BIO-INOVED
Jurnal Biologi-Inovasi Pendidikan
Volume 7, Issue 3, October 2025 page. 482-490

P-ISSN : 2684-9062 | E-ISSN : 2714-9803
https://ppjp.ulm.ac.id/journal/index.php/bino
DOI: 10.20527/bino.v7i3.23741

Enhancing numeracy literacy in embryology: Validity and practicality of augmented reality media for gametogenesis

M. Arsyad [1] *, Muhammad Zaini [1], Amalia Rezeki [1], Ika Wardani [2], Muhammad Iqbal Trinajah [3], Muhammad Aldy Nurrachman [3]

[1] Department of Biology Education, Faculty of Teacher Training and Education, Universitas Lambung Mangkurat, Banjarmasin, South Kalimantan, Indonesia
[2] Department of Biology Education, Faculty of Economics, Education, Social Humanities, and Science and Technology, Universitas Kristen Cipta Wacana, Malang, East Java, Indonesia
[3] Master Program of Biology Education, Postgraduate Program, Universitas Lambung Mangkurat, Banjarmasin, South Kalimantan, Indonesia

** Corresponding Author Email: muhammadarsyad@ulm.ac.id*

Article Information

Keyword:
Validity; Practicality; Augmented reality; Gametogenesis; Mathematical thinking

Kata Kunci:
Validitas; Kepraktisan; Augmented reality; Gametogenesis; Berpikir matematis

History:
Received : 28/08/2025
Revised : 12/10/2025
Accepted : 22/10/2025
Published : 25/10/2025

Abstract

Augmented reality (AR) offers immersive visualization that can transform learning of abstract biological processes. Yet, its pedagogical integration with mathematical thinking in higher education remains limited. This study developed AR media for gametogenesis to enhance students' numeracy literacy. Integrating mathematical thinking into AR media is essential to strengthen students' ability to interpret biological data quantitatively. According to OECD's PISA results, Indonesia's mathematics score (366) remains below the global average (472), consistent with findings showing that most students' literacy levels fall within low to moderate categories. This study is development research using a descriptive quantitative approach adapted from the Lee & Owens model. AR gametogenesis media were developed using Blender and Assemblr EDU, featuring spermatogenesis content and numeracy exercises based on six numeracy literacy indicators. Validation was conducted by three experts (content, language, and media), and practicality testing involved 14 Biology Education students from Lambung Mangkurat University. Data were analyzed using validity and practicality formulas. Results indicated that the media achieved "very valid" ratings in content, presentation, and graphics, and was considered practical in design, ease of use, and usefulness. Therefore, the AR gametogenesis media integrated with mathematical thinking is valid, practical, and beneficial for improving Biology Education students' numeracy literacy.

Abstrak. *Augmented reality (AR) menawarkan visualisasi imersif yang dapat mengubah pembelajaran proses biologis yang abstrak. Namun, integrasi pedagogisnya dengan berpikir matematis dalam pendidikan tinggi masih terbatas. Penelitian ini bertujuan mengembangkan media AR untuk gametogenesis untuk meningkatkan literasi numerasi siswa. Mengintegrasikan berpikir matematis ke dalam media AR sangat penting untuk memperkuat kemampuan siswa dalam menafsirkan data biologis secara kuantitatif. Menurut hasil PISA OECD, skor matematika Indonesia (366) masih di bawah rata-rata global (472), konsisten dengan temuan yang menunjukkan bahwa sebagian besar tingkat literasi siswa berada dalam kategori rendah hingga sedang. Penelitian ini merupakan penelitian pengembangan dengan menggunakan pendekatan kuantitatif deskriptif yang diadaptasi dari model Lee & Owens. Media gametogenesis AR dikembangkan menggunakan Blender dan Assemblr EDU, yang menampilkan konten spermatogenesis dan latihan numerasi berdasarkan enam indikator literasi numerasi. Validasi dilakukan oleh tiga ahli (konten, bahasa, dan media), dan uji praktikalitas melibatkan 14 mahasiswa Pendidikan Biologi dari Universitas Lambung Mangkurat. Data dianalisis menggunakan rumus validitas dan praktikalitas. Hasil penelitian menunjukkan bahwa media tersebut mencapai peringkat "sangat valid" dalam hal konten, presentasi, dan grafis, serta dinilai praktis dalam hal desain, kemudahan penggunaan, dan kegunaan. Oleh karena itu, media gametogenesis AR yang terintegrasi dengan pemikiran matematika valid, praktis, dan bermanfaat untuk meningkatkan literasi numerasi mahasiswa Pendidikan Biologi.*

A. Introduction

Technological developments in education have opened up significant opportunities to create more interactive, contextual, and meaningful learning. One form of technology currently widely utilized in education is virtual media, such as virtual reality and augmented reality (AR). Augmented reality based learning media have the advantage of realistically displaying three-dimensional objects in the user's environment, thereby enhancing student engagement, conceptual understanding, and learning experiences (Akçayır & Akçayır, 2017; Billinghurst et al., 2014). However, the current use of AR in biology classrooms still faces challenges, including the lack of subject-specific design, limited educator competence, and infrastructure constraints, particularly in higher education institutions in Indonesia.

