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Evaluating Students' Acceptance of Augmented Reality in Protist Learning: Insights in Developing Protist Learning Media

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ABSTRACT

Protist concepts pose significant challenges for students due to their abstract nature and the complexity of microscopic structures. This study evaluates the validity, practicality, and acceptance of the Augmented Reality-Based Protist Application (AR-BPA). Following the development model by Lee & Owens (2004), this research focuses on the development stage, involving validity tests, preliminary implementation, and practicality tests. Data quantitative data were gathered from 3 experts, 32 students, and 2 lecturers through questionnaires, while qualitative data were gathered from 3 students and 1 lecture through interviews. All data were analyzed descriptively. The findings indicate that AR-BPA effectively supports student learning by making abstract concepts more accessible. Nonetheless, improvements in content scope and interface design are suggested to further optimize user experience. The study highlights AR-BPA's potential to revolutionize protist education, with implications for broader applications in biology learning. Future research should explore scalability and additional factors to fully realize AR-BPA's educational impact.

Keyword: Augmented reality, Protist, Protist Learning Media, Student Acceptance

INTRODUCTION

Protist is often considered challenging by students because this topic involves abstract concepts and requires an understanding of the structure of microorganisms that are difficult to visualize (Elnissa & Jayanti, 2023). Protist ia a very diverse group of organisms with different microscopic sizes and characteristics, making it difficult for students to understand their diversity and functions as a whole (Hardianto et al., 2024). The use of conventional learning media, such as textbooks or two-dimensional images, is often inadequate to describe the complexity and dynamics that occur in protist (Kırmızıgül & Kızılay, 2020; Sihombing & Pranoto, 2021). This makes the learning process less effective and can reduce students' interest in protist learning (Hardianto et al., 2024).

Addressing the challenges in protist learning, Augmented Reality (AR) offers a promising solution by transforming traditional methods with interactive and immersive experiences. Previous research has shown that the use of AR in learning is able to increase student

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engagement, facilitate independent learning, increase student motivation, and increase conceptual understanding of the learning topics studied (Buchner & Kerres, 2023; Weng et al., 2020; Zhou et al., 2020). AR allows users to visualize abstract concepts and complex spatial relationships, thus allowing users to see phenomena that are difficult to see in the real world (Weng et al., 2020). AR is able to present an interactive learning experience that can increase student engagement and facilitate understanding of complex concepts through 3D visualization (Liang & Roast, 2014). With the continued advancement of AR technology, its potential use is becoming increasingly important and relevant, especially in fields that require complex visualizations, such as protist (Kusmahardhika, Mahanal, Balqis, & Faridha, 2024).

Despite the potential benefits of AR in education, the successful integration of AR in learning depends heavily on users' acceptance and willingness to engage with it. Technological acceptance is a crucial factor in determining the effectiveness of AR-based learning, as students and educators may exhibit resistance to new technologies due to factors such as unfamiliarity, perceived complexity, or lack of prior experience (Shyr et al., 2024). If users do not perceive AR as beneficial, user-friendly, or compatible with existing learning habits, the impact of AR on educational outcomes may be diminished (Park & Yun, 2024). Identifying factors influencing acceptance allows educators and developers to design AR-based learning experiences that are more accessible, enhancing outcomes and student satisfaction in complex subjects like protist in biology learning (Park & Yun, 2024; Shyr et al., 2024; Stojšić et al., 2022).

Several studies have demonstrated the significant potential of AR in biology education, particularly in enhancing engagement and understanding in topics such as anatomy, ecosystems, and molecular biology. For instance, AR has been used to improve spatial understanding in anatomy, visualize ecological interactions, and simplify complex molecular processes (Bryceson et al., 2022; Duncan-Vaidya & Stevenson, 2021; Gillet et al., 2005). However, these studies largely focus on structured and tangible subjects, leaving a notable research gap in understanding students' acceptance of AR in more abstract and diverse topics, such as protist learning. The unique characteristics of protist, including their microscopic size, variability, and complex life processes, pose distinct challenges that may influence students' perceptions and acceptance of AR technology. This study aims to bridge this gap by investigating students' acceptance of AR in protist learning, providing a foundation for designing tailored educational interventions that enhance learning outcomes in this challenging area. The insights gained could also inform the adoption of AR in other abstract and complex biological topics, contributing to broader applications in biology education.

