

Development of Augmented Reality-Based Biology Learning Tools to Support Deep Learning and Digital Literacy Skills in the Context of Education for Sustainable Development

¹Ilyas H. Husain, ²Herinda Mardin

^{1,2} Department of Biology, Faculty of Mathematics and Natural Science, Universitas Negeri Gorontalo, Gorontalo, Indonesia

Corresponding Author Contact: herindamardin@unq.ac.id

Abstract

This study aimed to develop an Augmented Reality-based biology learning tool using a Deep Learning approach to enhance high school students' digital literacy skills. The development of this learning tool also supports more meaningful and contextual biology learning, in line with the principles of Education for Sustainable Development (ESD), which emphasize the integration of knowledge, technology, and real-world relevance. This research employed the ADDIE research and development model, consisting of Analyze, Design, Develop, Implement, and Evaluate. The participants included one teacher as the instructor in a limited trial, 35 students for response and formative assessment, two experts for validation, and two practitioners. The research instruments consisted of validation sheets, an observation sheet for learning implementation, student and teacher response questionnaires, and a test to measure digital literacy skills. Data were analyzed using validation percentages, Rasch modeling with the Winstep application, and a t-test using SPSS version 26. The results showed that the developed AR-based biology learning tools on the excretory system material were categorized as highly valid and highly practical. The pretest and post-test results yielded an N-gain score of 0.37, categorized as moderate. These findings indicate that the developed learning tools are valid, practical, and effective in improving students' digital literacy skills while supporting engaging and contextual biology learning.

Keywords: Augmented Reality; Biology Learning Tools; Deep Learning; Digital Literacy, ESD

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*Corresponding Author: herindamardin@unq.ac.id

Introduction

Changes in education policy in Asta Cita support the implementation of deep learning, coding, and artificial intelligence/AR. This principle needs to be applied in all subjects, including biology. Biology learning faces various challenges. Some biology topics are considered difficult by students due to their high complexity ([Hadiprayitno G, et. al., 2019](#)), the large number of scientific terms, and the limited visualization of concepts ([Pavlopoulos GA, et. al., 2008](#); [Katari MS, et. al., 2010](#); [Tibell LAE, et al., 2017](#)). Externally, uninteresting and unengaging learning, a lack of visual media, and an inadequate learning environment are obstacles to the learning process ([Sundawiyani K., et al., 2022](#); [Sinaga C et al., 2022](#); [Busa, E. N., 2023](#)). It is also difficult to connect biological concepts in their entirety ([Diki D., 2013](#); [Mardin H, et al., 2017](#)). In online learning, obstacles include limited visual facilities and difficulty in understanding abstract material ([Thompson M. et al., 2020](#); [Rice M., et al., 2022](#)). Misconceptions occur in the biology learning process ([Soeharto, 2019](#); [Chen C., et. al., 2020](#); [Pulukuri S, et. al., 2020](#); [Soeharto, et. al., 2021](#)). The lack of interesting and enjoyable media is one of the obstacles to effective learning ([Yusuf FM, et. al., 2023](#)). The use of textbooks without visual technology ([Ruiz GJR, et. al., 2019](#)) makes contextual and exploratory learning experiences less than optimal.

To overcome these difficulties, the use of AR-based learning tools is a relevant solution ([Yusuf FM., et.al., 2022](#); [Mardin H. 2024](#)). Theoretically, the integration of AR in learning tools makes learning more interesting and multimodal through 3D visualization and digital interaction, thereby helping to

explain abstract biological concepts ([Hsu HP., et.al., 2023](#)). This approach supports deep learning and is capable of developing abstract thinking and digital literacy skills ([Ibáñez MB, et. al., 2018](#); [Hashim H, et.al., 2023](#)).

The integration of AR in learning tools is considered capable of training digital literacy skills. Digital literacy is the ability to obtain, understand, and use information from various digital sources ([Pratama WA, et. al., 2019](#); [Naufal HA, 2021](#); [Nugraha D. 2022](#)). Digital literacy skills have four indicators: 1) the ability to search the internet, 2) the ability to use hypertext navigation, 3) the ability to assemble knowledge, and 4) the ability to evaluate information content.