Although augmented reality technology has begun to be applied in education, its application in embryology courses is still relatively minimal and remains dominated by the medical and engineering fields in Indonesian higher education due to limited infrastructure, training, and human resources. The development of AR-based media is still focused on general science subjects and has not yet addressed specific biological topics such as gametogenesis (Rahayu et al., 2024; Rahmi & Guspatni, 2024; Yilmaz, 2021).

Research results show that developmental biology has great potential to be taught using AR media due to its visual and dynamic nature (Azzahra et al., 2024; Yapici & Karakoyun, 2021). Visualization of biological processes such as sex cell formation, meiosis, and changes in cell structure in gametogenesis can be more easily understood by students when visualized interactively through AR technology-based media (Ibáñez & Delgado-Kloos, 2018). However, studies integrating AR within tertiary-level biology programs in Indonesia remain scarce, and most existing works are limited to conceptual visualization without addressing cognitive or quantitative competencies.

In addition to conceptual understanding, important improving 21st-century skills, one of which is numeracy literacy. Numeracy literacy is essential for biology education students as future science teachers. Numeracy literacy not only involves the ability to perform calculations but also the capacity to interpret, analyze, and communicate quantitative information in real-life contexts (OECD, 2023). Mastery of these cognitive and numerical competencies (Klug et al., 2017; Nel, 2020) enables students to understand and explain the relationship between data and biological phenomena effectively (Arsyad et al., 2023; Arsyad & Wardani, 2025; Fauzi & Fadilah, 2024).

One measure of numeracy literacy can be analyzed from the results of the PISA assessment. The results of PISA (2022) show that the mathematical literacy of Indonesian students is still low. The average score of Indonesian mathematical ability is 366 points and is still below the OECD average of 472 points. More than 75% of Indonesian students do not reach the minimum proficiency level (Level 2), indicating difficulty in applying basic mathematical concepts in real-life contexts (OECD, 2023). These results indicate that mastery of numeracy remains a major challenge, even up to the tertiary level. The integration of numeracy literacy in biology learning is also still minimal (Fauzi & Fadilah, 2024; Frith & Lloyd, 2016; Nuraeni et al., 2020). Even though material such as gametogenesis contains a lot of quantitative data, such as the number of chromosomes, the ratio of cell division, and the speed of the differentiation process. The results of measuring numeracy literacy in 245 students in South Kalimantan showed that 44.49% of respondents had low quantitative literacy and 55.51% were in the moderate category.

Several studies have shown that AR has great potential in improving numeracy literacy due to its visual, interactive, and contextual nature (Cahyana et al., 2023; Erviani et al., 2024; Nafian, 2024; Paidi et al., 2021; Pasaribu et al., 2024). When numerical content is presented in the form of interactive visualizations, students more easily associate numbers with concrete concepts, improving their comprehension and data-based decision-making abilities (Weng et al., 2020) However, most of these studies are limited to general science or mathematics topics, and none have examined AR integration with mathematical thinking specifically within embryology or gametogenesis content. This gap underscores the novelty of the present research.

Mathematical thinking plays a crucial role in numeracy literacy development because the two are conceptually and functionally interrelated. Mathematical thinking, which encompasses the ability to reason, solve problems, generalize, and prove (Mason et al., 2010) serves as the foundation for individuals to understand, interpret, and use numerical information in a variety of real-life contexts. Numeracy literacy, as defined by the OECD (2023), extends beyond the ability to calculate, but also encompasses the application of mathematical reasoning and reasoning in data-driven decision-making. Therefore, the stronger a person's mathematical thinking skills, the stronger their numeracy literacy, as they are able to see patterns, understand quantitative relationships, and provide logical justification for number-based situations. Numeracy literacy, including mathematical thinking, is fundamental to the development of meaningful and contextual numeracy literacy.

Therefore, developing augmented reality media that integrates mathematical thinking into gametogenesis learning is crucial to enhance students' numeracy literacy and research reasoning. Mathematical thinking supports data analysis and quantitative decision-making (Lee-Post, 2019; Speth et al., 2010), yet its application in biology learning remains limited. Integrating it into AR-based gametogenesis learning represents a novel approach to improving the quality of embryology education through quantitative interpretation of biological data. This study aims to analyze the validity and practicality of AR media for gametogenesis integrated with mathematical thinking as an effort to improve the quality of embryology learning and support students' numeracy literacy.

B. Material and method

This research is descriptive quantitative research and is part of development research. The research procedure follows Figure 1 the design and development stages based on the model of Lee & Owens (2004).

Needs analysis was conducted among Biology Education students at Lambung Mangkurat University. The results indicated that augmented reality has never been used in gametogenesis learning, and there is a need for new, virtual, and interactive learning media. Front-end analysis was carried out involving 245 Biology Education students in South Kalimantan to assess their numeracy literacy skills. The results showed that 44.49% of the respondents had low quantitative literacy, while 55.51% were in the moderate category.

