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Research Article

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Improving students' digital literacy through an AR-assisted e-module on fruit and seed morphology using the RICOSRE model

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ABSTRACT

A preliminary study showed that students' digital literacy was still at a relatively sufficient level. Digital literacy, a key 21st-century skill, is essential for Biology Education students to thrive in the digital era. This research aims to determine the effect of the e-module morphological structure of fruits and seeds based on RICOSRE assisted by AR on students' digital literacy. This study employs a quantitative approach, utilizing a quasi-experimental design with a non-randomized control-group pretest-posttest design. The research subjects were third-semester students of the S1 Biology Education program at Malang State University, with a total of 57 students divided into two classes, 31 students in the experimental class and 26 students in the control class. Data were collected using three instruments: a 20-item multiple-choice test for the cognitive dimension, a 20-item Likert-scale questionnaire for the social-emotional dimension, and an observation sheet with 5 indicators for the technical dimension, and all these instruments have been validated. The data types included test scores, questionnaire responses, and observation results. Data analysis included normality and homogeneity tests, followed by One-Way ANCOVA. The results of research showed that the use of the AR-assisted RICOSRE-based e-module had a significant effect on students' digital literacy across all dimensions (sig. < 0.05). Future researchers may also explore the integration of AR and structured learning models like RICOSRE in other subjects to enhance various 21st-century skills.

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INTRODUCTION

The development of science and technology has encouraged various innovations in 21st century learning (Dakhi et al., 2022). The 21st century demands human resources that are superior, adaptive, and able to compete globally. In addition to mastering technical aspects, students also need to have conceptual skills and the ability to develop new innovations (Shahroom & Hussin, 2018). Some 21st century skills that students must master include critical thinking, communication, creativity, collaboration, and digital literacy (Wrahatnolo & Munoto, 2018). Mastery of 21st century skills is not only important for academic success, but also as a provision in the world of work (Mangiduyos & Subia, 2021).

Digital literacy is a crucial 21st century skill that helps students to understand and overcome challenges in the digital era wisely and effectively (Van Laar et al., 2017). Digital literacy encompasses a person's capability to utilize digital technology to access, select, and construct information effectively. Digital literacy consists of three interrelated dimensions, namely (i) the social-emotional dimension, (ii) the technical dimension, and (iii) the technical dimension (Ng, 2012). Students with strong digital literacy skills can more easily identify the information needed, find valid sources of information, and use the information to solve problems (Churchill, 2020). However, research shows that students' digital literacy level is still comparatively low in various countries, including in Indonesia (Kahar, 2018; Murray & Pérez, 2014). Low digital literacy level shows that students continue to face difficulties in utilizing digital technology optimally, even though students are accustomed to interacting with various digital information sources.

The results of the preliminary study analysis of S-1 Biology Education students at State University of Malang showed an average digital literacy score of 69, which falls into the "sufficient" category. In detail, the social-emotional dimension scored 68.3, the cognitive dimension 64.8, and the technical dimension 68.4. These findings indicate that students' digital literacy across all dimensions remains moderate and has not yet reached an optimal level. Several factors may contribute to this condition, such as limited exposure to interactive digital learning media, insufficient training on critical evaluation of digital information, and the lack of integration of digital tools in the learning process. Additionally, the tendency of students to use digital technology primarily for entertainment rather than academic purposes also contributes to the low cognitive engagement. These issues underscore the urgency of enhancing digital literacy through innovative learning approaches. Therefore, there is a need for learning interventions that integrate technology in a meaningful and structured way, such as the development of a RICOSRE-based e-module assisted by Augmented Reality (AR), to improve students' ability to access, analyze, and apply digital information effectively. Increased digital literacy occurs when students are accustomed to finding, processing, analyzing, and interpreting information through learning models integrated with digital media and online systems (Patmanthara & Hidayat, 2018).

Innovative and technology-based learning strategies are needed to improve students' digital literacy (Hardianto et al., 2024). One of the efforts that can be made is the use of electronic-based teaching materials, such as the AR-assisted RICOSRE-based fruit and seed morphology structure e- module in learning. The use of electronic teaching materials in learning will help students learn independently in facing technology in the Industry 4.0 era, which demands innovation and optimal technology utilization (Seruni et al., 2019). E-modules allow students to learn independently with more flexible access to learning materials (Franke et al., 2021).