A preliminary study of students' digital literacy skills revealed that these skills are still relatively low. The average score was 2.3 based on the indicator of the ability to evaluate information content (2.1), while the ability to search the internet was 2.4. These data indicate that students experience difficulties and are not yet able to filter digital information. Given the importance of these skills, various studies show that the development of learning tools using AR is effective in developing digital literacy and independent learning skills ([Suherman A., et.al., 2020](#)) because AR helps students understand abstract content while developing digital skills ([Pujiastuti H, et. al., 2023](#); [Mardin H, et. al., 2022](#)). AR-based worksheets in learning make it easier for students to explore and classify plants more effectively ([Zhang J. et. al. 2020](#)).

The problem-solving approach in this study is directed at developing AR-based learning tools that support the application of deep learning to train the digital literacy skills of high school students. This model is considered to be able to overcome various obstacles in biology learning. Students' digital literacy skills can be seen from several measurable indicators, including the ability to search the internet; the ability to use hypertext navigation; the ability to assemble knowledge; and the ability to evaluate information content ([Nusantari, E., et al., 2023](#); [Mardin, H., et al., 2024](#); [Damiti, F., et al., 2025](#)).

Problems in biology learning include abstract concepts that are difficult for students to understand, learning that is less interesting and in-depth (deep learning is not maximized), mostly dominated by lectures, and the lack of use of interesting and visual learning media. Therefore, the solution is to develop learning tools with AR and to create an in-depth learning experience that trains students' digital literacy skills. Thus, the problem-solving approach in this study emphasizes: 1) the development of AR-based learning tools, 2) the use of AR technology to present abstract concepts visually and attractively, 3) training digital literacy skills through the deep learning process, and 4) testing the validity and practicality of the product.

Augmented Reality (AR) has been used in recent years to increase motivation, visualize abstract concepts, and enhance student learning experiences, particularly in visual biology lessons ([Vari Y, et.al., 2021](#); [Anam RS., et.al., 2024](#); [Tomboo CI., et al., 2024](#)). AR can improve understanding of abstract concepts through 3D visualization and digital interaction, as well as significantly increase student motivation and engagement in learning ([Badia VP., et al., 2024](#); [Faria A., et al., 2024](#)).

The application of deep learning in learning tools involves the stages of exploration, idea reconstruction, concept application, and reflection. Biology learning tools that use AR can create an enjoyable learning experience and support the development of conceptual, abstract, and problem-solving thinking ([Kyza, 2019](#); [Samat C., et al., 2019](#)). This orientation is also relevant to the principles of Education for Sustainable Development (ESD), which encourage meaningful, contextual, and responsible learning. In biology education, such an approach helps students connect scientific understanding with health, well-being, and informed decision-making in everyday life. In this sense, AR-based learning tools do not only support conceptual understanding and digital literacy skills, but also contribute to more meaningful and contextual learning experiences. However, most studies are still limited to the use of AR in learning tools that support the application of deep learning specifically to biological concepts that emphasize visual and digital literacy skills.

Therefore, the novelty of this research is: 1) AR and deep learning in one learning tool, 2) Applying it specifically to biology, which is full of abstract and difficult-to-visualize concepts, 3) Training digital literacy skills simultaneously, and 4) Supporting deep learning through visual, exploratory, algorithmic, meaningful, enjoyable, and reflective learning, with the potential to foster more contextual learning in line with ESD principles.

Method

This study follows the ADDIE research and development model, namely Analyze, Design, Develop, Implement, and Evaluate ([Branch RM. 2010](#)).

