journal homepage: https://ojs3.unpatti.ac.id/index.php/biopendix

B I O P E N D I X P-ISSN: 2407-4969
Volume 12, Number 1, March 2025 E-ISSN:2684-8341
Pages: 25-36 DOI: https://doi.org/10.30598/biopendixvol12issue1page25-36

Exploring the Integration of TPACK in Post Pandemic Biology Education: A Study of Teachers in Magelang City

Muhammad Khoirul Antony[1*], Sendy Putra Pradana[2], Ahmad Naharuddin Ramadhan[3], Susi Dewiyeti[4], Iful Amri[5]

[1] Biology Education Study Program, Faculty of Teacher Training and Education of Sriwijaya University, Palembang, Indonesia
email: mkantony@fkip.unsri.ac.id
[2] Biology Education Study Program, Faculty of Teacher Training and Education of Pattimura University, Ambon, Indonesia
[3] Biology Education Study Program, Faculty of Math and Science of Semarang State University, Semarang, Indonesia
[4] Biology Education Study Program, Faculty of Teacher Training and Education of Muhammadiyah Palembang University, Palembang, Indonesia
[5] Physics Education Study Program, Faculty of Teacher Training and Education of Sriwijaya University, Palembang, Indonesia

Submitted: 9 December 2024; Revised: 11 February 2025; Accepted: 22 March 2025; Published: 31 March 2025

Abstract. This research aims to explore deeper into the perspectives of biology teachers in the Magelang city regarding the crucial of TPACK in post-pandemic learning to support the professional development of teachers and create more relevant and high-quality learning. The method applied in this research is qualitative interviews. The respondents in this study consisted of 9 biology teachers in Magelang city. The TPACK framework is essential for effectively integrating technology, pedagogy, and content, though challenges remain in selecting appropriate tools and ensuring student engagement. The COVID-19 pandemic accelerated technology adoption, and teachers emphasized the need for continuous training and support to improve technology integration. Overall, with adequate resources and training, technology can greatly transform biology learning.

Keywords: TPACK; Post-Pandemic Learning; Integration of TPACK

How to cite this article:
Antony, M., Pradana, S. P., Ramadhan, A. N., Dewiyeti, S., & Amri, I. (2025). Exploring the Integration of TPACK in Post-Pandemic Biology Education: A Study of Teachers in Magelang City. BIOPENDIX: Jurnal Biologi, Pendidikan Dan Terapan, 12(1), 25-36. https://doi.org/10.30598/biopendixvol12issue1page25-36

Journal homepage: https://ojs3.unpatti.ac.id/index.php/biopendix
Journal e-mail: jbiopendix@gmail.com
Research Article: Open Access

INTRODUCTION

In the modern era of globalization, the landscape of education is undergoing significant transformations, driven largely by rapid technological advancements. The demands of the twenty-first-century curriculum now go beyond traditional academic knowledge, incorporating essential skills such as digital literacy, critical thinking, teamwork, and problem-solving abilities. These competencies are considered fundamental for students to thrive in an increasingly interconnected and technology-driven world. As a result, educators are required to possess more than just a strong foundation in pedagogical knowledge (PK) and content knowledge (CK). Teachers must also develop technological knowledge (TK), which encompasses the ability to effectively integrate and utilize technology within the classroom setting. The Technological Pedagogical Content Knowledge (TPACK) framework emerges as a comprehensive model that combines the three pillars of CK, PK, and TK. Research has demonstrated that the synergy between these components can significantly enhance teaching effectiveness by facilitating the seamless incorporation of technology into the learning process. This integrated approach not only supports student learning but also equips educators with the tools necessary to navigate the evolving educational landscape.

TPACK provides guidance to teachers in designing interactive, innovative, and relevant learning that meets students' needs (Gozali, 2022). Although the City of Magelang has good access to technological devices, and its

teachers have received adequate technical training, challenges still arise in ensuring the effective integration of technology into the learning process. Teachers need to develop their competencies in optimally integrating technology, pedagogy, and content according to the characteristics of students and the local context. The great potential of Magelang City to develop technology-based learning Mar'atussolichah et al., (2024) is also supported by various government programs that encourage digital education initiatives with the provision of supporting facilities (Sukarno & Haryati, 2015).

Moreover, the COVID-19 pandemic has had a profound impact on the educational landscape, particularly in regions such as Magelang. Emphasizes that the pandemic significantly accelerated the adoption of technology in educational settings, making it an indispensable tool, especially for enabling distance learning during periods of lockdown and social distancing. As schools transitioned to online platforms, the reliance on technology became more apparent and essential than ever before. However, as the world gradually moves into the post-pandemic era, there are emerging challenges in maintaining the effective and sustainable integration of technology into traditional, in-person classroom environments. These ongoing challenges highlight the importance of understanding how educators view and utilize the TPACK framework as an effective teaching strategy in this new, digital age. It is essential to explore teachers' perspectives on the relevance of TPACK, as it can provide valuable insights into the long-term success and evolution of technology integration in education.

Extensive research has demonstrated that the application of the TPACK framework not only contributes to the professional development of educators but also plays a critical role in enhancing student learning outcomes. The implementation of TPACK allows teachers to refine their instructional practices by integrating technology in a way that complements both their pedagogical approaches and subject-specific content knowledge (Chen et al., 2023). This holistic integration fosters a more effective and adaptive learning environment. Moreover, the strategic incorporation of technology alongside well-constructed pedagogical methods enables educators to craft dynamic, interactive, and student-centered learning experiences that actively engage learners in the process of knowledge acquisition. In the context of biology education, the TPACK approach proves particularly valuable as it empowers teachers to design more innovative and engaging instructional activities that can stimulate curiosity and promote deeper comprehension of complex biological concepts. By blending technological tools with appropriate teaching strategies, the TPACK framework facilitates the development of more interactive and immersive learning environments that encourage critical thinking, problem-solving, and collaboration among students. Furthermore, the integration of technology within the biological sciences classroom helps to create opportunities for students to visualize abstract concepts, conduct virtual experiments, and access a wealth of online resources, thus enhancing their understanding of the subject in a more comprehensive and meaningful way. Through this integrated approach, the TPACK framework not only strengthens teachers' ability to meet the diverse needs of their students but also leads to the creation of more engaging, effective, and enriching educational experiences.