METHOD

Research Design

The conducted study is part of the research and development (R&D) of Augmented Reality-Based Protist Application (AR-BPA)'s learning media. The study design follows the five stages of the Lee & Owens (2004) model: assessment/analysis, design, development, implementation, and evaluation. This study specifically reports on the development stage, including validity test, preliminary implementation, and practicality test. The development stage plays a crucial role in assessing the learning media's initial effectiveness and usability, providing valuable insights into potential improvements. Findings from this phase will inform further refinement of the media, setting the foundation for subsequent stages in the full implementation process.

Participants

Before collecting data, we obtained research permission from the university and participants. To see the quality of the media developed, validity tests were conducted based on standard reviews, editorial reviews, and functional reviews (Lee & Owens, 2004). In this study, 3 experts consisting of media experts, content experts, and learning experts, were involved to assess the quality of AR-BPA. In a preliminary implementation, 32 students who had completed the Protist course participated in assessing their acceptance of AR-BPA. Additionally, for the practicality test, two lecturers teaching this course were also included.

Instruments

We used a questionnaire of expert responses to measure the validity of AR-BPA. For media experts, the questionnaire consists of 34 items measuring the feasibility of content, presentation and display quality, practicality of language use, and suitability for learning. For content experts, the questionnaire consists of 18 items measuring the relevance, accuracy of content, completeness of content, and language feasibility. For learning experts, the questionnaire consists of 34 items measuring the feasibility of content, presentation and display quality, practicality of language use, and suitability with learning. After measuring the validity test, it was continued to measure the practicality test for students and lecturers using a questionnaire. The questionnaire consisted of 21 items measuring ease of use, graphical feasibility, benefits, and effectiveness. The Likert scale (1-5) is used, adjusted to the validity criteria (Table 1) and practicality criteria (Table 2). The data were analyzed by descriptive statistics to describe the results of the validity, preliminary implementation, and practicality test on AR-BPA. In addition, we also conducted interviews with three students and a lecturer to get a comprehensive overview of the use of AR-BPA. A total of 3 items of open-ended questions were used in the student interview, including comfort, clarity, and motivation to learn with AR-BPA. Meanwhile, for lecturers, an item of questions is about the benefits and challenges of AR-BPA in learning.

Table 1. Validity criteria

Percentage	Criteria	Description
90,0 ≥	Very valid	Used without revision
75,0 < 90,0	Valid	Used with minor revision
65,0 < 75,0	Quite valid	Used with major revision
55,0 < 65,0	Less valid	Recommended unused
< 55,0	Invalid	Unused

Source: adapted from Tegeh et al., (2014)

Table 2. Practicality criteria

Percentage	Criteria	Description
90,0 ≥	Very practical	Used without revision
75,0 < 90,0	Practical	Used with minor revision
65,0 < 75,0	Quite practical	Used with major revision
55,0 < 65,0	Less practical	Recommended unused
< 55,0	Impractical	Unused

Source: adapted from Tegeh et al., (2014) In measuring students' acceptance of AR-BPA, we used 16 questionnaire items adopting a technology acceptance model (TAM) measuring its perceived usefulness (PU), perceived ease of use (PEOU), attitude towards technology (ATT), and behavioral intention (BI) (Shyr et al., 2024). PU refers to the degree to which a user believes that using AR-BPA enhances their learning performance. PEOU evaluates how effortlessly users can interact with the AR-BPA system. ATT assesses users' overall feelings or inclinations towards employing AR-BPA in their educational activities. Lastly, BI captures the likelihood that users will continue using the technology in the future. We used a 5-point Likert scale to quantify responses to these constructs, ranging from 1 (strongly disagree) to 5 (strongly agree). The data collected were analyzed using descriptive statistics, offering valuable insights into the levels of acceptance among users of AR-BPA.