Learning the morphological structure of fruits and seeds is constructivistic, facilitating students not only memorize the parts of fruits and seeds, but also understand their function in the process of plant reproduction and their relation to the environment. Therefore, it is essential to develop teaching materials that facilitate independent exploration of content and are able to visualize concepts more interactively using digital technology. The e-module developed in this study is based on the RICOSRE learning model (Reading, Identifying the Problem, Construction the Solution, Solving the Problem, Reviewing the Problem Solving, and Extending the Problem Solving), which has the potential to improve student understanding of learning material more deeply and systematically (Mahanal & Zubaidah, 2017). In addition to applying the RICOSRE model, the e-module is also integrated with Augmented Reality (AR) technology to support a more visual and interactive learning experience. AR allows students to visualize complex biological structures in three-dimensional form, thereby facilitating better conceptual understanding (Maulana et al., 2019).

Several previous studies have shown that AR-based e-modules can improve student engagement and digital literacy. For instance, Soutthaboualy et al. (2021) demonstrated that cloud-based AR learning models can enhance digital literacy in blended instruction settings. Similarly, Sulisetijono et al. (2023) found that AR-assisted e-modules on flower structure were effective in improving science literacy among biology students. Another study by Sumiati et al. (2024) reported that the use of e-modules based on the Notion platform increased students' digital literacy, especially in terms of information access and technical navigation. However, those studies mostly focused on general digital media or basic AR features without combining structured learning models that foster critical thinking and systematic problem-solving. None of the above studies integrated AR technology specifically with the RICOSRE model, which uniquely emphasizes a multi-stage cognitive process to promote deeper understanding. Moreover, most previous research only assessed single aspects of digital literacy (e.g., technical skills), whereas this study evaluates digital literacy comprehensively across social-emotional, cognitive, and technical dimensions. Therefore, this research fills a crucial gap by presenting a comprehensive instructional design that integrates RICOSRE with AR and by measuring its holistic impact on students' digital literacy in the context of fruit and seed morphology learning.

Based on this background and supported by the identified research gaps, this study aims to examine the effect of an e-module on the morphological structure of fruits and seeds that integrates the RICOSRE learning model and Augmented Reality (AR) on the digital literacy of biology education students. While prior research has demonstrated the effectiveness of AR-assisted learning in enhancing engagement and certain aspects of digital competence (Soutthaboualy et al., 2021; Sulisetijono et al., 2023; Sumiati et al., 2024), few have implemented a structured problem-solving model like RICOSRE in conjunction with AR to systematically develop all three dimensions of digital literacy-social-emotional, cognitive, and technical. This study fills that gap by integrating AR into the structured cognitive framework of RICOSRE, enabling not only enhanced visualization but also deeper analytical learning. Furthermore, the study provides a comprehensive measurement of digital literacy, unlike previous studies, which tended to focus on isolated aspects. The results are expected to contribute to instructional innovation in higher education by offering a model that simultaneously promotes conceptual understanding and strengthens students' holistic digital literacy, particularly in science education contexts in the digital era.

RESEARCH METHODS

This study was carried out at the Malang State University in the Plant Generative Structure and Development course. The research subjects were 3rd semester students at the Malang State University with a population of 2 classes consisting of 57 students, 31 students in the experimental class and 26 students in the control class. This digital literacy test aims to measure students' abilities based on three dimensions, namely the social-emotional dimension, cognitive dimension, and technical dimension (Ng, 2012). Data were collected using three instruments, a 20-item multiple-choice test for the cognitive dimension, a 20-item Likert-scale questionnaire (with categories of strongly disagree (score 1), disagree (score 2), neutral (score 3), agree (score 4), and strongly agree (score 5)) for the social-emotional dimension, and an observation sheet with 5 indicators for the technical dimension. The lectures utilizing the RICOSRE learning model were conducted over four meetings from November to December 2024. The RICOSRE learning process consists of six stages, as outlined in Table 1.