1. Analyze stage, (a) performance analysis: includes students' initial digital literacy skills, cognitive and non-cognitive diagnostic tests, and learning motivation. (b) Needs analysis: covering the independent learning-based curriculum, student needs related to the use of technology, learning outcomes, learning objectives, the scope of abstract and visual biology material, and related digital literacy and technology-based learning media. This stage also considered the need to design learning experiences that are meaningful, contextual, and relevant to students' real-life understanding, in line with the broader orientation of Education for Sustainable Development (ESD).
2. Design Stage, this stage begins with an analysis of learning outcomes, the determination of biology material, and the formulation of learning objectives that are incorporated into learning tools, namely teaching modules and learning modules, the design of teaching modules and learning modules based on Augmented Reality, student worksheets, the preparation of digital literacy tests, the design of AR Application Storyboards, and the design process continues with the creation of AR-based learning media tools. The learning tools were designed not only to support deep learning and digital literacy skills, but also to encourage more meaningful and contextual biology learning experiences.
3. Development Stage, this stage involves validation by 1 media expert, 1 biology expert, and 2 practitioners, followed by formative assessment. Digital literacy skills are measured to determine the effectiveness of AR-based learning tools in training students' digital literacy skills. At this stage, the developed product was refined to ensure that the learning tools were pedagogically appropriate, visually engaging, and supportive of meaningful student learning.
4. Implementation Stage, the development results are implemented on a broader scale in several schools. The AR-based learning tools were implemented for 10th grade high school students. The implementation process was supported by other tools that had been developed and met the criteria of validity and practicality, but this study was limited to a limited trial that was not implemented on a large scale.
5. Evaluation Stage, the results of the trial will then be analyzed as a reference for improving the product in the revision stage. The final product of this research is an AR-based learning tool that has been validated by subject matter experts, media experts, and field practitioners, and tested for its practicality in learning, so that it can be used as a tool and medium to support the quality of biology learning in high schools. This evaluation stage is carried out at each step of the ADDIE process.

The research location is State Senior High School 1 Tibawa, Gorontalo Regency. This study used 1 teacher as an instructor in limited trials, 35 students for formative response and assessment, and 2 experts for validation, namely subject matter experts and learning experts, as well as 2 practitioners. The research instruments included a learning tool validation sheet, an observation sheet for the implementation of AR-based learning tools, a learning implementation questionnaire, a student response questionnaire, a teacher response questionnaire, and a test to measure digital literacy skills. Data analysis included calculating the percentage of expert and practitioner validation, Rasch modeling

for instrument validity using the Winstep application, Cohen's d effect size, and t-tests using SPSS version 26 software to determine the significant changes in students' digital literacy skills before and after learning.

Research Results and Discussion

Research Results

Based on the research results, the validation percentages for the modules and learning media are presented in Tables 1 and 2 below.

Table 1. Percentage of Validation of Media Expert Learning Modules

Assessment Aspect	Validator Score	Maximum Score	Presentage	Criteria
Cover Design	10	10	100%	Very Valid
Teks Massage Design	27	30	90%	Very Valid
Figure Massage Design	8	10	80%	Valid
Module Organization Design	14	15	93%	Very Valid
Language	16	20	80%	Valid
Average	15	17	89%	Very Valid

Based on Table 1 above regarding the validation of learning modules by media expert validators, it shows that the validation of modules is “highly valid” with a percentage of 100% for the cover design assessment aspect, 90% for the text message design aspect, 80% for the image message design aspect, 93% for the module organization design aspect, and 80% for the linguistic aspect.

Table 2. Percentage of Validation of Learning Modules by Subject Matter Experts

Assessment Aspect	Validator Score	Maximum Score	Presentage	Criteria
Content Suitability	13	15	87%	Very Valid
Presentation Components	10	10	100%	Very Valid
Language Assessment	20	20	100%	Very Valid
PBL-Based Module (Problem-Based Learning)	10	10	100%	Very Valid
Average	13.25	13.75	97%	Very Valid

Based on Table 2 above regarding the validation of learning modules by subject matter experts, it shows that the validation of modules is “highly valid” with a percentage of 87% for content feasibility, 100% for presentation components, 100% for language assessment, and 97% for PBL (Problem Based Learning) based modules. Based on the research results, the validation percentages for the learning media are presented in Tables 3 and 4 below.