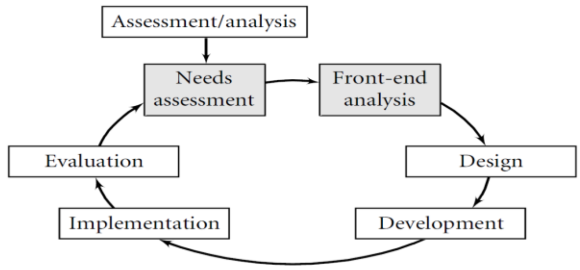

Figure 1 Lee & Owens development model design

In the design stage, augmented reality media was designed by incorporating gametogenesis materials tailored to the learning outcomes of the Embryology course, namely, analyzing the gametogenesis process and the factors that influence it. The selection of the six numeracy literacy indicators (interpretation, representation, calculation, analysis, assumptions, and communication) was based on their suitability for higher-order thinking integration and their prior validation in STEM education frameworks. In addition, the design stage also aims to integrate mathematical thinking exercises to improve students' numeracy literacy skills. The numeracy literacy indicators used in this media refer to the guidelines of Association of American Colleges and Universities (2009) which include interpretation, representation, calculation, analysis, assumptions, and communication (see Tabel 1).

Table 1 Indicators and description of numeracy literacy

Indicator	Description
Interpretation	The ability to translate and understand information presented in mathematical form.
Representation	The ability to convert appropriate information into a variety of relevant mathematical forms (e.g., graphs, diagrams, equations, and mathematical sentences).
Calculation	Ability to do calculations comprehensively to help the problem-solving process or provide answers to some questions. The calculations are also presented elegantly (clear, concise, etc.).
Application/Analysis	The ability to assess and make accurate conclusions based on the results of quantitative data analysis.
Assumptions	Ability to compose assumptions and evaluate important assumptions in estimation, modeling, and data analysis.
Communication	Presenting quantitative evidence to support an argument that is formatted, presented, and contextualized.

The development stage consists of three stages: pre-development, development, and post-development. In the pre-development stage, a final design check is carried out to ensure the suitability of the material and content of numeracy literacy skills. In the development stage, augmented reality media is prepared according to the design agreed upon by the developer using Blender software and the Assemblr EDU platform. In the post-development stage, an evaluation is carried out on the validity and practicality of the augmented reality learning media for gametogenesis integrated with mathematical thinking.

The design and development of augmented reality gametogenesis media integrated with mathematical thinking was carried out in December 2024. The practicality test stage was carried out in January 2025. All research activities from the design stage to the practicality test were carried out in the Biology Education Study Program, Lambung Mangkurat University. This was based on the results of the needs analysis, which indicated that gametogenesis learning requires new media utilizing virtual and interactive technology.

The subjects in this study were 3 lecturers from the ULM Biology Education Study Program for the validation test subjects who acted as expert validators, consisting of material experts, multimedia experts, and language experts. In addition to the subjects for the validation test, the subjects needed for this study were also required for the practicality test. The population for the practicality test consisted of Biology Education students at Lambung Mangkurat University. The sample included third-year (sixth-semester) Biology Education students who had taken the Embryology course. This selection was made so that the participants could evaluate and compare the developed media with the media previously used in the Embryology course, including the integration of mathematical thinking within the developed media.

The research instrument is a validity test sheet to collect data related to the validity of augmented reality media that integrates mathematical thinking into gametogenesis learning, based on the assessment of material experts and media experts. The validity instrument was developed by referring to Sari et al. (2022) with the aspects assessed being content, language, presentation, and graphics. Another instrument is a practicality test sheet to collect data on the results of practicality assessments from potential users. The practicality test instrument was developed by referring to Munir et al. (2022) with the aspects assessed being media design, ease of use of the media, and benefits of using the media. scores for validity and practicality using a Likert scale of 1-5.

The type of data in this study is qualitative data in the form of suggestions and input from validators regarding the augmented reality media that integrates mathematical thinking into gametogenesis learning. Other types of data are quantitative data obtained from the scores of the validator (expert) and prospective student user assessment results. The score data from the validator (expert) assessment results were obtained at the validity test stage, and the score data from the assessment results and prospective student users were obtained at the practicality test stage. Quantitative data were analyzed using descriptive statistics by calculating the percentage of validity (V) and practicality (P) using the Formulas 1 and 2.

$$V = (\Sigma x / N) \text{ ……………Formula 1}$$
$$P = (\Sigma f / N) \text{ ……………Formula 2}$$

Description:
V = validity score
P = practicality score
Σx = total obtained score
Σf = total obtained score
N = maximum possible score.

The criteria for validity and practicality followed Aka et al. (2018) as shown in Tables 2 and 3. Results will be adjusted according to the criteria of media validity. Media is said to be valid if it fulfills the criteria of validity presented in Table 2. The practicality category can be seen in Table 3. Media is declared valid or practical if the average score ≥ 4.00 (Valid/Practical category).