This research aims to delve deeper into the views of biology teachers in Magelang City regarding the importance of TPACK in learning. Their experiences during the pandemic serve as an important foundation for evaluating the relevance and effectiveness of TPACK in the post-pandemic period. By understanding this perspective, the research is expected to provide new insights into the application of TPACK to support the professional development of teachers and create more relevant and high-quality learning. With an integrated TPACK approach, education in the city of Magelang has a great opportunity to continue developing. This implementation will not only improve the quality of teaching but is also expected to prepare the younger generation to face global challenges. This research makes a significant contribution to understanding how TPACK can be effectively adopted by teachers to support more inclusive, adaptive, and innovative 21st-century learning.

MATERIALS AND METHODS

The method applied in this research is qualitative interviews to explore the experiences and perspectives of biology teachers in integrating technology into learning in grades X, XI, and XII at three high schools in Magelang City, namely SMAN 1, SMAN 3, and SMAN 5. This research was conducted in 2023, after the COVID-19 pandemic, with the aim of exploring the application of technology in biology teaching post-pandemic. The respondents in this study consisted of 9 biology teachers, with one teacher from each grade level (X, XI, and XII) in each school.

The researcher used semi-structured interviews, which allowed the researcher to delve into the personal experiences and views of the teachers more flexibly. The interviews were conducted by asking 10 main questions designed to gain insights into the application of technology in biology teaching and the challenges faced by teachers. Here are the 10 interview questions posed to the respondents:

1. What is your view on the role of technology in supporting biology learning in the current digital era?
2. In your opinion, how the TPACK concept help teachers integrate technology into biology teaching?
3. How was your experience using technology for teaching during the COVID-19 pandemic? Did that experience change the way you view the use of technology in learning?
4. What are the main challenges you face in integrating technology, pedagogy, and content in biology learning in the classroom?
5. How often do you use technology, such as digital devices or learning applications, in the process of teaching biology?
6. How is the training support you received regarding technology mastery for learning? Was the training helpful enough in the implementation of TPACK?
7. What strategies do you use to ensure that the technology used in biology learning can enhance students' understanding of the material?
8. How do you adjust the use of technology in biology learning to the characteristics of students and local needs in the city of Magelang?
9. According to you, what is the greatest benefit of applying TPACK in biology education? Have those benefits been felt in your daily practice?
10. What are your hopes for the development of teacher professionalism in the City of Magelang, especially in enhancing the ability to integrate technology through the TPACK framework?

Data Analysis

The data obtained from the interviews will be analyzed using thematic analysis techniques, which are effective methods for analyzing qualitative data to identify patterns, themes, or main ideas that emerge from the respondents' answers. The data analysis process consists of the following steps:

1. Interview Transcription: All conducted interviews will be transcribed verbatim to ensure that every piece of information provided by the respondents is recorded accurately.
2. Initial Coding: After the transcription is complete, the researcher will conduct initial coding of the interview text. This involves assigning codes or labels to parts of the text that relate to specific themes, such as the use of technology, challenges in integrating TPACK, or the benefits of using technology.
3. Grouping Codes into Themes: The identified codes will be grouped into larger themes. For example, codes related to the challenges of technology use can be combined into one theme that discusses "the challenges of technology integration in biology learning."
4. Analysis and Interpretation of Themes: After the main themes are formed, the researcher will conduct an in-depth analysis of each theme. These themes will be compared among respondents to see the general patterns that emerge, as well as differing views or experiences relevant to the research context.
5. Conclusion : From the thematic analysis, the researcher will draw conclusions regarding how technology is integrated into biology learning in the City of Magelang, the benefits and challenges faced, and how the application of TPACK influences teaching. The results of this analysis will provide important insights into the practice of technology use in those schools.

RESULTS AND DISCUSSION

What is your view on the role of technology in supporting biology learning in the current digital era?

Based on research involving 9 teachers as respondents, it was found that technology plays a very important role in supporting biology learning in the current digital era. All respondents agreed that the use of digital technology is crucial for improving the quality of learning. Technology, according to them, provides ease in delivering complex biology material, especially on topics that are difficult to observe or practice directly. The use of digital tools such as projectors, multimedia applications, and animated videos allows teachers to explain abstract biological concepts or those that cannot be directly observed by students, such as material about viruses or the mechanisms of body physiology. Another example, the material about viruses that requires an understanding of microscopic particles that cannot be directly observed by students, can be more easily understood with the help of technology. Through animated videos or digital 3D models, students can see the structure of the virus, how it works, and its interactions with human body cells. This helps students to understand concepts that should only be understood theoretically, (Maulana et al., 2022) with more concrete and easily comprehensible visualizations. With technology, understanding viruses, which was previously hard to imagine, becomes more tangible and accessible for students.

Technology also greatly aids in the learning process by presenting materials more realistically (Ramaila & Molwele, 2022). This is certainly in line with biology learning that involves body mechanisms such as

respiration, excretion, circulation, and other physiological processes. These materials are generally related to processes that cannot be directly observed by students in their daily lives. The use of digital simulations or animations allows students to visualize and understand the steps in these physiological processes (Muhazaroh, 2023). For example, with animations, students can see how blood flows through the circulatory system or how oxygen is processed in the body during respiration. This provides a deeper learning experience and helps students understand the dynamics within the human body.