Table 3. Percentage of Learning Media Validation by Media Experts

Assessment Aspect	Validator Score	Maximum Score	Presentage	Criteria
Cover Design	10	10	100%	Very Valid
Teks Massage Design	27	30	90%	Very Valid
Figure Massage Design	8	10	80%	Valid
Module Organization Design	14	15	93%	Very Valid
Language	16	20	80%	Valid
Average	15	17	89%	Very Valid

Table 3 above, related to the validation of learning media by media expert validators, shows that the percentage of learning media that meets the “highly valid” criteria is 100% for the cover design aspect, 90% for the text message design aspect, 80% for the image message design aspect, 93% for the module organization design aspect, and 80% for the linguistic aspect.

Table 4. Percentage of Learning Media Validation by Subject Matter Experts

Assessment Aspect	Validator Score	Maximum Score	Presentage	Criteria
Content Suitability	13	15	87%	Very Valid
Presentation Components	10	10	100%	Very Valid
Language Assessment	28	30	93%	Very Valid
Average	17	18.3	93%	Very Valid

Table 4 above shows the validation of learning media by subject matter experts, indicating that the percentage of learning media that meets the “highly valid” criteria is 87% for content feasibility, 100% for presentation components, and 93% for language assessment. The results of the study on the percentage of responses from students and teachers are presented in Table 5 and 6 below.

Table 5. Percentage of Student Responses

Assessment Aspect	Validator Score	Maximum Score	Presentage	Criteria
Interest	660	720	92%	Very Practice
Material	456	540	92%	Very Practice
Convenience	586	720	81%	Very Practice
Average	567.3	660.0	88%	Very Practice

Table 6. Percentage of Teacher Responses

Assessment Aspect	ΣF_x	N	Presentage	Criteria
Practicality	15	15	100%	Very Practice
Readability	20	20	100%	Very Practice
Benefits	20	20	100%	Very Practice
Average	20	20	100%	Very Practice

The results of the study shown in Table 3 regarding the percentage of student responses that met the “very practical” criteria had an average percentage of 88%, covering the aspects of interest assessment at 92%, material assessment at 92%, and ease of use assessment at 81%. Meanwhile, the research results in Table 4 show the percentage of teacher responses to the “very practical” criterion with a percentage value of 100%, covering the aspects of practicality, readability, and usefulness, each with a score of 100%.

Based on the research results, the implementation of learning is presented in Figure 1 below.

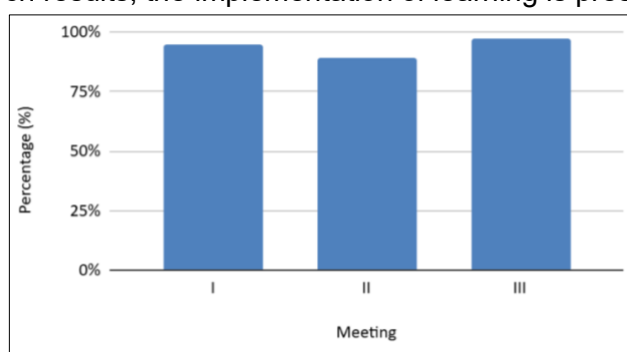


Figure 1. Percentage of Learning Implementation

Figure 1 above shows the percentage of learning implementation, with the results for Meeting I at 85%, Meeting II at 89%, and Meeting III at 97%. Thus, the average percentage of learning implementation is 90.3%. Based on the results of the research on the pretest, posttest, and N-Gain scores for students' digital literacy skills, the results are presented in Table 7 and Figure 2 below.

Table 7. Pretest, Posttest, and N-Gain Scores for Students' Digital Literacy Skills

Class	Pre Test	Post Test	N - Gain Score %
XI - 4	52.03	67.83	47.55
XI - 5	50.16	70.13	57.55
Average	52.03	67.83	0,37