Procedure

The questionnaires were given to experts in measuring the validity of AR-BPA. The feedback from the experts helped refine the questionnaire, ensuring its relevance and accuracy in assessing the validity of AR-BPA. Furthermore, the preliminary implementation was continued for 32 students to see the acceptance of technology. The results were analyzed to evaluate the extent to which AR-BPA is useful and easy to use, as well as their attitudes and intentions to continue using AR-BPA in the future. Then a practicality test was conducted through filling out questionnaires and interviews by students and lecturers. Three students were selected based on the highest, medium, and lowest scores on the practicality test for further interviews. The interview aims to delve deeper into the students' experiences in using AR-BPA, including the factors that support or hinder the practicality of this media. The results of these interviews will complement the quantitative results of the questionnaire, so that it can provide a more comprehensive view of the practicality of the AR-BPA.

RESULTS AND DISCUSSION

Prototype of Augmented Reality-Based Protist Application (AR-BPA)

The prototype of AR-BPA represents a significant innovation in educational technology, particularly in protist learning. This prototype aims to address the challenges students face in understanding complex, microscopic organisms such as protist, which are often difficult to visualize through traditional learning methods. AR-BPA provides an interactive platform that allows students to view and manipulate 3D models of protist, thereby enhancing their comprehension of critical biological concepts such as cellular structure, movement, and function. The integration of AR-BPA into the learning process is expected to promote a more engaging and effective educational experience, aligning with contemporary approaches that prioritize active and experiential learning in science education.

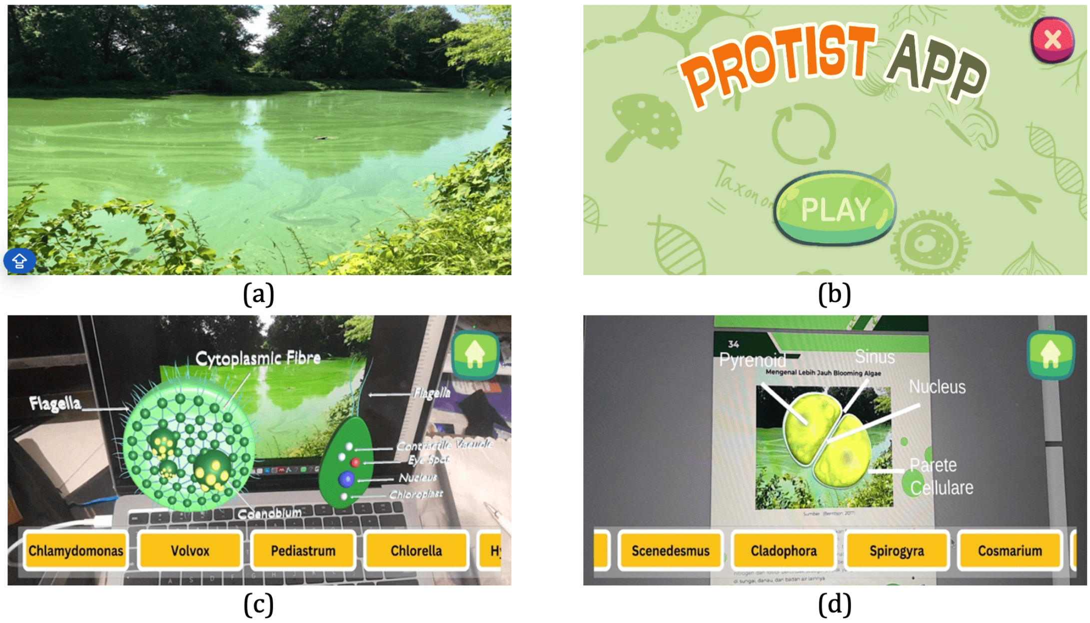

Figure 1. (a) marker of AR-BPA; (b) AR-BPA initial view; (c-d) visualization of some protist genera