In your opinion, how does the TPACK concept help teachers integrate technology into biology teaching?

Based on research involving 9 teachers as respondents, it was found that the concept of TPACK greatly assists teachers in integrating technology into biology learning. The respondents stated that understanding TPACK allows them to effectively integrate knowledge of technology, pedagogy, and content in the learning process. This is very important, considering that biology as a subject involves many scientific concepts that are difficult to understand without a deep understanding of how to teach them with the appropriate technology. The teachers explained that by understanding TPACK, they can choose technology that is appropriate for the biology material being taught. For example, in teaching abstract or microscopic concepts such as viruses or cell structures, teachers can utilize technology like 3D videos or interactive simulations that help students better understand these concepts visually and practically. TPACK also enables teachers to combine effective pedagogical methods with supporting technology, thereby creating a more engaging and in-depth learning experience. For example, when teaching the mechanisms of respiration or blood circulation, teachers can use animations to illustrate these processes in detail, which is difficult to achieve with just verbal explanations or static images.

Teachers can adapt their usage of technology to fit the needs of their students by having a solid understanding of TPACK (Saharuddin et al., 2025). The respondents mentioned that with TPACK, they can assess which technology is most effective in enhancing students' understanding of specific biology material. In biology education, where many topics require detailed explanations and visualizations, such as the digestive or excretory systems, TPACK provides a strong foundation for teachers to select the appropriate tools and learning media, which will enhance student engagement and understanding of difficult-to-grasp material. However, despite the many advantages of TPACK, some respondents also expressed that mastering this concept requires time and intensive training. Some teachers still find it difficult to integrate technology in a pedagogical way that meets the needs of the biology content being taught. Therefore, they emphasize the importance of continuous training and support from schools or educational institutions to enhance understanding of TPACK, so that the use of technology in biology learning can be more optimal and effective.

How was your experience using technology for teaching during the COVID-19 pandemic? Did that experience change the way you view the use of technology in learning?

Based on a study involving 9 teachers as respondents, the experience of utilizing technology for teaching during the COVID-19 pandemic offered varied perspectives. Some respondents felt relatively comfortable with the integration of technology in online learning. For those already familiar with digital devices, the transition to online learning proceeded fairly smoothly. Technology, particularly in the form of online learning platforms, videos, and simulations, facilitates the delivery of biology content, such as the concept of viruses or respiratory mechanisms that require visual explanations (Roy, 2019). They believe that technology enables them to stay connected with students, distribute learning materials, and assign tasks and feedback efficiently. However, the majority of respondents expressed that they initially felt overwhelmed by the sudden shift to online learning. For teachers who previously prioritized face-to-face methods, adapting to technology posed a significant challenge. Some teachers found it difficult to manage online classes, especially when explaining complex biology topics that require hands-on demonstrations, such as microscopic observations or laboratory experiments. This aligns with the view of Theodorio et al., (2024), that more creative approaches, such as animated videos or interactive simulations, are needed, though some teachers initially struggled to implement these methods effectively.

Over the time, most respondents acknowledged that they were able to adapt more easily, largely due to the support provided by the school and the collaboration with fellow teachers and school leaders. The school offered technical training and adequate facilities, such as hardware, improved internet connectivity, and more stable online learning platforms. This support significantly helped teachers reduce the technical challenges they faced during the online learning process. As a result, teachers could focus more on developing teaching materials and engaging with students, rather than being preoccupied with technical difficulties. Additionally, the support and cooperation among teachers played a vital role in the adaptation process. Some respondents mentioned that they frequently shared experiences, strategies, and tips on using technology, which enabled them to more quickly

master new methods of teaching biology online. Through group discussions or joint training sessions, teachers exchanged ideas on the most effective ways to explain complex biology concepts in an online setting. This collaborative environment made the adaptation process smoother and more enjoyable for many teachers.

The experience during the COVID-19 pandemic has also brought significant changes in the perspective of most respondents towards the use of technology in learning. Although initially burdened, they now realize that technology not only facilitated teaching during emergencies but also has the potential to enhance the quality of learning in the long term. The use of technology provides students with the opportunity to learn more flexibly and independently, with access to various learning resources such as educational videos, digital materials, and online discussion forums that can be accessed anytime and anywhere (Khong et al., 2023). Thus, the teaching experience during the pandemic not only helped teachers adapt to technology but also changed their views on the importance of technology in education. Many teachers are now more open to integrating technology into their teaching, even after the pandemic has ended. They see technology as an effective tool to enrich students' learning experiences, make learning more interactive, and open up opportunities for the development of more creative and engaging teaching materials. With a better understanding of technology usage, teachers are becoming more confident in implementing various digital tools to support more innovative biology learning.

What are the main challenges you face in integrating technology, pedagogy, and content in biology learning in the classroom?

A study involving nine teacher respondents revealed that the primary challenge in integrating technology, pedagogy, and content in biology education lies in selecting appropriate technological tools and aligning them with effective pedagogical strategies. Several teachers reported difficulties in identifying the most suitable technology for specific biology topics. For instance, highly microscopic concepts such as viral structures or respiratory mechanisms require applications or tools capable of delivering detailed and accurate visual representations. The challenge for educators is to identify technologies that are not only engaging but also enhance students' conceptual understanding of these topics. Furthermore, respondents highlighted challenges in merging technology with pedagogical approaches that align with the unique characteristics of biology content. Biology education often involves holistic concepts, such as ecosystem dynamics or metabolic processes, which demand comprehensive teaching methods. The role of technology should extend beyond information delivery to fostering students' ability to comprehend and apply these concepts. Some teachers struggled to balance the use of interactive technologies with in-depth instructional methods, ensuring that learning objectives are met effectively without compromising the depth of understanding.