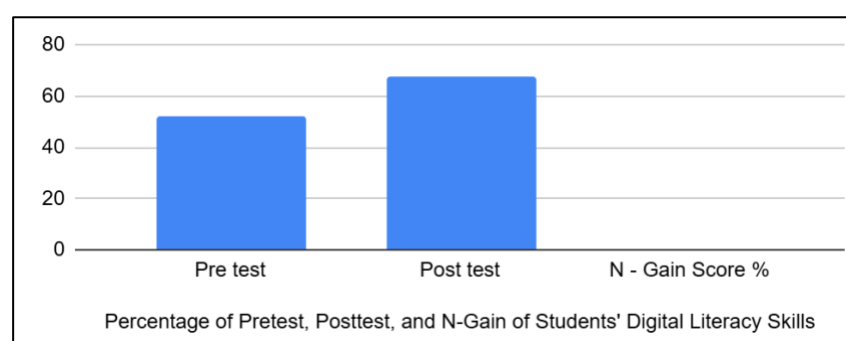


Figure 2. Pretest, Post-test, and N-Gain of Students' Digital Literacy Skills

Table 5 and Figure 2 show the pretest, posttest, and n-gain values for students' digital literacy skills, indicating a difference between the pretest and posttest scores. The average pretest score for students' digital literacy skills was 52.03, while the average posttest score was 67.83, resulting in an n-gain value of 0.37 for students' digital literacy skills, which falls into the "moderate" category.

Discussion

The validation of the learning module shows that the module is "highly valid" with a percentage of 100% for the cover design aspect, 90% for the text message design aspect, 80% for the image message design aspect, 93% for the module organization design aspect, and 80% for the linguistic aspect. Based on the results of the learning module validation by media experts, there are two assessment components for the cover design aspect, namely an appropriate and attractive cover appearance and a cover design that can illustrate the content of the module media. Both components received a percentage of 100% because the cover appearance attracted the reader's interest and was able to illustrate the content of the module. The text message design assessment aspect includes components of color, spacing, and font size suitability; readability; text presentation accuracy; punctuation and symbol accuracy; word choice accuracy; and text color suitability with the background. The text message design aspect received a score of 90% because improvements are still needed in the accuracy of word choice, the accuracy of punctuation and symbol usage, and the suitability of text color to the background. When validated, the learning module still contained inappropriate punctuation and several words that needed to be replaced to make it easier to understand, and the text color needed to be adjusted to the module background so that the text color was not blurred and could be read clearly.

For the module organization design assessment aspect, there were three components assessed, namely the clarity of the module usage instructions; the module's ability to develop students' visual representation skills; and the ease of use of the module. Of these three components, the clarity of the

module usage instructions still needs improvement, such as ambiguous command words in the module usage instructions, which need to be replaced with active verbs that are easier to understand when using the learning module. In addition, there are images in the instructions and the layout of the usage instructions that are ineffective, so they need to be revised and improved to make the module usage instructions more effective and easier for users to understand. The image message design aspect scored 80% because there are still several components that need improvement, such as the suitability of the images to the text message (material) and the suitability of the image layout in the material. The suggestions for improvement for these two components are that the images included in the learning module must be clear, not blurry, with clear and easy-to-read captions that are relevant to the material listed in the module, and the layout of the images must be in accordance with the material and reflect the aesthetics of the module. The language assessment aspect scored 80% because each component of the language aspect still needs improvement, such as using language that is in accordance with Indonesian language rules, interactive communication sentence structures, clarity of language used, and appropriateness in using language in communication with students. These findings indicate that the developed module is not only feasible in terms of technical and visual quality, but also able to support more meaningful learning experiences. In the context of Education for Sustainable Development (ESD), meaningful learning is important because it enables students to connect scientific concepts with real-life understanding and responsible decision-making.