Building on the initial concept, the AR-BPA application uses AR markers that connect directly to real-world ecological issues, such as blooming algae, a phenomenon often linked to certain protist species. The application employs a blooming algae image as a marker (Figure 1a), setting the context of the problem and preparing students for a deeper exploration. Upon entering the application (Figure 1b), students can interactively observe the structures of some protist genera (Figure 1c-d) that are known to contribute to algal blooms. This immersive experience enables students to visually explore each genus in detail, enhancing their understanding of the structural characteristics and behaviors that can lead to ecological impacts (Tene et al., 2024). AR-BPA facilitates an integrated learning experience, encouraging students to analyze the environmental role of protist while engaging with the content on a more meaningful level by connecting biological concepts to real-world issues.

Validity Test

A multimedia product must undergo a review stage to assess its quality before implementation. Product quality testing is conducted based on standard reviews, editorial reviews, and functional reviews (Lee & Owens, 2004). Validation of AR-BPA involved evaluations by media experts, content experts, and learning experts to ensure a comprehensive assessment of the media's validity. The standard review, conducted by media experts, measured the feasibility of the content, presentation and display quality, practicality of language use, and suitability for learning in AR-BPA. Table 3 presents the results of media expert validation of AR-BPA, with each indicator classified in the valid category and an overall average score of 89.00%. These findings confirm that AR-BPA meets the required quality standards for feasibility based on the developed media's quality. Furthermore, editorial reviews were conducted by content experts to assess the relevance, content accuracy, content completeness, and language feasibility of AR-BPA. Table 4 presents the content expert validation results for AR-BPA, with each indicator categorized as highly valid and an overall average score of 100.00%. These results confirm that AR-BPA meets high-quality standards, ensuring it contains content suitable for student application. The functional review was conducted by learning experts who assessed the feasibility of content, presentation and display quality, practicality of language use, and suitability for learning in AR-BPA. Table 5 presents the results of learning expert validation of AR-BPA, with each indicator falling into the "very valid" category, achieving an overall average score of 99.50%. These results confirm that AR-BPA is feasible for application in educational settings based on its learning utility.

Table 3. Media expert validation

Indicators	Percentage (%)	Criteria
Feasibility of content	80.00	Valid
Presentation and display quality	88.00	Valid
Practicality of language use	100.00	Very valid
Suitability for learning	88.00	Valid
Mean	89.00	Valid

Table 4. Content expert validation

Indicators	Percentage (%)	Criteria
Relevance	100.00	Very valid
Accuracy of content	100.00	Very valid
Completeness of content	100.00	Very valid
Language feasibility	100.00	Very valid
Mean	100.00	Very valid

Table 5. Learning expert validation

Indicators	Percentage (%)	Criteria
Feasibility of content	100.00	Very valid
Presentation and display quality	98.00	Very valid
Practicality of language use	100.00	Very valid
Suitability for learning	100.00	Very valid
Mean	99.50	Very valid

AR effectively helps students in connecting and visualizing abstract concepts. This design aligns with Dale’s Cone of Experience Theory, which posits that interactive experiences enable learners to explore learning resources in detail and strengthen their understanding through visual exploration, moving from concrete to abstract experiences (Masters, 2013). AR encourages an active learning approach, where students are not just passive recipients but active participants in the educational process (Kececi et al., 2021). This engagement potentially improves both comprehension and motivation, as students are more likely to retain information when they interact with it meaningfully (Lin & Yu, 2023).