Table 2 Validity criteria

No	Mark	Criteria	Validity level description
1	X = 5	Very valid	The product can be continued without revision.
2	4 ≥ X < 5	Valid	The product can be continued by adding something that is missing, taking certain considerations into account, the additions made are not too large, and are not fundamental.
3	3 ≥ X < 4	Quite valid	The product cannot be continued by adding something that is lacking in moderate amounts and taking certain considerations into account.
4	2 ≥ X < 3	Invalid	Major revision by carefully re-examining and looking for product weaknesses to improve.
5	1 ≥ X < 2	Invalid	Total and fundamental revision of the product content is required and requires further consultation.

(Source: Aka et al., 2018)

Table 3 Practicality criteria

No	Mark	Criteria
1	X = 5	Very practical
2	4 ≥ X < 5	Practical
3	3 ≥ X < 4	Quite practical
4	2 ≥ X < 3	Less practical
5	1 ≥ X < 2	Not practical

(Source: Aka et al., 2018)

C. Results and discussion

The design process resulted in an initial design for gametogenesis augmented reality media integrated with mathematical thinking. Furthermore, during the development stage, this design was used as a reference for developing augmented reality media. The media contains spermatogenesis material. The media was also developed interactively. Users can select additional information from the media and can return to the initial media display interactively. The media was also developed by integrating numeracy literacy indicators based on Association of American Colleges and Universities (2009), namely Interpretation, representation, calculation, application, analysis, and communication. The appearance of several sample media pages can be seen in Figure 2.

In the post-development stage, an evaluation was conducted in the form of a validity test and a practicality test of the augmented reality gametogenesis media. Validation was carried out by three experts, including a multimedia expert, a material expert, and a language expert. The material expert validator assessed the media content aspect, the media expert validator assessed the media presentation and graphics, and the language expert validator assessed the language aspect. Validation was carried out in two stages, namely stage I validation and stage II validation, which was carried out after revisions based on the results of stage I validation. The results of the media validity are presented in Table 4. During the validation process, several suggestions for improvement were provided by the validators, which were then used as the basis for revising the product. The details of the validators' feedback and the corresponding improvements made at the validation stage are presented in Table 5.

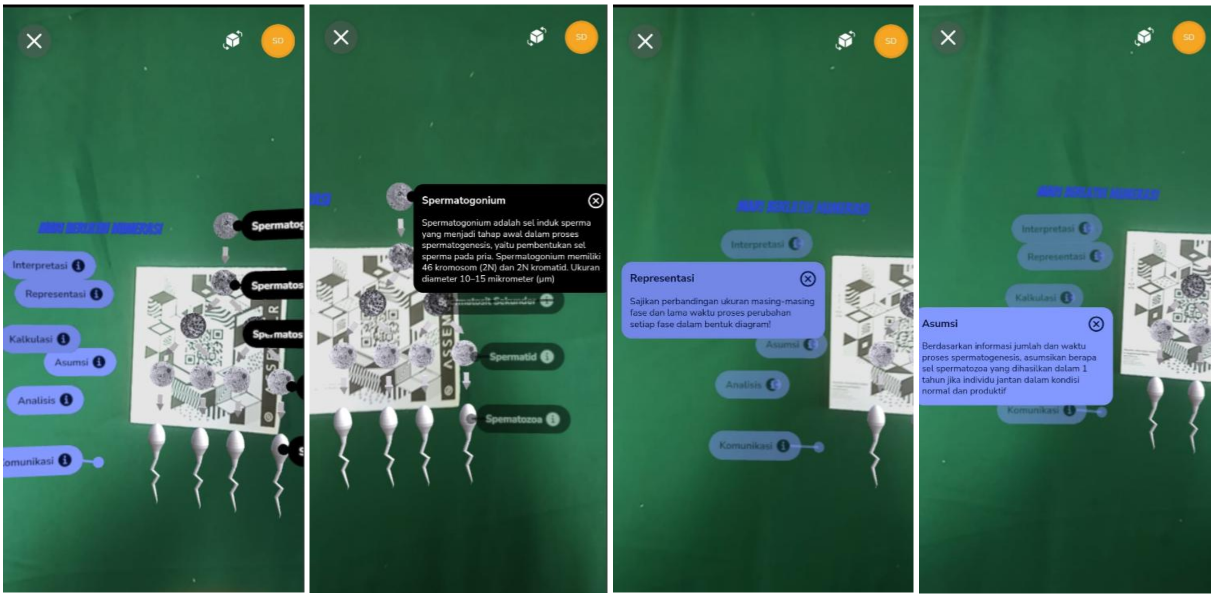

Figure 2 Augmented reality media display of gametogenesis (in Indonesian)

Table 4 Validity results of augmented reality gametogenesis media

Aspect	Assessment items	Validation I		Validation II	
		Score	Final value and criteria per aspect	Score	Final value and criteria per aspect
Contents	Conformity to learning objectives and materials	4	3.5 (Quite valid)	5	5 (Very valid)
	The suitability of AR media for mathematical thinking	3		5	
Language	Language suitability for student development level	3	3.75 (Quite valid)	5	4.67 (Valid)
	Clarity of information conveyed	4		4	
	The language used is Coherent	3		5	
Presentation	The order of presentation is as per	4	3.67 (Quite valid)	5	5 (Very valid)
	Presentation brings up interaction with users	4		5	
	The information presented is complete	3		5	
Graphic	Layout according to	4	4 (Valid)	5	5 (Very valid)
	Suitability of type and size				
	Animations, illustrations, and images are appropriate	4		5	