Another challenge faced is the difference in students' abilities to access and master technology. Although the infrastructure at the school is adequate, not all students have the same ability to use technology. Some students adapt more quickly to digital tools, while others take longer to understand how to use them optimally. This requires teachers to adjust their teaching methods to reach all students, both those who are already skilled in technology and those who are less accustomed to it. Teachers also need to provide additional guidance or create materials that can be accessed in various formats to ensure that every student can follow the lessons well. Additionally, the respondents expressed challenges in the limited time to master new technologies and prepare for lessons. Although the technological facilities are adequate, many teachers feel pressured by the demands to continuously learn and adapt to rapidly evolving learning devices and applications. Teachers find it difficult to make use of their limited time to learn the new features of the technology being used, even though a deep mastery of technology is crucial for effectively integrating it with content and pedagogy.

The biggest challenge faced by most teachers is how to maintain student interaction and engagement in online learning. Although technology allows for efficient delivery of material, keeping students engaged in learning and ensuring they actively participate in discussions or assignments remains a challenge. Some teachers find it difficult to maximize the use of technology without losing an important element in the learning process, which is direct interaction with students. Therefore, although technology provides many benefits, teachers must continue to find ways to balance the use of technology and student engagement in more in-depth biology learning.

How often do you use technology, such as digital devices or learning applications, in the process of teaching biology?

A study conducted with nine biology teachers as participants highlights a significant shift in the integration and frequency of technology usage in the teaching of biology before and after the onset of the COVID-19 pandemic. The majority of respondents indicated a substantial increase in their reliance on digital tools, such as tablets, computers, and various educational applications, following the pandemic. This transition to frequent technology use has been particularly evident in the adoption of online learning platforms, educational videos,

interactive simulations, and other digital resources designed to support remote learning. These tools have proven instrumental in ensuring that students remained engaged with the curriculum, even in the absence of face-to-face instruction. Prior to the pandemic, the use of such technologies in biology classrooms was limited; however, the necessity of adapting to a remote learning environment significantly accelerated their incorporation into everyday teaching practices. The integration of technology has not only facilitated the continuity of education during periods of physical school closures but also enhanced the delivery of complex and abstract biological concepts. Teachers reported that digital tools, such as simulations and interactive visualizations, have been particularly beneficial in clarifying difficult-to-understand topics like viruses, the respiratory system, and metabolic processes. These technologies enable more dynamic and detailed explanations, offering students a deeper understanding of biological phenomena that may have been challenging to convey through traditional teaching methods. Furthermore, the shift towards technology-enhanced teaching has contributed to a more personalized learning experience, allowing students to explore topics at their own pace while accessing a wide range of educational resources.

A small proportion of teachers reported that prior to the pandemic, they rarely utilized technology in their biology instruction. The majority of these teachers expressed a preference for face-to-face teaching methods, as they felt more comfortable delivering biology lessons in person. They argued that direct interaction with students facilitated easier explanation of complex biological concepts that required real-time engagement. Several teachers emphasized the effectiveness of traditional teaching methods, such as class discussions, experimental demonstrations, and the use of the blackboard, in enhancing students' understanding of intricate biological topics. At that time, technology was perceived as a supplementary tool, not deemed essential for biology education, which focused more on understanding through direct, in-person teaching. However, the respondents who favored direct teaching acknowledged that the pandemic compelled them to integrate technology into their instructional practices more frequently. As a result, they began to recognize the advantages of using digital tools in their teaching. The use of technology provided new, engaging, and interactive ways to present material methods that had not been previously considered. Despite initial challenges in adapting to new technologies, these teachers reported that the experience broadened their perspectives, revealing the potential of digital tools in enhancing biology education. Consequently, they became more open to incorporating technology into their future teaching practices, recognizing its potential to offer innovative and dynamic approaches to delivering biological content.

The majority of teachers have now come to fully recognize the critical role that technology plays in enhancing the quality of their teaching, especially for subjects or topics that demand complex visualizations or simulations that are difficult to achieve through traditional, direct instruction. These teachers have progressively integrated various learning applications into their teaching practices, using them to deliver content in a more interactive and engaging manner, facilitate online discussions, and provide timely and effective feedback to students. This shift towards technology adoption is particularly evident in the context of biology education, where concepts such as cellular processes, genetic mechanisms, and ecological systems can benefit greatly from dynamic visualizations and interactive simulations. By incorporating these tools, teachers can offer students a richer, more immersive understanding of complex biological phenomena that might otherwise be difficult to convey through conventional methods alone. As a result, despite some teachers' previous preference for face-to-face, traditional instructional methods, the pandemic has significantly altered their approach to teaching. The necessity of adapting to remote learning and hybrid environments has fostered a change in mindset, increasing the frequency of technology use in biology instruction. Teachers who once favored in-person interaction have reported a growing appreciation for the value of digital tools in enhancing learning outcomes. They have acknowledged that the integration of technology not only supports remote learning but also enriches in-person teaching by offering diverse, innovative approaches to presenting content, engaging students, and providing additional resources for deeper learning. Furthermore, this transformation in teaching practices aligns with the findings of Bueno et al., (2023), who asserts that technology has become an indispensable tool in supporting biology instruction, both in remote learning contexts and in traditional face-to-face classrooms. According to Rafael, the integration of digital tools has proven essential in maintaining educational continuity during periods of disruption, while also enhancing the quality of teaching and learning experiences. The pandemic has thus acted as a catalyst, encouraging educators to adopt technology more frequently and fostering a deeper integration of digital tools into their instructional strategies. This ongoing shift towards technology-driven education is expected to continue, as teachers increasingly recognize its potential to offer new, innovative, and effective methods of delivering biology content, promoting student engagement, and facilitating a more interactive and dynamic learning environment.