The content is arranged logically and systematically, making it easier for students to understand, remember, and apply information (Adorni & Koceva, 2015; Ulimaz et al., 2020). This principle aligns with Jerome Bruner's Information Processing Theory, which addresses how students process (Axelrod, 1973; Chaijaroen et al., 2020; Simon, 1979; Wu, 2013). AR-BPA is effective not only in its design but also in its content, which can maximize students' learning potential (Lampropoulos et al., 2020; Panda & Kaur, 2023). Such a structured approach, emphasizing clear, coherent organization, helps students engage more deeply with the material, fostering long-term retention and practical application (Lin & Yu, 2023).

The integration of AR-BPA aligns with constructivist principles, where students build upon prior knowledge through active, immersive experiences (Mooij, 2007; Winarni et al., 2022). AR-BPA enables learners to process complex concepts more efficiently, encouraging a deeper level of comprehension and engagement by presenting information in a digestible and sequential manner. Consequently, AR-BPA can significantly enhance educational outcomes by bridging the gap between theory and practice, ultimately facilitating a more holistic learning experience for students.

Assessing students' acceptance towards AR-BPA in preliminary implementation

In this study, student acceptance of AR-BPA was tested on a specific group of students who had previously received instruction on protist. This group was chosen to ensure a relevant knowledge background, allowing for a more focused and measurable assessment of technology acceptance related to AR-BPA. Figure 2 provides an overview of students' acceptance levels of AR-BPA technology through four key indicators: Perceived Usefulness (PU), Perceived Ease of Use (PEOU), Attitude Toward Technology (ATT), and Behavioral Intention (BI). The data reveals a generally high acceptance of AR-BPA, with the ATT (87.19%) and PU (86.26%) indicators being the most favorable. Although slightly lower, PEOU (80.47%) and BI (79.07%) still reflect positive attitudes toward the technology. These findings indicate that students perceive AR-BPA as beneficial and are willing to adopt it, signifying a positive reception and readiness to integrate it into educational settings.

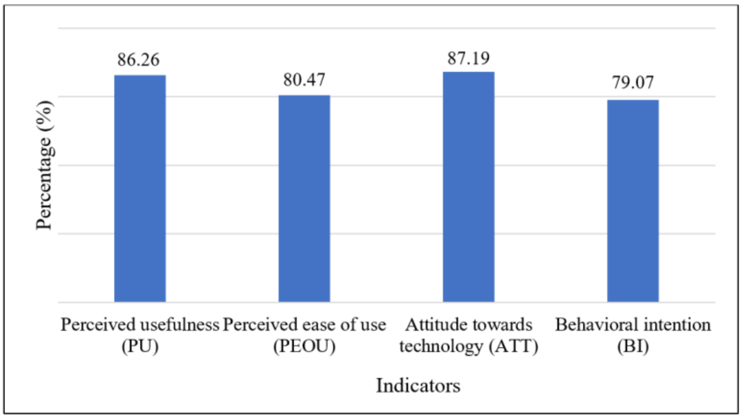

Figure 2. Students' Acceptance to AR-BPA

The percentage PU was obtained at 86.26%, indicating that this technology supports students' understanding of the material being taught. This figure shows that the presence of AR-BPA plays a role in improving protist learning. Through AR-BPA, students can engage with content in a way that is both relevant and aids in understanding concepts that were previously challenging. The high level of PU demonstrates that AR-BPA aligns well with students' learning needs, supporting the effective integration of technology into the educational process. The perceived benefits for students are crucial in supporting the effective use of technology in learning, which serves as a compelling reason to consider the application of AR-BPA in protist education (Toros et al., 2024).