Table 1. Syntax of the RICOSRE Learning Model

No	Learning Stage	Control Class	Experiment Class
1	Reading	Students discuss in groups, explore related readings, and find problems from the Student Worksheet	Students discuss in groups, explore related readings, and find problems from the e-module.
2	Identifying the problem	Students discuss to identify, categorize, and formulate problems from the reading in the Student Worksheet.	Students discuss to identify, categorize, and formulate problems from the readings in the e- module.
3	Construction the solution	Students are guided to find solutions through external information sources and practicum, then design strategies based on problem identification.	Students are guided to find solutions through Augmented Reality (AR) and practicum, then design strategies based on problem identification.
4	Solving the problem	Students apply solutions from external information sources and practicum, then choose the best solution based on the analysis of	Students apply solutions from Augmented Reality (AR) and practicum, then choose the best solution based on the analysis of advantages and disadvantages.
5	Reviewing the problem solving	Students discuss, present results, analyze other groups' solutions, and assess whether they meet the original learning objectives.	Students discuss, present results, analyze other groups' solutions, and assess whether they meet the original learning objectives.
6	Extending the problem solving	Students evaluate, respond, and conclude on the suitability of the solution to similar problems.	Students evaluate, respond, and conclude on the suitability of the solution to similar problems

This study employs a quantitative approach, utilizing a quasi-experimental design with nonrandomized control-group pretest-posttest design. This design aims to find out the cause-and-effect correlation between one variable and another. This research design used can be seen in Table 2.

Table 2. Nonrandomized control-group pretest-posttest design

Group	Pretest	Treatment	Posttest
Eksperimental Group	Obs	X_1	Obs
Control Group	Obs	X_2	Obs

(Leedy & Ormrod, 2021)

Keterangan:

Obs : Student digital literacy test

X1 : Learning activities using the e-module morphological structure of fruits and seeds based on RICOSRE assisted by AR

X2 : Learning activities using the RICOSRE learning model

Digital literacy data is obtained from questionnaire instruments, questions test and observation sheets. The results obtained from each student will be assessed using an assessment rubric that refers to the digital literacy indicators according to Ng (2012), with social-emotional dimension, cognitive dimension, and technical dimension. The instruments used have previously been tested for validity and reliability. The test of validity was conducted using SPSS version 27.0 through the test of Product Moment correlation with a significant level of 0.05. Test of reliability was conducted using Cronbach Alpha and Kuder Richardson 20. The findings of the Pearson Product Moment test of validity show that all items are valid because all calculated values > r_{table} value. The r_{table} value with N = 30 is 0.361 and the r_{count} value of all items is in the range of 0.375 to 0.736. The test of reliability results utilizing Cronbach's Alpha for the questionnaire indicated a value of 0.809 > 0.700 while the reliability test using Kuder Richardson 20 for the test questions indicated a value of 0.775 > 0.700 that can be understood as reliable.

The data obtained was then subjected to prerequisite tests, including test of normality (Kolmogorov-Smirnov) and test of homogeneity (Levene's Test of Equality of Error Variance), this test was carried out to assess whether the collected data followed a normal distribution and demonstrated homogeneity. After the data stated normally distributed and proven homogeneous, hypothesis testing (One Way Ancova) is conducted to assess the use of the e-module morphological structure of fruits and seeds based on AR-assisted RICOSRE affects students' digital literacy.

FINDING AND DISCUSSION

The research findings on the use of e-module morphological structure of fruits and seeds based on RICOSRE assisted by AR on students' digital literacy of previous students were carried out precondition tests, namely tests of normality and homogeneity. The normality test of digital literacy uses the test of Kolmogorov- Smirnov. The test of normality results indicates that all digital literacy data covering social-emotional, cognitive, and technical dimensions have a significance > 0.05, which indicates that all digital literacy data follow a normal distribution. A summary of the test of normality results is presented in Table 3.