Table 5 Suggestions from the validator and improvements made at the validation stage

Aspect	Advice from the validator	Improvements made
Contents	1) Distinguish the shape of the nucleolus in each phase of spermatogenesis.	1) The image of the nucleolus is made more specific so that the differences in each phase are clearly visible.
	2) Add time information description.	2) Time information is added for each phase.
	3) Numeracy literacy training questions on representation indicators should not only be in tabular form.	3) Adjustments to the representation indicator exercise by creating instructions to present data in the form of diagrams.
Language	4) The language is more tailored to undergraduate-level education.	4) Language adjustments, especially for the use of terms.
	5) Language should relate between phases.	5) The relationship between information, especially language, between phases in the spermatogenesis process.
	6) Simplify text display.	6) The text display is simpler, so it is easier to read.
Presentation	7) The buttons of each indicator should be made more interactive.	7) The button for each numeracy literacy indicator menu is made more interactive by simply displaying the indicator text, and can be touched to bring up practice questions.
	8) Clarify information about each stage of spermatogenesis.	8) Provides information on each stage of spermatogenesis.
Graphic	9) The size of the information button can be reduced.	9) Adjust the size of the information button.
	10) The 3D shape of the sperm animation can be made clearer.	10) Improving the 3D shape of spermatozoa.

The validity aspect of media content increased significantly after revision from 3.5 to 5. This shows that media content has been customized more precisely with course learning outcomes (CLO) and sub-course learning outcomes (sub-CLO). Research results Musliadi (2022) show that AR media contains detailed, coherent, and curriculum-based concepts that have a positive effect on understanding conceptual. This supports our findings that additional information time and form nucleolus, making the media more representative. This is also supported by Aripin and Suryaningsih (2019) in the development of AR Biology media. Conclude that the validity of content is greatly influenced by clarity, 3D visual narrative, and integration. This visualization, in the context of gametogenesis learning, can significantly help overcome biological abstraction.

The developed gametogenesis learning media aims to improve the quality of mathematical thinking exercises by strengthening students' abilities to represent, analyze, and interpret biological data quantitatively. One key improvement is found in the representation indicator. Previously, students were only required to create graphs based on data already presented in tabular form. In the new version, the exercises have been enhanced to include tasks that require students to generate their own comparative visualizations of the size of each spermatogenesis phase and the duration of each stage. This modification encourages deeper engagement with data and fosters students' ability to construct representations from raw or contextual information. Another improvement is made to the assumption indicator. Earlier exercises focused only on numerical analysis without involving prediction using quantitative data. The revised version now includes predictive tasks, such as estimating the number of spermatogonia cells produced in one year based on calculated division rates and biological variables. This enhancement trains students to formulate assumptions grounded in data and to make reasoned quantitative predictions, thereby strengthening both analytical reasoning and the integration of mathematical thinking within the biological learning context.

The increase in the language score from 3.75 to 4.67 reflects improved readability and coherence. Language in learning media must be tailored to students' cognitive development and free from interpretation bias. Yusa et al. (2024) emphasized the importance of clear sentence structure in AR media due to limited duration and visual space. Short, concise, yet scientific language increases students' focus on essential content, thus helping them understand the material.

Validation assessments for the media presentation aspect increased dramatically to a highly valid level. This aligns with the explanations of Mustaqim (2016) and Pasaribu et al. (2024) who stated that presenting material through interactive elements in AR increases attention and information retention, thus aiding comprehension. Structured visualizations and the use of navigation buttons play a significant role in avoiding cognitive overload.

The graphical aspect showed consistency and improvement from valid to very valid after revision of the 3D form and button adjustments Aini & Zulfadewina (2024) and Oktaviani et al. (2020) proved that the quality of graphics and images in AR significantly influenced students' learning interest. Spatial visualization and the ability to interact with AR objects improved students' spatial understanding and visual logic.

Table 6 Results of practicality test augmented reality gametogenesis media

No	Aspect	Final score	Criteria
1	Media design	4.64	Practical
2	Ease of use of media	4.68	Practical
3	Benefits of using media	4.75	Practical

The media design aspect obtained a score of 4.64 (see Table 6). This indicates that the media design has met the criteria for integration between interface appearance, content structure, and visual appeal. Research by Olim et al. (2024) shows that AR media design that combines dynamic illustrations, narrative flow, and visual icons increases efficiency and interest in learning. In this AR media, intuitive interface features have been shown to support flexible learning flows.

The ease-of-use aspect received a high score (4.68), indicating that students can use the media without technical barriers or difficulty understanding navigation. Mobile-based learning media with a simple interface design is more easily accepted by students than desktop media (Daeng et al., 2017; Maknuni, 2020; Sipayung & Munawaroh, 2025). The principle of user-centered design is essential in creating interactive media. Aripin and Suryaningsih (2019) also explained that the ease of access and operation of AR-based educational media directly contributes to independent learning that can be accessed anytime and anywhere.