How is the training support you received regarding technology mastery for learning? Was the training helpful enough in the implementation of TPACK?

Based on research involving 9 teachers as respondents, the majority stated that the training support they received related to technology mastery for learning was very adequate and quite helpful in the implementation of TPACK. The respondents expressed that the school leadership provided high support in the training process and the development of technological skills for the teachers. The school actively provides training opportunities, both internal and external, to enhance teachers' abilities in using technology in biology teaching. This greatly assists teachers in integrating technology with pedagogical approaches and content that aligns with the material being taught.

Several respondents indicated that the training they received encompassed a comprehensive range of aspects related to the integration of technology into the learning process, from the utilization of learning applications to the innovative use of technology in conveying complex biological concepts. This professional development provided educators with the opportunity to familiarize themselves with a diverse array of digital tools and platforms that are essential for enhancing biology instruction, including simulations, educational videos, and interactive applications. Through this training, teachers not only gained proficiency in navigating and employing these technological resources but also developed the confidence necessary to incorporate them effectively into their teaching practices. Consequently, the training significantly contributed to the teachers' ability to implement the TPACK framework, facilitating a more seamless integration of technology, pedagogy, and content knowledge within the classroom setting. The ability to apply TPACK more effectively was particularly evident in the teachers' increased engagement with students and the enhanced learning experiences facilitated by the use of digital tools. Overall, this professional development process has proven instrumental in equipping teachers with the skills and knowledge required to leverage technology in ways that align with pedagogical goals and enhance the teaching of biology.

The support provided by school leadership is also clearly reflected in the allocation of necessary resources to facilitate the integration of technology into teaching practices. This includes the provision of adequate digital devices, reliable internet access, and digital learning materials, all of which are essential for effective technology use in the classroom. School leadership has shown a strong commitment to fostering the professional growth of teachers by actively supporting their initiatives to enhance their technological competencies. This support is further demonstrated through the consistent provision of time for training sessions and workshops, which enable teachers to refine their skills and deepen their understanding of technology integration. In addition to individual professional development, the administration promotes a collaborative environment among teachers, encouraging the exchange of experiences, strategies, and best practices related to the use of technology in biology instruction. This collaborative culture not only enhances individual teachers' abilities to integrate technology but also strengthens the overall teaching community, fostering a shared commitment to improving educational outcomes through innovative technological applications.

While the majority of respondents expressed that the training they received was highly beneficial, several teachers noted that it did not comprehensively address all aspects essential for the optimal implementation of the TPACK framework. Some teachers reported that the training primarily emphasized the use of specific digital tools, without sufficiently focusing on the pedagogical strategies required to integrate technology effectively with the content being taught. This gap in coverage led to concerns that while technological proficiency was enhanced, the pedagogical integration of technology with the curriculum remained underdeveloped. Despite these limitations, the teachers acknowledged that the training provided a solid foundation, enabling them to build upon their existing knowledge and continue developing their ability to integrate technology with the appropriate pedagogical approaches. Consequently, while the training was a crucial first step, the need for more comprehensive professional development that balances technological tools with pedagogical theory and practice was highlighted as a key area for future improvement. Overall, the training support provided by the school and leadership greatly assists teachers in mastering technology and implementing TPACK in biology teaching. Although there are still some areas that need improvement, the majority of teachers feel that the training provided has significantly benefited them in enhancing their ability to integrate technology, pedagogy, and biology content more effectively.

What strategies do you use to ensure that the technology used in biology learning can enhance students' understanding of the material?

A study involving nine teachers as participants revealed that most educators employ a variety of strategies to ensure that technology enhances students' comprehension of biological concepts. One of the most frequently employed strategies involves the use of educational videos and interactive simulations. Several teachers indicated that they leverage videos to clarify complex and abstract biological concepts, such as cellular

respiration or virus replication. These educational videos provide students with a visual representation of the processes, making challenging material more accessible and engaging. Additionally, interactive simulations are incorporated to offer students virtual, hands-on experiences, allowing them to actively engage with biological phenomena. For example, simulations enable students to explore and manipulate aspects of the circulatory system, thereby deepening their understanding through interactive learning. This combination of visual and interactive technological tools not only facilitates the understanding of intricate biological processes but also fosters a more dynamic and engaging learning environment for students. The integration of such technologies highlights the potential of digital resources in enhancing biology instruction and improving student outcomes.

Many respondenses have increasingly adopted quiz-based learning applications or interactive question exercises as effective tools for directly assessing students' understanding of the material. These applications, such as Kahoot and Quizizz, allow educators to design engaging quizzes that provide immediate insights into how well students comprehend the content being taught. This approach not only enhances the interactivity of the learning process but also facilitates the provision of real-time feedback, enabling students to identify any misconceptions or errors and correct them promptly. The immediate nature of this feedback helps reinforce the learning process, ensuring that students are able to address gaps in their understanding before they progress further in the material. In addition to improving students' comprehension, the use of interactive quizzes has been shown to significantly boost student motivation. Teachers report that students are more engaged and willing to participate in lessons when these quizzes are incorporated, as the competitive and game-like nature of platforms such as Kahoot or Quizizz makes learning more enjoyable and dynamic. This increase in student engagement can result in more focused attention during lessons, fostering a greater sense of participation and enthusiasm for learning. The interactive and competitive elements of these quizzes promote a sense of achievement and encourage students to approach learning in a more active and self-directed manner. This approach aligns with the research of (David & Weinstein, 2024) and (Agustriana et al., 2022), who emphasize that enjoyable and engaging learning experiences contribute significantly to increased student motivation. According to their findings, when students find learning to be fun and interactive, they are more likely to invest effort into their studies, leading to improved academic outcomes. These findings support the idea that the integration of gamified learning tools, such as quiz-based applications, plays a crucial role in enhancing students' overall learning experiences. By combining immediate feedback, interactive content, and increased motivation, quiz-based learning applications provide a robust framework for not only assessing but also enhancing students' understanding and engagement with educational material. Consequently, this strategy aligns with contemporary pedagogical theories that advocate for the integration of technology to foster active learning environments and improve student performance.

