrid learning, teacher education programmes must prioritise targeted professional development, ensuring pre-service teachers gain the necessary skills to integrate technology and 21st-century competencies effectively. In response to these findings, this study proposes a TPACK training framework tailored for hybrid science education. The framework includes structured modules such as (1) Foundations of TPACK in Science Teaching, (2) Designing Technology-Integrated Inquiry-Based Lessons, (3) Facilitating Online and In-Person Collaboration, and (4) Assessing Learning in Hybrid Environments. The training is designed to be implemented over multiple semesters, ideally before pre-service teachers begin their teaching practicum. Its effectiveness can be evaluated through a combination of reflective journals, lesson plan analyses, microteaching assessments, and teaching e-portfolios, all of which serve to track professional growth and practical application of TPACK principles. By strengthening institutional support, refining pedagogical strategies, and embedding structured interventions, teacher education programmes will be better positioned to prepare future science educators for the demands of dynamic, hybrid classroom environments. Addressing these gaps also supports the realisation of Sustainable Development Goal (SDG) 4: Quality Education by cultivating a digitally competent, reflective, and adaptable teaching workforce.

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