The PEOU significantly influences students' acceptance of AR-BPA, with 80.47% of students considering AR-BPA relatively easy to use. However, some students reported a few of difficulties with usability, highlighting areas for improvement in the technology's intuitive design and the need to address technical barriers. These challenges, which may stem from unfamiliarity with AR technology or technical issues, suggest that further refinement could enhance the overall user experience. Despite these hurdles, the high percentage indicates that AR-BPA is largely intuitive for most students. Focusing on continuous improvements in usability and reducing technical challenges could further increase students' interest in integrating AR-BPA into their learning experience, ultimately leading to greater acceptance among new users (Toros et al., 2024).

The ATT showed the highest percentage, 87.19%, indicating that students possess a very positive attitude toward the use of AR-BPA in the learning process. The ATT is crucial, as it promotes students' openness to adopting and utilizing new technologies in educational settings. A constructive attitude also enhances the likelihood of students becoming more engaged and actively involved in technology-based learning processes (Wekerle et al., 2022). AR-BPA is perceived not only to offer academic advantages but also to stimulate students' interest in educational technology. Such a positive attitude serves as a strong foundation for the successful (Toros et al., 2024), large-scale implementation of AR-BPA. A high ATT score reflects students' enthusiasm for integrating new technologies into their learning experience (Ardıç, 2021).

The BI score for using AR-BPA reached 79.07%. This score still reflects a relatively high level of student interest in reusing AR-BPA. The findings suggest that most students are inclined to use this technology in the future. Strong BI is crucial for ensuring the sustained integration of technology in educational settings (Bitangcol et al., 2024). While AR-BPA is perceived as an innovative tool, it requires further efforts to enhance its relevance and accessibility. The high BI score indicates the potential for sustainable use of AR-BPA, where high acceptance must be supported by the intent to continue engaging with it (Wekerle et al., 2022). With targeted improvements in the BI aspect, AR-BPA has the potential to increase student interest in utilizing this media across various learning contexts.

Overall, the acceptance of AR-BPA technology among students showed highly positive results, especially in protist learning which does require interactive visualization media. Protist learning requires tools such as AR-BPA to make it easier for students to understand important concepts, such as the structure and movement of protist, which are often difficult to visualize through traditional media. AR-BPA technology allows students to see and interact directly with 3D models of protist, which strengthens conceptual understanding and increases interest in learning (Hu et al., 2021). This interactive approach not only makes complex biological structures more accessible but also fosters a deeper engagement with the content (Panda & Kaur, 2023). Students can explore details that are often overlooked in textbook diagrams or two-dimensional images. Additionally, the use of AR-BPA aligns with modern educational practices that emphasize active learning, allowing students to take a more participatory role in their education.

Practicality Test

The practicality test was conducted by both students and lecturers, evaluating four key aspects: ease of use, graphical feasibility, benefits, and effectiveness of the AR-BPA. Among the 32 participating students, the results indicated a high level of practicality across all assessed aspects. The ease of use scored an average of 83.75%, categorizing it as practical. Graphical feasibility was rated at 84.45%, also practical, while benefits received a score of 85.42%, and effectiveness was rated at 85.00%, both categorized as practical. These findings suggest that the AR-BPA was well-received by students, particularly in terms of its usefulness and overall impact on their learning experience (Table 6). Similarly, the results from the two lecturers indicated a very high level of practicality. Each aspect (ease of use, graphical feasibility, benefits, and effectiveness) has received a score of 90.00%, classifying them as very practical. This consistent assessment from the lecturers aligns with the positive feedback from students, further validating the AR-BPA's functionality and educational value in supporting the learning of protist.

The interview data revealed valuable insights into the experiences and perceptions of both students and lecturers regarding the use of AR-BPA. Student A expressed strong enthusiasm, stating that the learning media was: "... *very engaging and made me enjoy the learning process*". This highlights how the interactive and immersive nature of the AR-BPA contributed to an enjoyable learning experience, which can positively influence student motivation and sustained attention during the learning process.