The benefit aspect of use obtained the highest score (4.75), indicating that media use contributes significantly to conceptual understanding and active engagement in learning. The results of research by Cahyana et al. (2023); Erviani et al. (2024); and Nafian (2024) showed that students who used AR media showed an increase in numeracy literacy scores and retention of biological concepts compared to the control group. This supports that this media is not only visually appealing but also pedagogically meaningful. Ghifari et al. (2025) also proved that the benefits of learning using AR media can improve critical thinking skills, especially in analyzing dynamic biological processes such as gametogenesis.

This research presents a significant novelty by integrating augmented reality (AR), numeracy literacy, and embryology learning into a unified pedagogical framework. Previous studies on AR in biology education have mostly focused on visualization and conceptual understanding without embedding analytical or quantitative reasoning (Aripin & Suryaningsih, 2019; Musliadi, 2022; Mustaqim, 2016). Meanwhile, numeracy literacy has been recognized as a key 21st-century skill but remains underrepresented in biology education contexts (Klug et al., 2017; Nel, 2020; OECD, 2023).

The development of AR media that integrates gametogenesis content with mathematical interpretation demonstrates innovation not only in visualizing biological processes but also in strengthening students' data analysis and reasoning abilities. This integration enables students to interpret biological phenomena quantitatively, thereby enhancing conceptual and numeracy literacy simultaneously (Cahyana et al., 2023; Erviani et al., 2024; Ghifari et al., 2025).

The implications for future biology education and digital learning innovation are extensive. First, this approach promotes a shift from conceptual learning toward data-driven biology education, training preservice biology teachers to analyze, interpret, and communicate quantitative information (Olim et al., 2024; Pasaribu et al., 2024). Second, AR-numeracy-based modules can support adaptive learning experiences that are analytical, personalized, and interactive. Third, from a curricular perspective, this model offers a practical framework to strengthen numeracy literacy in biological contexts, a domain still identified as weak in teacher training programs (Aini & Zulfadewina, 2024; Sipayung & Munawaroh, 2025). Future collaborations among experts in biology, mathematics, and educational technology are essential to extend this AR–numeracy integration to broader biological topics such as cell biology, genetics, and ecology, aligning with the demands of digital transformation and Education 5.0 (Maknuni, 2020; Prasetya et al., 2024).

D. Conclusion

This study concludes that the augmented reality (AR) gametogenesis media integrated with mathematical thinking demonstrates high validity and practicality. Expert validation confirmed that the content, language, and graphics effectively support learning objectives, while student testing showed the media to be user-friendly and pedagogically useful. The integration of numerical reasoning tasks into visual 3D gametogenesis simulations represents a novel approach to fostering numeracy literacy within biology education. Next steps following the validation and practicality tests of the AR Gametogenesis media integrated with mathematical thinking are the implementation and evaluation stages. In the implementation stage, the validated and practical media will be applied in real classroom settings involving Biology Education students who are currently taking the Embryology course. The evaluation stage will be conducted in two forms: formative and summative evaluation. Future research may extend this development to other cellular or physiological topics to strengthen students' quantitative literacy and digital learning competence.

E. References

Aini, D. N., & Zulfadewina, Z. (2024). Pengaruh penggunaan media pembelajaran berbasis AR (augmented reality) terhadap hasil belajar IPA materi siklus air siswa kelas V di SDN Ciracas 01 Pagi. *Jurnal Manajemen Pendidikan dan Ilmu Sosial (JMPIS)*, *5*(5), 1721–1730. DOI: https://doi.org/10.38035/jmpis.v5i5.2486

Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review*, *20*, 1–11. DOI: https://doi.org/10.1016/j.edurev.2016.11.002

Aripin, I., & Suryaningsih, Y. (2019). Pengembangan Media pembelajaran biologi menggunakan teknologi augmented reality (AR) berbasis android pada konsep sistem saraf. *Sainsmat: Jurnal Ilmiah Ilmu Pengetahuan Alam*, *8*(2), 47-57. DOI: https://doi.org/10.35580/sainsmat82107192019

Arsyad, M., Lestari, S. R., Sari, M. S., & Rohman, F. (2023). Construction of structural correlation of quantitative literacy and critical thinking, and factors affecting them in students of pre-service biology teachers. *Eurasia Journal of Mathematics, Science and Technology Education*, *19*(10), 1–15. DOI: https://doi.org/10.29333/ejmste/13651

Arsyad, M., & Wardani, I. (2025). Validity and practicality of integrated interactive digital timeline infographic learning media for mathematical thinking on the concept of metamorphosis. *Practice of The Science of Teaching Journal: Jurnal Praktisi Pendidikan*, *4*(1), 18–27. DOI: https://doi.org/10.58362/hafecspost.v4i1.119

Association of American Colleges and Universities. (2009). Value rubrics. *Multi-State Collaborative to Advance Learning Outcomes Assessment*, 1–32. Retrieved from http://www.aacu.org/value