Based on the results of the learning module validation by subject matter experts, the module validation was rated “highly valid” with a percentage of 87% for content feasibility, 100% for presentation components, 100% for language assessment, and 97% for PBL (Problem Based Learning) based modules. There are four assessment aspects, each of which has components that are assessed. For the learning module content feasibility aspect, there are two components that need improvement, namely the completeness, breadth, and depth of the material, as well as the accuracy of concepts and facts, and the accuracy of questions. Although it has been well organized, specifically for material on kidney disorders (diabetes mellitus) and liver disorders (jaundice), it is necessary to focus on the excretory system material. The components in the other assessment aspects are already good and do not need revision, such as the suitability of the learning material with the development of science, the layout and systematics of the module writing are appropriate, the pictures and videos clarify the material in each learning activity, and the practice questions to measure student learning outcomes are appropriate, which are included in the presentation component aspect. The developed module uses standard, clear, and appropriate sentences, the language used in interacting with students is appropriate, and the sequence and coherence of sentences between paragraphs are good, which is included in the language assessment component. The developed module includes learning activities that are integrated with the PBL (Problem Based Learning) stages, and the module develops students' abilities, especially digital literacy skills. PBL-integrated learning modules that emphasize problem-based learning guide students to identify problems, describe problems, analyze problems and provide alternative solutions, make lists of reasons and correct facts to gain a complete understanding of the learning material ([Christiyoda, S., et.al., 2016](#)). PBL-based modules hone critical thinking skills, problem identification, fact gathering, estimation and prediction skills, data and information organization, conclusion making, and problem evaluation ([Wiele, 2010](#); [Karlov & Ley, 2012](#)). This result is also relevant to the broader orientation of ESD, which emphasizes meaningful, contextual, and problem-solving-oriented learning. The integration of PBL and digital literacy in biology learning encourages students not only to understand concepts, but also to develop reflective and responsible ways of thinking when engaging with scientific information and everyday issues.

Validation of AR media by learning media experts shows that the percentage of learning media meets the “highly valid” criteria with a percentage of 100% for the cover design assessment aspect, 90% for the text message design aspect, 80% for the image message design aspect, 93% for the

module organization design aspect, and 80% for the linguistic aspect. From the display design aspect, it is necessary to improve the component of selecting the appropriate font type and size, while from the content design aspect, it is necessary to revise the component of the accuracy of punctuation and symbols as well as text color with the background color. For the AR-based image design aspect, it is necessary to revise the consistency of the use of terms. The expert media validator's suggestion is that the method of using the media should be provided in text form and the learning objectives should be adjusted to the function of the flashcards and additional usage information in the flashcard box. The other components are fine without the need for revision, such as the overall visual design is attractive, the text on the flashcards is clear and easy to read, the consistency of the layout and placement of elements is good, and the quality of the AR markers is easily detected by the camera. In terms of content design, readability, accuracy of text presentation, and accuracy of word choice are good and do not require revision. The design of AR-based images, AR-based image components with text messages are appropriate, AR-based images with text descriptions are appropriate, 3D AR objects are proportionate, and the colors of 3D AR objects are appropriate. From an ESD perspective, the visual and interactive quality of AR media is important because contextual and engaging learning tools can support deeper understanding and help students connect biological knowledge with real-life relevance. Thus, the high validity of the AR media indicates that it can support not only technology-enhanced learning, but also more meaningful and context-rich learning experiences.

Validation of learning media by subject matter experts shows that the percentage of learning media meets the criteria of "highly valid" with a percentage of 87% in terms of content suitability, 100% in terms of presentation components, and 93% in terms of language assessment. Comments or suggestions provided by expert material validators indicate that the flashcards are well-made, but some cards explaining common disorders of the excretory system found in the community need to be added. Overall, the other components in each assessment aspect are good without the need for revision, such as learning materials that are in line with scientific developments, the layout of the material in the learning media is appropriate, the material presented in the learning media is appropriate, the use of sentences is standard, clear and precise, spelling and grammar are appropriate, the use of language in the learning media is appropriate, and AR-based learning media can display attractive and clear images. The high validity of the AR-based learning media also suggests that the content was considered suitable for supporting biology learning in a more accessible and contextual manner. In line with ESD principles, learning media of this kind can help students relate scientific concepts to health, well-being, and informed decision-making, especially when complex content is presented in forms that are easier to explore and understand.