Table 3. Normality Test of Digital Literacy

Dimensions	Experiment Class Significance		Information	Control Class Significance		Information
	Pretest	Posttest		Pretest	Posttest	
Social-Emosional	0,200*	0,200*	Normal	0,185	0,200*	Normal
Cognitive	0,177	0,103	Normal	0,200*	0,056	Normal
Technical	0,070		Normal	0,067		Normal

Levene's Test of Equality of Error Variance was used to assess data homogeneity. The test of homogeneity results is presented in Table 4. The test of homogeneity results show that all digital literacy data covering social-emotional, cognitive, and technical dimensions have a sig. > 0.05, which means that all digital literacy data are homogeneous.

Table 4. Homogeneity Test of Digital Literacy

Dimensions		Signifikansi	Information
Social-Emosional	Pretest	0,693	Homogeneous
	Posstest	0,116	Homogeneous
Cognitive	Pretest	0,107	Homogeneous
	Posstest	0,638	Homogeneous
Technical	Observation	0,620	Homogeneous

Digital literacy research data in the social-emotional, cognitive, and technical dimensions have met the prerequisite tests so that they can be continued by testing the hypothesis analyzed using the One-Way ANCOVA test. One-way ANCOVA test was conducted to determine whether the e-module morphological structure of fruits and seeds, based on RICOSRE assisted by AR, affects students' digital literacy. The test of ANCOVA results for digital literacy in the social-emotional dimension is presented in Table 5. The hypothesis test results for social-emotional digital literacy reveal a significance value of 0.000 < 0.05. This indicates a significant difference in the social-emotional dimension of digital literacy between the experimental and control classes. Meanwhile, the results of the ANCOVA test of cognitive dimension digital literacy are presented in Table 6.

Table 5. ANCOVA Test Results of Digital Literacy Social Emotional Dimension

Tests of Between-Subjects Effects					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2863,322[a]	2	1431,661	18,919	,000
Intercept	2699,624	1	2699,624	35,676	,000
PreLitdigSM	334,333	1	334,333	4,418	,040
Kelas	2450,772	1	2450,772	32,387	,000
Error	4086,257	54	75,671		
Total	355143,000	57			
Corrected Total	6949,579	56			

Table 6. ANCOVA Test Results of Digital Literacy Cognitive Dimension

Tests of Between-Subjects Effects					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4699,760[a]	2	2349,880	19,448	,000
Intercept	4301,681	1	4301,681	35,601	,000
PreLitdigKognitif	2987,233	1	2987,233	24,723	,000
Kelas	1380,915	1	1380,915	11,429	,001
Error	6524,801	54	120,830		
Total	347025,000	57			
Corrected Total	11224,561	56			

The hypothesis test results for the cognitive dimension of digital literacy reveal a significance value of 0.001, which is less than 0.05. This indicates a significant difference in digital literacy within the cognitive dimension of the experimental and control classes. Meanwhile, the results of the ANCOVA test of technical digital literacy are presented in Table 7.

Table 7. ANCOVA Test Results of Digital Literacy Technical Dimension

Tests of Between-Subjects Effects					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1706,739[a]	1	1706,739	48,086	,000
Intercept	241757,897	1	241757,897	6811,345	,000
Kelas	1706,739	1	1706,739	48,086	,000
Error	1952,138	55	35,493		
Total	250896,000	57			
Corrected Total	3658,877	56			

The results of the technical dimension digital literacy hypothesis test show that the significance value is 0.000 < 0.05. These results indicate that there is a significant difference in the digital literacy of the technical dimension between the experimental and the control classes. Referring to Tables 3, 4, and 5, it can be inferred that the e-module morphological structure of fruits and seeds based on RICOSRE assisted by AR has a substantial impact on students' digital literacy. Therefore, further tests were carried out to determine the type of treatment that had the greatest impact on students' digital literacy.

The results of further tests carried out using the test of LSD as in Table 8 show that a variation exists in the mean score between the class taught using the e-module morphological structure of fruits and seeds based on RICOSRE assisted by AR and the class using the RICOSRE model of learning. The highest average score was obtained In the experimental class, the highest average score was achieved, whereas the control class had the lowest. In addition, the average scores of the pretest and posttest on the social-emotional and cognitive dimensions are also different, it was found that the average score increased in both classes, with the highest improvement observed in the experimental class.

