



TPACK-based augmented reality learning media for human excretory biology education

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ARTICLE INFO	ABSTRACT
<p>Article history Received: 06 July 2025 Revised: 27 August 2025 Accepted: 22 January 2026</p> <p>Keywords: Biology Instruction Educational Technology Interactive Media Science Learning Student Engagement.</p>	<p>This study aimed to develop Technological Pedagogical Content Knowledge (TPACK)-based Augmented Reality (AR) learning media on the topic of the human excretory system for high school students. The research was conducted from October to December 2024 at a sample high school in Palembang and the Biology Education Laboratory of Sriwijaya University. The research method used the ADDIE development model (Analysis, Design, Development, Implementation, Evaluation), reported up to the small group trial stage. Media validation was carried out by a material expert and a media expert, while practicality testing involved 30 students and 1 biology teacher. Validation results showed content validity of 81.7% (very valid) and media design validity of 92.5% (very valid). The small group trial revealed practicality scores of 95.2% from students and 100% from the teacher. Student learning evaluation results indicated that all students scored above 80 after using the media, demonstrating its effectiveness in enhancing conceptual understanding of the excretory system. In conclusion, the TPACK-based AR learning media developed is valid, practical, and effective for improving biology learning on the human excretory system topic.</p>

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INTRODUCTION

The rapid development of digital technology in the 21st century has significantly transformed education, enhancing accessibility, engagement, and personalized learning experiences. Digital learning tools such as virtual reality (VR), augmented reality (AR), and artificial intelligence (AI) have been integrated into pedagogical practices, supporting innovative teaching methods like flipped classrooms and blended learning, which improve student outcomes and motivation (Amalia et al., 2022; Muttaqin, 2022; Ng et al., 2023; Zou et al., 2025). In this century, technology has changed not only for itself but also changed what people do. It makes people become very possible to access and represent knowledge in many forms, start from pictures to movies (Huang et al., 2021). In this context, educators face the urgent challenge of equipping students with crucial 21st century skills, including critical thinking, creativity, communication, and collaboration, to thrive in a complex and fast-evolving global society (Amiruddin et al., 2024; Claro & Grau, 2023; Iryanto, 2025)

In biology education, teaching complex and abstract systems such as the human excretory system presents a persistent challenge. Traditional two-dimensional media often fail to help students visualize physiological processes like urine formation and detoxification, leading to widespread difficulties in comprehension (Rizalia et al., 2024; Yoedtadi & Pribadi, 2020; Yusa et al., 2023). Augmented Reality (AR) emerges as a promising tool by providing interactive three-dimensional visualizations that make abstract biological concepts tangible, thereby enhancing student motivation and reducing misconceptions (Arena et al., 2022; Ariso, 2017; Nengsih et al., 2023; Yapici & Karakoyun, 2021). Experimental evidence confirms that AR media significantly improve students' academic achievement in biology compared to conventional methods (Lampropoulos et al., 2022; Oktavianda et al., 2024). Additionally, the high degree of readiness of teachers for using Augmented Reality has been revealed (Jwaifell (2019) Nahampun (2023)). It shows the importance of using Augmented Reality as an effective tool in education nowadays.

The Technological Pedagogical Content Knowledge (TPACK) framework offers a critical theoretical foundation to effectively integrate technology into education by aligning content knowledge, pedagogical strategies, and technological tools (Mgeladze & Kapanadze, 2025). Based on the research of science education from 2013 to 2023, Amiruddin et al. (2024) find that TPACK-related publications have grown consistently. While TPACK is increasingly recognized as vital in science education, including biology, empirical studies show that teachers' TPACK competencies remain uneven, signalling the need for targeted interventions to strengthen technology integration in classrooms (Amiruddin et al., 2024; Buchner & Zumbach, 2020; Koehler & Mishra, 2009; Nabilah & Anwar, 2023; Nurmatin & Abdurrahman, 2024). Additionally, Arifuddin et al. (2025) notice that over the last half a decade, research trends emphasize that for integrating TPACK successfully, teachers should have high self-confidence. They must believe in their capability to operate technology for learning.

This study addresses the research gap by combining TPACK principles with AR Development focused on the human excretory system. Unlike prior studies that have examined AR or TPACK separately, this study integrates both to enhance instructional design quality. Additionally, it employs accessible platforms like Assemblr Studio and Canva to produce AR media suitable for diverse classroom contexts, enabling implementation in both online and offline modalities.

METHODS

Research Design

This study employed a Research and Development (R&D) approach using the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) as outlined by Branch (2010) to develop a TPACK-based Augmented Reality (AR) learning media focused on the human excretory system for high school biology students. The development process followed the analysis, design, and development phases, concluding with a small group trial to assess practicality. The research was conducted from October to December 2024 at a high school in Palembang and the Biology Education Laboratory of Sriwijaya University.