The responses from students and teachers indicate that the criteria are very practical, because the appearance of the learning modules attracts students' attention, the material is presented clearly and is easy to use and accessible to students. Likewise, teachers find the learning modules practical to use, easily accessible, clearly legible, and interesting, as well as beneficial for teachers in teaching, especially material on the excretory system. Teachers have no difficulty explaining the material on the excretory system because they are assisted by AR media. This is also because the AR media accessed using devices is in line with the conditions of students who like to use devices during learning. The benefit of AR, which has a QR code, is that students can study independently anywhere and anytime. [Rachmawati et al. \(2020\)](#) explain that students can strengthen their memory when the responses they get while interacting in learning are good. The motivation that is built makes the learning experience for students so that their responses to learning are good ([Setyoningtyas, N. M. et. al., 2022](#)). The learning module developed based on AR will make it easier for students to understand the material on the excretory system more clearly. The level of practicality can be seen from the ease of use of the teaching materials and media developed, the ease of interpreting the material, time efficiency, the suitability of the material, and an attractive appearance ([Utama, 2022](#); [Anapia, S. et.al., 2024](#)). These practical

findings suggest that the developed learning tools are well received not only because of their usability, but also because they support more engaging and student-centered learning. This is consistent with ESD-oriented learning, which emphasizes participation, meaningful engagement, and active knowledge construction rather than passive reception of information. These practical findings suggest that the developed learning tools are well received not only because of their usability, but also because they support more engaging and student-centered learning. This is consistent with ESD-oriented learning, which emphasizes participation, meaningful engagement, and active knowledge construction rather than passive reception of information.

The implementation of learning in three meetings obtained an average score of 90.3%, which was declared practical because it had a very good category, meaning that the implementation of learning could be carried out well. The learning modules designed proved to be effective and supported the smooth running of the learning process. The percentage increased gradually at each meeting as teachers and students adjusted to the learning modules used ([Hakim, et. al., 2020](#)). This gradual increase is important because meaningful learning often develops through repeated interaction, adaptation, and reflection. In relation to ESD, such a process reflects how students and teachers engage progressively with learning experiences that are interactive, contextual, and relevant to authentic classroom situations.

The n-gain value of students' digital literacy skills was 0.37 in the "moderate" category. Students are considered to have digital literacy skills if they meet several indicators, namely the ability to search the internet; the ability to use hypertext navigation; the ability to assemble knowledge; and the ability to evaluate information content. The learning modules developed use several learning resources from the internet, use hypertext, and the material is presented in line with the latest developments. Learning that emphasizes students' digital literacy includes tool literacy in using software and hardware; source literacy in learning resources through the internet; structural social literacy, which is an understanding of how to search for material through the internet; and research literacy in using information technology for knowledge ([Hadayani et al., 2020](#)). Views related to digital literacy include computer literacy as a person's technical ability to use computer devices; information literacy as a person's ability to find, use, package, evaluate, and disseminate digital information correctly ([Safitri et al., 2020](#)). The ability to optimize digital literacy through the use of technology such as gadgets in learning will improve the quality of education ([Masitoh, 2018](#)). The improvement in students' digital literacy skills also has broader implications beyond technical competence. From the perspective of ESD, digital literacy is an important capacity because students need to access, interpret, evaluate, and use information responsibly in responding to contemporary issues. Therefore, the moderate increase in digital literacy found in this study suggests that the developed learning tools may support more meaningful and responsible learning practices in biology education.

Overall, the findings of this study demonstrate that the developed AR-based biology learning tools are not only valid, practical, and effective in improving students' digital literacy skills, but also have the potential to support more meaningful and contextual learning. This aligns with the general orientation of ESD, which encourages students to connect scientific understanding, digital competence, and responsible decision-making in learning. In this sense, AR-based biology learning contributes not only to technology-enhanced instruction, but also to the development of more reflective, relevant, and engaging educational experiences.

Conclusion

The Augmented Reality (AR)-based biology learning tool developed for excretory system material was categorized as Highly Valid and Highly Practical. The results of the pretest and posttest analysis showed an increase in students' learning outcomes, with an N-gain score of 0.37 in the

Moderate category. Students' digital literacy skills also improved by 0.37, indicating that the developed learning tool using a deep learning approach is valid, practical, and effective in improving students' digital literacy skills. These findings also suggest that the learning tool can support more meaningful, contextual, and technology-enhanced biology learning, with potential relevance to the principles of Education for Sustainable Development (ESD).

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