Table 6. Practicality test

Indicators	Students (n=32)		Lectures (n=2)	
	%	Criteria	%	Criteria
Ease of use	83.75	practical	90.00	very practical
Graphical feasibility	84.45	practical	90.00	very practical
Benefits	85.42	practical	90.00	very practical
Effectiveness	85.00	practical	90.00	very practical
Mean	84.65	practical	90.00	very practical

Student B focused on the instructional clarity that AR-BPA provides, remarking that: "*the use of AR-BPA gave me a clearer understanding of protist through 3D visualization*". This indicates that AR-BPA's ability to present complex biological organisms in 3D visualization, interactive format enhanced the student's conceptual understanding of Protist. Students were able to grasp abstract concepts more concretely by visualizing protist in detail and from different views. This finding underscore AR-BPA's role in improving comprehension by turning theoretical content into more tangible experiences.

Student C appreciated the comprehensive nature of the topics covered, stating: "*the topics presented were very comprehensive, expanding my knowledge of Protist diversity and helping me to explore more about Protist*". This suggests that the AR-BPA was not only effective in conveying specific content but also succeeded in broadening students' overall understanding of the Protist kingdom. The depth of the content, paired with the immersive technology, provided students with a richer learning experience, which likely contributed to their enhanced awareness of Protist diversity.

From the lecturers' perspective, the AR-BPA showed significant potential, though with some limitations. One lecturer remarked: "*although not all topics can be delivered using AR, its use increases students' motivation and engagement*". This statement acknowledges that while AR-BPA may not be applicable for every aspect of the course, its overall impact on student engagement is substantial. Lecturers observed that the use of AR-BPA sparked higher levels of motivation and interest among students, which can positively influence learning outcomes. However, as noted by the lecturers, not all biology topics are amenable to AR-based learning. To address this limitation, a hybrid approach combining AR with other instructional methods could be explored, ensuring a more comprehensive and flexible teaching strategy that aligns with the varied nature of biology content.

The findings of this study indicate the AR-BPA is perceived as highly practical by both students and lecturers. High practicality scores demonstrate that the integration of AR into protist learning is well-designed to facilitate learning. These results align with findings by Liang & Roast (2014), which show that AR can provide interactive learning experiences, making complex concepts easier to understand through visual aids. The positive feedback suggests that students and lecturers found the AR-BPA intuitive and beneficial for learning complex biological concepts, supporting the notion that effective technology integration enhances learning outcomes. Students' responses, particularly their high appreciation for the AR-BPA's comprehensiveness and visual clarity, highlight the application's practicality and relevance in an academic context.

The AR-BPA successfully met student expectations by offering a user-friendly interface and engaging content. As indicated by the feedback from students, the AR-BPA made learning more enjoyable and interactive. Student B's perception that integration AR into AR-BPA "gives a clearer understanding of protist through 3D visualization" highlights the strength of AR in simplifying complex topics. This feature aligns with Mustami et al., (2019) who emphasized that practical media must facilitate normal learning conditions, reflected in positive responses. Through the AR features presented, students can interact with protist objects virtually, allowing them to better understand the structure and function of protist (Sungkur et al., 2016). Thus, AR-BPA is expected not only to improve students' cognitive skills, but also to support the development of their metacognitive skills (Dahlberg et al., 2019; Sungkur et al., 2016). Furthermore, research shows that AR-based learning can encourage self-directed learning as well as provide a more enjoyable and immersive learning experience (Mokoena & van Tonder, 2024).

However, there are challenges in fully meeting student expectations, especially in covering all topics within the Protist kingdom. As noted by one of the lecturers, while AR is excellent for boosting motivation, it cannot be applied to every learning topic. This observation suggests that although AR enhances student engagement and comprehension, its utility is somewhat limited by the scope of the learning topics that can be adapted to AR-based learning. Despite this, the potential of the AR-BPA to transform biology education is evident by making abstract biological processes more tangible through 3D visualization (Petrov & Atanasova, 2020), the AR-BPA enhances students' grasp of difficult concepts, making it a promising tool for broader educational applications.