Several respondents reported adopting a blended learning approach, which integrates traditional face-to-face instruction with technology-enhanced learning. In this model, teachers dedicate part of the instructional time to direct classroom teaching, where they can elaborate on the material in detail and interact with students. The remainder of the learning time is spent utilizing technology, such as e-learning platforms, which enable students to independently access learning resources. This combination of in-person and online learning allows students the flexibility to learn at their own pace while still benefiting from the guidance and support of their teachers. By incorporating both face-to-face and digital learning components, this strategy ensures that all students have the opportunity to fully understand the material, regardless of whether they are participating in physical or virtual learning environments. Some teachers use technology to assign project-based tasks that encourage students to apply biological concepts to real-world situations. For example, students may be given assignments to create presentations or videos on specific topics in biology, such as ecosystems, evolution, or environmental issues. These project-based assignments not only evaluate students' grasp of the biological content but also engage them in developing technological skills, such as creating digital presentations or editing videos. This approach ensures that technology is not only used to deliver educational content but also to foster the development of important skills needed in today's digital world. This method aligns with the work of Hsbollah, H.M. & Hassan, H. (2022), who emphasize that technology in education should extend beyond content delivery to include the cultivation of skills that are essential for students' success in a technology-driven society. By incorporating technology into project-based learning, teachers promote a more hands-on, interactive learning experience, allowing students to engage deeply with the subject matter while developing transferable digital skills. Ultimately, the blended learning strategy, coupled with project-based assignments, offers a well-rounded educational approach that enhances both content mastery and the acquisition of critical 21st-century skills, equipping students for future challenges in both academic and professional contexts.

Several respondents emphasized the importance of using online discussion forums and virtual classes to ensure student understanding. They utilize platforms such as Google Classroom or Microsoft Teams to create discussion spaces where students can ask questions and discuss the biology material that has been taught. This

discussion provides students with the opportunity to share their understanding and delve into specific topics that may still be confusing. Teachers are also actively involved in this discussion, providing clarifications and enriching students' insights with additional explanations, thereby deepening their understanding of the material. Overall, the strategies used by teachers to integrate technology into biology learning are very diverse, but they all aim to ensure that technology is not only used as a tool for delivering material but also as a means to enhance students' understanding, encourage their engagement, and provide a deeper learning experience (Romano et al., 2023).

How do you adjust the use of technology in biology learning to the characteristics of students and local needs in the city of Magelang?

A study involving nine teachers as participants revealed that the majority of respondents found it relatively easy to adapt the use of technology in biology instruction to the needs and characteristics of the tech-savvy Generation Z and Alpha students. Teachers leverage digital devices that are commonly used by students, such as smartphones and tablets, to facilitate access to learning materials and interactive quizzes. Given that students are already well-versed in using technology, the integration of applications and digital learning platforms, including educational videos and simulations, has proven to be highly effective in capturing students' attention and fostering greater engagement in the learning process. The familiarity of students with digital tools enhances the effectiveness of technology-based learning strategies, making it easier for educators to create interactive, compelling learning experiences that resonate with modern learners. Consequently, the use of technology not only facilitates content delivery but also plays a crucial role in maintaining student interest and participation in the learning environment.

Several teachers have incorporated social media platforms, which are highly popular among students, such as Instagram and YouTube, as part of their teaching strategy to share videos that explain biology concepts in a more engaging and accessible manner. These platforms, familiar and easily accessible to students, provide a unique opportunity for teachers to create content that is both visually stimulating and easily digestible. Through the use of videos, teachers can break down complex biological topics into more manageable segments, incorporating visual elements and interactive features that appeal to students' learning preferences. These platforms not only facilitate engagement but also allow students to access educational content in a more dynamic way compared to traditional methods. The integration of Artificial Intelligence (AI) in the classroom has emerged as another compelling tool to enhance the learning experience. AI offers students innovative ways to gather information, making the process of acquiring knowledge faster and more efficient. With AI, students can quickly access and process vast amounts of data, enabling them to engage with learning materials in real-time and at their own pace. The use of AI in education not only streamlines the research process but also helps in personalizing learning experiences, as AI can be used to provide tailored feedback and recommendations based on individual student performance. This increased accessibility and ease of use make AI an attractive tool for students, as it facilitates more interactive and autonomous learning. This approach to teaching, utilizing social media and AI, offers significant flexibility, allowing students to access learning materials anytime and anywhere. The convenience of accessing educational content in a relaxed environment, yet still receiving effective instruction, supports the learning preferences of modern students. This is particularly beneficial for Generation Z and Alpha, who are accustomed to consuming content on-demand and are highly engaged by visual and interactive formats. As these generations tend to gravitate toward digital content that is visually rich and interactive, the integration of social media platforms and AI in biology instruction is seen as highly effective in optimizing their understanding of complex biological concepts. The interactive nature of these technologies enhances student engagement, provides opportunities for self-paced learning, and fosters a more personalized learning experience, making them well-suited to meet the needs of today's tech-savvy learners.

The teachers also adjusts the lessons to the local needs in the city of Magelang by relating biology material to the students' daily life context. For example, when teaching ecosystems or the environment, the teacher often uses local examples, such as mountain ecosystems or agriculture found around Magelang. This approach makes the material more relevant and easier for students to understand, and enriches their learning experience with a direct connection to the surrounding environment.