The study used the Grade 11 Biology syllabus from the *Kurikulum Merdeka*, validated 3D models of human excretory organs, and instructional content based on the Content Representation (CoRe) and Technological-Pedagogical-Professional Experience Repertoires (PaP-eRs) framework. The AR learning media was developed using Assemblr Studio and Canva, accessible via laptops and smartphones (Android/iOS).

Population and Samples

The target population comprised all Grade 11 students in the selected high school. A purposive sample of 30 students was chosen for the small group trial based on accessibility and consent. One biology teacher also participated in expert feedback on needs analysis and practicality.

Table 1

Demographics Data.

Participant Type	Population Size	Sample Size	Sampling Technique
Grade 11 Students	All students	30	Purposive Sampling
Biology Teacher	1 (all)	1	Convenience Sampling

Instrument

Data collection instruments included structured interviews, questionnaires, and expert validation checklists. Interviews with the biology teacher identified instructional challenges. Questionnaires assessed student learning needs and media responses. Validation was conducted by two domain experts—one focusing on biology content and one on educational biology—using Likert-scale instruments that measured content relevance, pedagogical quality, technological usability, and alignment with the TPACK framework. The instruments demonstrated acceptable validity (content validity index ≥ 0.81) and reliability.

Procedure

The research procedure comprised four sequential stages: (1) analysis, identification of learning challenges and media requirements via interviews and questionnaires; (2) design, development of detailed storyboards, flowcharts, and AR content outlines grounded in TPACK principles; (3) development: creation of AR media using Assemblr Studio and Canva, followed by expert validation and iterative revisions; (4) small group trial: implementation of the developed media with 30 students and a biology teacher for practicality assessment and feedback.



Figure 1. Research Procedure

Data Analysis Techniques

Measurement parameters encompassed: (1) content validity, assessed by expert judgment with a threshold of $\geq 81\%$ for “very valid”; (2) media practicality, percentage of positive responses from teachers and students with $\geq 81\%$ denoting “very practical”; (3) user experience and learning ease, qualitative assessment via observations and open-ended questionnaire responses. Quantitative data were analyzed descriptively through percentage scores, while qualitative data underwent thematic analysis to explore perceptions about the media’s interactivity, usability, and educational value.

RESULTS AND DISCUSSION

The needs analysis revealed that the current instructional media used in teaching the human excretory system at the selected high school were limited to textbooks and conventional PowerPoint presentations. According to the interviewed biology teacher, these methods inadequately support students’ visualization of complex biological mechanisms. This finding aligns with previous research suggesting that traditional 2D media are insufficient for conveying abstract scientific concepts effectively (Rizalia et al., 2024). The student questionnaire (n=30) further confirmed this, with 73.3% of respondents reporting difficulties in understanding key excretory system concepts such as kidney structure and urine synthesis.

To address these pedagogical challenges, the teacher completed the Content Representation (CoRe) and Technological Pedagogical and Professional Experience Repertoires (PaP-eRs) instruments to identify essential learning goals and effective teaching approaches. The CoRe results highlighted three focal areas: (1) anatomical structures and functions of excretory organs; (2) physiological processes including urine formation and detoxification, and (3) common disorders affecting the excretory system. PaP-eRs emphasized the use of visualization and interactive questioning as critical strategies to enhance

conceptual understanding. These insights underscore the necessity of employing models or simulations to render abstract biological phenomena more tangible for students. Based on these findings, the instructional design of the AR learning media was systematically developed, integrating 3D AR visuals sequenced through a detailed storyboard and flowchart. Assemblr Studio and Canva were utilized to create and design the AR content, ensuring technological integration was closely aligned with pedagogical and content needs identified via the TPACK framework.

The developed AR media was validated by two experts, yielding very valid scores: 81.7% for content accuracy and 92.5% for media design and functionality (Table 2). These results demonstrate strong alignment with curriculum standards and effective technological and pedagogical integration, which Koehler & Mishra (2009), Celik (2023) emphasize as essential for meaningful technology-enhanced learning. The slightly lower score in content accuracy suggests room for minor content refinement, such as enhancing explanatory depth to meet diverse learner needs.

Table 2
Validation Results of AR Learning Media

Aspect	Score (%)	Category
Content Accuracy	81.7	Very Valid
Media Design and Functionality	92.5	Very Valid

Subjecting the AR learning media to a small group trial with 30 students and one biology teacher resulted in very high practicality scores: 95.2% from students and 100% from the teacher (Table 3). Student learning outcomes improved notably, with most students achieving high scores post-intervention, underscoring the media's effectiveness in facilitating comprehension.