The success of the AR-BPA in the Protist course suggests that it could be further developed and integrated into more areas of biology education, especially those that require visualizing complex structures or processes. Based on Student C's feedback that the AR-BPA expanded their knowledge of Protist diversity, future iterations of the AR-BPA could include a wider array of organisms within the Protist kingdom, or even extend to other biological kingdoms and topics such as cell biology or microbiology. The inclusion of more diverse content could further enrich students' understanding of complex biological phenomena (Flowers et al., 2023), making the AR-BPA a versatile tool in the biology curriculum.

In terms of improvements based on student and lecturer feedback, enhancing the interactive features of the AR-BPA could help address its current limitations. For instance, while AR has proven useful for some topics, expanding the AR-BPA to cover more topics with greater interactivity could increase its educational value. Additional features such as adaptive learning paths, personalized feedback, and more detailed 3D models could also improve its functionality (Abriata, 2022; Chen et al., 2023). Furthermore, refining the graphical interface to make it more intuitive could enhance the user experience, making the AR-BPA even more accessible to a wider range of learners. These enhancements would not only meet the current needs of students but also provide a foundation for integrating more advanced learning technologies in the future (Kusmahardhika, Mahanal, Balqis, Faridha, et al., 2024).

In conclusion, the AR-BPA has demonstrated its potential to enhance biology education by improving student engagement, motivation, and understanding of complex biological concepts. The AR-BPA has the capacity to become a transformative educational tool across a broader spectrum of biological topics. Future studies should also explore how students' attitudes toward technology and their technological literacy levels influence the effectiveness of AR-based learning tools like the AR-BPA. In addition, measuring understanding of concepts related to protist also needs to be carried out through biological literacy, protist literacy, or algae literacy studies, ensuring that it caters to diverse student needs and learning styles.

Limitations of Research

This study has several limitations. First, the sample size was limited to 3 experts, 32 students, and 2 lecturers, which may not fully represent the broader population of students studying protist. Additionally, the study was conducted within a specific educational setting with students who had prior knowledge of protist, which may limit the generalizability of the findings to other groups and contexts. Broader testing across more diverse samples and varied settings is needed to establish its universal efficacy. Another limitation concerns the limited interactivity of the AR-BPA. Feedback indicated the need for more dynamic and adaptive interactive features, such as personalized feedback, detailed 3D models, and adaptive learning paths. These enhancements could make the AR-BPA more engaging and effective for a wider range of learners.

Lastly, the study focused solely on the initial acceptance of AR-BPA, without exploring its long-term impact on student learning outcomes. Ensuring the sustainability and scalability of AR-BPA requires addressing challenges such as cost, accessibility, and technological literacy among both educators and students. Future research should explore these aspects through larger, more diverse samples, longitudinal studies, and strategies for making AR-BPA more interactive and scalable to support its long-term adoption in biology education.

CONCLUSION

The Augmented Reality-Based Protist Application (AR-BPA) has proven to be a valuable tool in enhancing student acceptance in protist learning. AR-BPA allows students to interact with 3D models, providing an immersive experience that aids in visualizing complex biological structures and processes that are challenging to grasp through traditional media. This positive reception underscores AR-BPA's potential as an effective educational tool for visualizing and understanding abstract concepts in protist learning. To ensure sustained impact and scalability, future development should prioritize the integration of dynamic and adaptive features, including personalized feedback, detailed and scalable 3D models, and adaptive learning paths that cater to individual student progress. Furthermore, addressing practical challenges such as cost, accessibility, and varying levels of technological literacy among educators and students is essential for promoting widespread adoption. A comprehensive evaluation of AR-BPA's impact should also incorporate the measurement of variables such as technology literacy, biology literacy, protist literacy, and algae literacy. These efforts would support the continuous refinement of the application to meet the diverse educational needs and enhance its effectiveness across various academic contexts.

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