According to you, what is the greatest benefit of applying TPACK in biology education? Have those benefits been felt in your daily practice?

Based on research involving 9 teachers as respondents, most teachers stated that the greatest benefit of applying TPACK (Technological Pedagogical Content Knowledge) in biology learning is the ability to effectively integrate technology with appropriate pedagogical approaches and relevant content. The application of TPACK allows teachers to present biology material in a more engaging and interactive way, utilizing various

digital tools to visualize concepts that are difficult to understand directly, such as the processes of metabolism, respiration, or the structure of viruses. Technology used appropriately helps clarify the material, making it easier for students to understand and actively engage in learning. Some respondents also expressed that the benefits of implementing TPACK are felt in daily practice, especially in increasing student engagement and making learning more enjoyable. By using technology, such as interactive learning applications, educational videos, and simulations, students can learn in a more creative way and are not limited to just textbooks. Teachers find it easier to motivate students to learn and understand the material more deeply, because technology provides a variety of tools that can be tailored to the different needs and learning styles of students.

Furthermore, the application of the TPACK (Technological Pedagogical Content Knowledge) framework significantly enhances teachers' flexibility in managing both time and teaching methods, whether in face-to-face or online settings. By integrating technology into the instructional process, teachers are able to deliver content in multiple formats, such as videos, simulations, and interactive quizzes, which accommodates diverse learning styles and promotes deeper student comprehension. The ability to present material through various technological tools allows for a more dynamic and engaging learning experience, ultimately facilitating better retention and understanding of complex concepts. While the initial adoption of TPACK may require considerable time and effort, particularly in terms of familiarizing oneself with new technological tools and integrating them into established teaching practices, many teachers report that the long-term benefits far outweigh these initial challenges. Over time, the use of TPACK enables educators to design more relevant and meaningful learning experiences that are closely aligned with the needs of modern students. It allows for the creation of learning environments that are not only more engaging but also better suited to fostering critical thinking, creativity, and problem-solving skills skills that are increasingly important in today's rapidly evolving educational landscape. Moreover, the integration of TPACK helps teachers to adapt their instructional strategies based on the specific needs of their students, whether they are engaging in traditional classroom learning or remote education. The flexibility provided by this framework ensures that teachers can continue to offer high-quality education regardless of the mode of delivery. In the long run, teachers who successfully implement TPACK find that it not only enhances their teaching effectiveness but also promotes more student-centered learning, where students are active participants in their own educational journey. Thus, while the initial implementation may present challenges, the sustained application of TPACK empowers educators to create more engaging, interactive, and impactful learning experiences, benefiting both students and teachers alike.

What are your hopes for the development of teacher professionalism in the City of Magelang, especially in enhancing the ability to integrate technology through the TPACK framework?

Based on research involving 9 teachers as respondents, most teachers have high hopes for the development of teacher professionalism in the City of Magelang, particularly in enhancing the ability to integrate technology through the TPACK framework. They hope for more in-depth and continuous training on how to integrate technology with appropriate pedagogical approaches in biology teaching. Training that can help teachers further understand how to effectively use various digital tools to deliver complex biology material and facilitate students in understanding difficult concepts. With the ongoing development of professionalism, it is hoped that teachers will be better prepared to face the challenges of integrating technology into learning.

In addition to advocating for ongoing professional development, respondents also expressed a desire for stronger collaboration among teachers in the City of Magelang to share experiences and best practices related to the implementation of the TPACK framework. They believe that fostering a collaborative environment would allow educators to exchange valuable insights and strategies for effectively integrating technology into their teaching practices, particularly within the context of biology instruction. Collaboration plays a critical role in expanding teachers' understanding of innovative and contextually appropriate ways to utilize technology in the classroom. By engaging in collective discussions, teachers can explore new technological tools, pedagogical approaches, and challenges specific to biology education, which can ultimately enhance their overall teaching effectiveness. Some respondents specifically hoped that the teacher community in Magelang City could become more proactive in organizing workshops, seminars, or discussion forums focused on the application of TPACK. These events would provide teachers with opportunities to come together, share their successes and challenges, and collaboratively explore how best to incorporate technology into biology lessons. Such gatherings would not only facilitate the exchange of practical knowledge but also create a supportive network of educators who can learn from one another and continuously refine their teaching methods. Furthermore, the respondents emphasized that these collaborative efforts would not only improve individual teaching skills but also contribute to a broader, more cohesive approach to technology integration within the local education system. By learning from one another and sharing expertise, teachers can collectively enhance their ability to integrate technology effectively, making it a more seamless and impactful component of their teaching. In this way, collaboration

among educators in Magelang City is seen as a key factor in advancing the successful implementation of TPACK, ultimately leading to more effective and engaging learning experiences for students.

The teachers hope that the government and related parties can provide more resources to support the development of teacher professionalism in technology integration. This includes providing easier access to training, more adequate equipment (García-Martínez et al., 2022). There is a need for a platform that supports collaboration among teachers so that it can be conducted online. With strong support from various parties, teachers in the city of Magelang will be better prepared to develop their TPACK skills and create better and more relevant biology learning experiences for students.

CONCLUSION

The research highlights the significant role of technology in enhancing biology learning, particularly in the digital era, by providing tools like animations, simulations, and interactive platforms that make complex and abstract concepts more accessible and engaging for students. The TPACK framework is crucial for effectively integrating technology, pedagogy, and content, enabling teachers to create more dynamic and interactive learning experiences. However, challenges such as selecting appropriate technological tools, ensuring student engagement, and addressing varying levels of technological proficiency among students remain. The COVID-19 pandemic accelerated the adoption of technology in teaching, shifting perspectives on its importance and leading to increased use of digital tools even post-pandemic. Teachers emphasized the need for continuous training, collaboration, and support from schools and governments to further develop their TPACK skills and improve technology integration in biology education. Overall, the research underscores the transformative potential of technology in biology learning, provided that teachers receive adequate training and resources to implement it effectively.