Azzahra, W., Diana, S., Nuraeni, E., Yusni, D., & Andriyatno, I. (2024). Integration of augmented reality (AR) in biology education: A systematic literature review. *The Eurasia Proceedings of Educational and Social Sciences*, *34,* 61–70. DOI: https://doi.org/10.55549/epess.792

Billinghurst, M., Clark, A., & Lee, G. (2014). A survey of augmented reality. *Foundations and Trends in Human-Computer Interaction*, *8*(2–3), 73–272. DOI: https://doi.org/10.1561/1100000049

Cahyana, U., Roland, J., Luhukay, L., Lestari, I., Irwanto, I., & Suroso, J. S. (2023). Improving students' literacy and numeracy using mobile game-based learning with augmented reality in chemistry and biology. *Internastional Journal of Interactive Mobile Technologies*, *17*(16), 4–15. DOI: https://doi.org/10.3991/ijim.v17i16.42377

Daeng, I. T. M., Mewengkang, N.., & Kalesaran, E. R. (2017). Penggunaan smartphone dalam menunjang aktivitas perkuliahan oleh mahasiswa Fispol Unsrat Manado. *Acta Diurna*, *6*(1), 1–15. Retrieved from https://ejournal.unsrat.ac.id/v3/index.php/actadiurnakomunikasi/article/view/15482

Erviani, E., Putri, A. D., Agustiani, R., Zahra, A., & Faisal, M. (2024). Numeracy literacy ability in three - dimensional topic learning design using augmented reality. *Jurnal Pendidikan Matematika RAFA*, *10*(1), 46–64. DOI: https://doi.org/10.19109/jpmrafa.v10i1.22014

Fauzi, A., & Fadilah, M. (2024). Literatur review: Implementasi literasi numerasi pada pembelajaran biologi di SMA. *Biodik*, *10*(2), 132–137. DOI: https://doi.org/10.22437/biodik.v10i2.33802

Frith, V., & Lloyd, P. (2016). Investigating proportional reasoning in a university quantitative literacy course. *Numeracy*, *9*(1), 3. DOI: http://dx.doi.org/10.5038/1936-4660.9.1.3

Ghifari, Y., Rienovita, E., & Amelia, D. (2025). Penggunaan augmented reality untuk meningkatkan kemampuan berpikir kritis dalam pelajaran IPA. *Jurnal Education and Development*, *13*(1), 28–36. DOI: https://doi.org/10.37081/ed.v13i1.6459

Ibáñez, M. B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education*, *123*, 109-123. DOI: https://doi.org/10.1016/j.compedu.2018.05.002

Klug, J. L., Carey, C. C., Richardson, D. C., & Gougis, R. D. (2017). Analysis of high-frequency and long-term data in undergraduate ecology classes improves quantitative literacy. *Ecosphere*, *8*(3), e01733. DOI: https://doi.org/10.1002/ecs2.1733

Lee-Post, A. (2019). Developing numeracy and problem-solving skills by overcoming learning bottlenecks. *Journal of Applied Research in Higher Education*, *11*(3), 398–414. DOI: https://doi.org/10.1108/JARHE-03-2018-0049

Lee, W. W., & Owens, D. L. (2004). *Multimedia-based instructional design* (2nd ed.). Pfeiffer An Imprint of Wiley.

Maknuni, J. (2020). Pengaruh media belajar smartphone terhadap belajar siswa di era pandemi covid-19. *Indonesian Educational Administration and Leadership Journal*, *2*(2), 94–106. DOI: https://doi.org/10.22437/ideal.v2i2.10465

Mason, J., Burton, L., & Stacey, K. (2010). Thinking mathematically. In *Pearson Education Limited* (2nd ed.). Pearson Education Limited.

Munir, N. P., Anas, A., Suryani, L., & Munir, F. S. (2022). The practicality of geometry learning media based on augmented reality praktikalitas media pembelajaran bangun ruang sisi datar berbasis augmented reality. *Al-Khwarizmi: Jurnal Pendidikan Matematika dan Ilmu Pengetahuan Alam*, *10*(1), 75–84. DOI: https://doi.org/10.24256/jpmipa.v10i1.2241

Musliadi, M. (2022). Pengembangan media berbasis augmented reality (AR) pada pembelajaran biologi kelas XI SMA Negeri 13 Pangkep. *UNM Journal of Biological Education*, *5*(2), 83-93. DOI: https://

doi.org/10.35580/ujbe.v5i2.34184

Mustaqim, I. (2016). Pemanfaatan augmented reality sebagai media pembelajaran. *Jurnal Pendidikan Teknologi dan Kejuruan*, *13*(2), 174–183. DOI: https://doi.org/10.23887/jptk-undiksha.v13i2.8525

Nafian, M. I. (2024). Development of augmented reality media to grow numerical literacy of elementary school students. *International Journal of Educatio Elementaria and Psychologia*, *1*(3), 125–134. DOI: https://doi.org/10.70177/ijeep.v1i3.947

Nel, B. P. (2020). Implications of the quantitative literacies test results of the national benchmark test project (NBTP) for teachers. *South African Journal of Education*, *40*(1), 1–8. DOI: https://doi.org/10.15700/saje.v40n1a1792