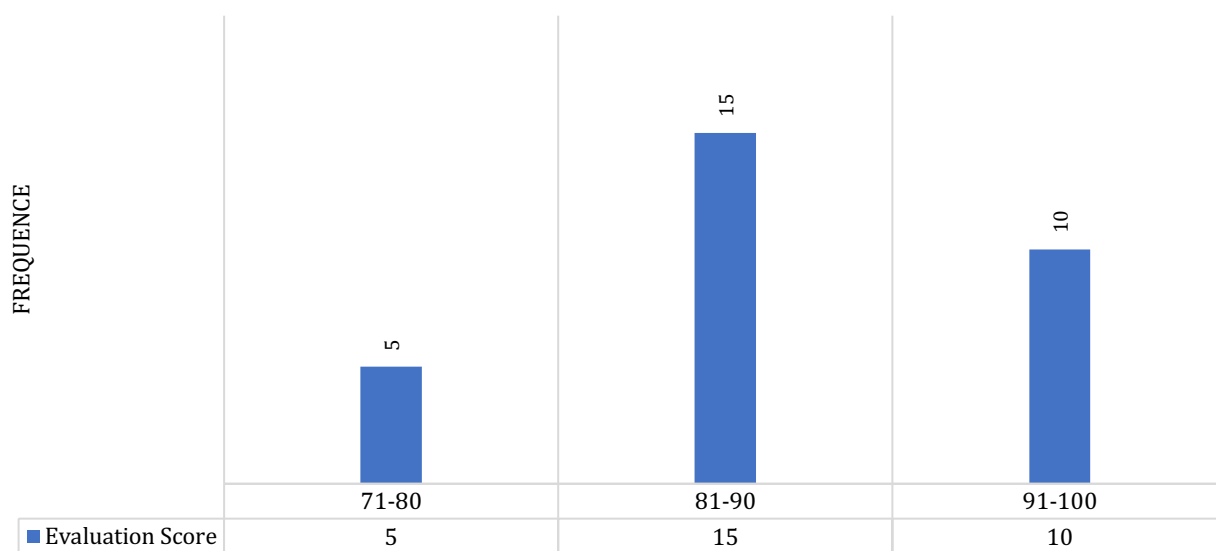


Figure 2. Distribution of Student Scores in Small Group Trial

Table 3
Practicality Test Results of AR Media

Aspect	Score (%)	Category
Biology Teacher	100.00	Very Practical
Students	95.20	Very Practical

The positive feedback from students highlighted that interacting with 3D AR models clarified the visualization of excretory organs and made learning activities more engaging. These qualitative insights are congruent with findings from Omurtak & Zeybek, (2022), Nengsih et al. (2023) and Yapici & Karakoyun (2021), who documented enhanced motivation and comprehension resulting from AR-based learning. The theoretical underpinning of this study is supported by cognitive theory Rudolph (2017), which posits that combining verbal and visual information through interactive media enhances cognitive processing and retention. Furthermore, the AR media likely reduced cognitive load, consistent

with Sweller's Cognitive Load Theory, Sweller (2024) and the research by Antony et al. (2025) transforming abstract, complex concepts into accessible, concrete learning experiences. Despite these positive outcomes, the study acknowledges limitations. The AR media requires compatible devices and stable internet connectivity for optimal functionality, which may limit accessibility for some students. Additionally, while the media substantially improves visualization, it currently lacks advanced interactive elements such as gamified features, which could further boost engagement, as noted in Lampropoulos et al. (2022), Cahyana et al. (2023), and Oktavianda et al. (2024)

Importantly, this study bridges learning of the Human Excretory System with TPACK-based AR media development. The high validation and practicality scores indicate successful integration of technological, pedagogical, and content knowledge, enabling effective delivery of complex biological content. This is in line with research by Nuruzzakiah et al. (2022) and Bereczki & Kárpáti (2021), who emphasize the critical role of TPACK in enhancing learning media quality and student engagement. Furthermore, Bungai et al. (2024) underscore that improving teachers' TPACK competence leads to enriched learning experiences, a theoretical lens through which this development can be viewed. This research provides a practical and replicable model for AR media development in biology education, especially for abstract topics like the excretory system. It opens avenues for future large-scale implementation, enhanced interactivity, and broader STEM applications.

CONCLUSION

The present study demonstrates that a TPACK-based Augmented Reality (AR) learning media can enhance student understanding, engagement, and achievement in biology, particularly in the human excretory system topic. The media was found to be valid in content and design, highly practical, and effective, enabling students to better visualize and grasp complex biological concepts, with all participants achieving strong academic results. These findings imply that integrating TPACK principles with AR technology not only fulfills contemporary educational demands but also offers a replicable model for improving learning outcomes in science. The implications extend to curriculum developers and educators, suggesting that similar approaches can be scaled for diverse topics and student populations, while continuous collaboration among stakeholders can foster richer, more accessible, and engaging STEM learning environments. Future work should prioritize the inclusion of advanced interactive features and broader accessibility strategies to maximize educational impact and address equity concerns.

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