ACKNOWLEDGMENTS

Future research on the implementation of TPACK in biology education should focus on investigating the specific challenges teachers face, particularly regarding the integration of pedagogical and content knowledge. A deeper exploration could analyze how educators adjust their teaching approaches to effectively utilize technology, especially when addressing the complexities of biology content. Additionally, expanding the research to include a larger and more diverse sample of teachers from various regions would offer a more comprehensive understanding of how TPACK is applied in different local contexts, highlighting regional variations and unique challenges. Moreover, further studies could examine the long-term impact of TPACK on student learning outcomes, assessing how sustained technology integration influences student engagement, comprehension, and academic performance over time. Finally, research should also explore how technology can evolve alongside the changing needs of education, ensuring that TPACK remains a relevant and effective framework for enhancing biology teaching and learning in an increasingly digital landscape.

REFERENCES

Agustriana, N., Kurniah, N., Alexon, A., Kusumah, R. G. T., & Adiarti, W. (2022). Edutainment Method Learning: Exploration of Variables and Implications on Children's Social Skills. *Al-Athfal: Jurnal Pendidikan Anak*, *8*(1), 27–38. https://doi.org/10.14421/al-athfal.2022.81-03

Bueno, R., Niess, M. L., Aldemir Engin, R., Ballejo, C. C., & Lieban, D. (2023). Technological pedagogical content knowledge: Exploring new perspectives. *Australasian Journal of Educational Technology*, 88–105. https://doi.org/10.14742/ajet.7970

Chen, M., Chai, C., & Jong, M. S.-Y. (2023). Actualization of teaching conceptions in lesson design: How teaching conceptions shape TPACK regarding spherical video-based virtual reality-supported writing instruction. *Educational Technology Research and Development*, *71*(6), 2321– 2344.https://doi.org/10.1007/s11423-023-10295-0

David, L., & Weinstein, N. (2024). Using technology to make learning fun: Technology use is best made fun and challenging to optimize intrinsic motivation and engagement. *European Journal of Psychology of Education*, *39*(2), 1441–1463. https://doi.org/10.1007/s10212-023-00734-0

García-Martínez, I., Tadeu, P., Montenegro-Rueda, M., & Fernández-Batanero, J. M. (2022). Networking for online teacher collaboration. *Interactive Learning Environments*, *30*(9), 1736 - 1750. https://doi.org/10.1080/10494820.2020.1764057

Gozali, I. (2022). Students' Perspective on the Importance of EFL Teachers' TPACK (Technological Pedagogical Content Knowledge) and XK (Contextual Knowledge) for learning English during the Pandemic. *PASAA*, *64*(1), 244–277. https://doi.org/10.58837/CHULA.PASAA.64.1.11

Khong, H., Celik, I., Le, T. T. T., Lai, V. T. T., Nguyen, A., & Bui, H. (2023). Examining teachers' behavioural intention for online teaching after COVID-19 pandemic: A large-scale survey. *Education and Information Technologies*, *28*(5), 5999–6026. https://doi.org/10.1007/s10639-022-11417-6

Mar'atussolichah, M., Ibda, H., Al Hakim, M. F., Faizah, F., Aniqoh, A., & Mahsun, M. (2024). Benkangen game: Digital media in elementary school Indonesian language. *Journal of Education and Learning (EduLearn)*, *18*(2), 480–488. https://doi.org/10.11591/edulearn.v18i2.21091

Maulana, I., Harahap, R. D., & Safitri, I. (2022). Use of learning media through technology for biology education students. *BIO- INOVED : Jurnal Biologi Inovasi Pendidikan*, *4*(3), 282. https://doi.org/10.20527/bino.v4i3.13418

Muhazaroh, I. (2023). PEMANFAATAN MEDIA DIGITAL DALAM PEMBELAJARAN BIOLOGI DI ERA GLOBALISASI. *Jurnal Penelitian Multidisiplin*, *2*(1), 153–157. https://doi.org/10.58705/jpm.v2i1.116

Ramaila, S., & Molwele, A. J. (2022). The Role of Technology Integration in the Development of 21st Century Skills and Competencies in Life Sciences Teaching and Learning. *International Journal of Higher Education*, *11*(5), 9. https://doi.org/10.5430/ijhe.v11n5p9

Romano, M., Díaz, P., & Aedo, I. (2023). Empowering teachers to create augmented reality experiences: The effects on the educational experience. *Interactive Learning Environments*, *31*(3), 1546–1563. https://doi.org/10.1080/10494820.2020.1851727

Roy, A. (2019). TECHNOLOGY IN TEACHING AND LEARNING. *International Journal for Innovation Education and Research*, *7*(4), 414–422. https://doi.org/10.31686/ijier.vol7.iss4.1433

Saharuddin, M. H., Nasir, M. K. M., & Mahmud, M. S. (2025). Exploring Teachers' Technological Pedagogical Content Knowledge in Utilising Artificial Intelligence (AI) for Teaching. *International Journal of Learning, Teaching and Educational Research*, *24*(1), 136–151. https://doi.org/10.26803/ijlter.24.1.7

Sukarno, S., & Haryati, S. (2015). Developing a Model of Compulsory Basic Education Completion acceleration in Support of Millennium Development Goals in Magelang, Indonesia. *International Education Studies*, *8*(7), p127. https://doi.org/10.5539/ies.v8n7p127

Theodorio, A. O., Waghid, Z., & Wambua, A. (2024). Technology integration in teacher education: Challenges and adaptations in the post- pandemic era. *Discover Education*, *3*(1), 242. https://doi.org/10.1007/s44217-024-00341-1