Nuraeni, E., Soesilawaty, S., Permana, I., & Rahmania, S. (2020). Students' biological-mathematical attitude in quantitative literacy-based learning on the topic of ecosystem. In *Proceedings of the 7th Mathematics, Science, and Computer Science Education International Seminar, MSCEIS* (Vol. 12). DOI: https://doi.org/10.4108/eai.12-10-2019.2296319

OECD. (2023). PISA 2022 results (Volume I): The state of learning and equity in education. In *PISA, OECD Publishing*. DOI: https://doi.org/10.22201/iisue.24486167e.2024.183.61714

Oktaviani, Y., Lusa, H., & Noperman, F. (2020). Pengaruh augmented reality sebagai media pembelajaran terhadap minat belajar siswa mata pelajaran IPA SD Kota Bengkulu. *JURIDIKDAS: Jurnal Riset Pendidikan Dasar*, *2*(3), 202–208. DOI: https://doi.org/10.33369/juridikdas.2.3.202-208

Olim, S. C., Nisi, V., & Romão, T. (2024). Augmented reality interactive experiences for multi-level chemistry understanding. *International Journal of Child-Computer Interaction*, *42*, 100681. DOI: https://doi.org/10.1016/j.ijcci.2024.100681

Paidi, P., Subali, B., & Handoyo, L. D. (2021). The mastery of technological, pedagogical, and content knowledge among indonesian biology teachers. *European Journal of Educational Research*, *10*(3), 1063-1073. DOI: https://doi.org/10.12973/eu-jer.10.3.1063

Pasaribu, R. S., Husna, A., & Hanggara, Y. (2024). The Impact of augmented reality media integrated with ethnomathematics on students' numeracy literacy skills. *Jurnal Cahaya Pendidikan*, *10*(2), 133–144. DOI: https://doi.org/10.33373/chypend.v10i2.6312

Prasetya, F., Fortuna, A., Samala, A. D., Rawas, S., Mystakidis, S., Syahril, Waskito, Primawati, Wulansari, R. E., & Kassymova, G. K. (2024). The impact of augmented reality learning experiences based on the motivational design model: A meta-analysis. *Social Sciences and Humanities Open*, *10*(February), 100926. DOI: https://doi.org/10.1016/j.ssaho.2024.100926

Rahayu, D. A., Junaidin, Fakhrudin, A., Mutiah, C., Mardikawati, B., & Rachman, R. S. (2024). Analisis penerapan teknologi augmented reality (AR) dalam pembelajaran di perguruan tinggi. *Jurnal Review Pendidikan dan Pengajaran*, *7*(3), 11995–12001. DOI: https://doi.org/10.31004/jrpp.v7i3.33261

Rahmi, F., & Guspatni, G. (2024). Augmented reality sebagai inovasi teknologi dalam pengajaran kimia di tingkat universitas: Tinjauan literatur. *Jurnal Pendidikan Tambusai*, *8*(3), 43657–43662. DOI: https://doi.org/10.31004/jptam.v8i3.20833

Sari, D. R., Yamtinah, S., Ariani, S. R. D., Saputro, S., Susanti V. H. E., & Shidiq, A. S. (2022). Augmented reality media validity based on tetrahedral chemical representation with Aiken Validation Index. *Jurnal Penelitian Pendidikan IPA*, *8*(6), 3139–3145. DOI: https://doi.org/10.29303/jppipa.v8i6.2333

Sipayung, J., & Munawaroh, M. (2025). Peran teknologi smartphone sebagai media pembelajaran interaktif bagi mahasiswa di era digital. *Trending: Jurnal Ekonomi, Akuntansi dan Manajemen*, *3*(1), 167–176. DOI: https://doi.org/10.30640/trending.v3i1.3662

Speth, E. B., Momsen, J. L., Moyerbrailean, G. A., Ebert-may, D., Long, T. M., Wyse, S., & Linton, D. (2010). 1, 2, 3, 4: infusing quantitative literacy into introductory biology. *CBE—Life Sciences Education*, *9*(3), 323-332. DOI: https://doi.org/10.1187/cbe.10

Yapici, I. Ü., & Karakoyun, F. (2021). Using augmented reality in biology teaching. *Malaysian Online Journal of Educational Technology*, *9*(3), 40–51. DOI: https://doi.org/10.52380/mojet.2021.9.3.286

Yilmaz, O. (2021). Augmented reality in science education: An application in higher education. *Shanlax International Journal of Education*, *9*(3), 136–148. DOI: https://doi.org/10.34293/education.v9i3.3907

Yusa, I. W., Suwasono, P., Wulandari, A. Y. R., Tamam, B., Rosidi, I., Yasir, M., & Setiawan, A. Y. B. (2024). Pengembangan media pembelajaran berbasis augmented reality (AR) pada materi interaksi makhluk hidup dan lingkungan. *Jurnal MIPA dan Pembelajarannya*, *4*(3), 1–12. DOI: https://doi.org/10.17977/um067.v4.i3.2024.1