Table 8. LSD Post Hoc Test Results Digital Literacy

Dimensions	Class	Pretest ± SE	Posttest ± SE	Corrected Mean ± SE	Percentage Increase (%)
Social-Emosional	Experiment	60,7 ± 1,3	84,3 ± 1,6	84,2 ± 1,6	38,9
	Control	60,1 ± 1,5	70,9 ± 1,8	71,0 ± 1,7	18
Cognitive	Experiment	57,6 ± 2,2	81,8 ± 2,4	81,3 ± 2,0	42
	Control	55,8 ± 2,4	70,8 ± 2,6	71,4 ± 2,2	26,9
Technical	Experiment		70,9 ± 1,1		34
	Control		59,9 ± 1,2		29,8

The LSD test results in Table 8 show that students who are taught using the e-module morphological structure of fruits and seeds based on RICOSRE assisted by AR have a mean digital literacy posttest score that is greater than the pretest. The percentage results of students' digital literacy in the social-emotional aspect. amounted to 84.3 (good), the cognitive dimension amounted to 81.8 (good), and the observation results in the technical dimension amounted to 70.9 (good). The LSD test results also showed a notable variation in the corrected mean and improvement of students' digital literacy between the experimental and control classes. Within experimental class, the corrected mean score of the social-emotional dimension was 84.2; the cognitive dimension was 82.3; and the technical dimension was 70.9. This proves that after the learning intervention, participants experienced an increase in understanding and better digital literacy skills compared to the control class. According to Sulisetijono et al. (2023), AR e-modules are proven to be quite effective in improving life skills in the 21st century that can support and motivate students to learn effectively and independently. In line with research by Sumiati et al. (2024), stated that the use of e-modules has a significant impact on increasing students' digital literacy.

The percentage increase also shows that the experimental class has a notable improvement in comparison to the control class. The cognitive dimension has the highest increase (42%), social-emotional (38.9%), and technical dimension (43%). There is a simultaneous influence of the three dimensions of digital literacy that have been measured. This shows that the AR-assisted RICOSRE-based fruit and seed morphology structure e-module has an effect on student digital literacy. According to Ismail et al. (2024), e-modules can facilitate active learning to develop digital literacy. In line with research by Wahyuni and Nayazik (2023), stated that interactive e-modules used in learning can improve digital literacy skills.

The implementation of the RICOSRE-based AR-assisted fruit and seed morphology structure e-module has a syntax or learning stages contained in the content in the e-module. At each stage of the RICOSRE learning model, it has the potential to train and improve students' digital literacy. The first stage is reading, where students focus on readings related to the problem to be discussed through e-module access supported by digital information from various sources such as electronic journals, e-books, scientific articles, and online media. The reading stage in the RICOSRE learning model is closely related to Ausubel's theory of meaningful learning. According to Ausubel (1968), learning will be more effective if students can link new knowledge to the cognitive structures they already have, through what is called an advance organizer.

In the reading stage, students begin to read and explore the initial material, which aims to activate their prerequisite knowledge. This enriches their understanding because new information becomes more concrete and easily connected to previous learning experiences. Previous studies have shown that reading activities carried out during the learning process can facilitate the acquisition of broader knowledge to support problem-solving activities (Badriah et al., 2023). This can improve their ability to search for, sort, and understand relevant and credible digital information. According to Yu (2022), digital literacy among students can be improved by incorporating digital devices into the learning process.

The second stage, identifying the problem, is the stage where students formulate problem points that have been categorized into a problem formulation writing format. In this case, students can provide diverse perspectives and expected results from the problem-solving process that can develop during the learning process. The identifying the problem stage in the RICOSRE learning model is closely related to Jean Piaget's constructivist learning theory. According to Piaget, learning occurs when students experience cognitive balance and imbalance (equilibration), namely when they face new situations or information that are not in accordance with previously possessed knowledge. In conditions of imbalance, students are encouraged to identify problems, explore, and form new understandings through the processes of assimilation and accommodation (Piaget, 1950).

At this identifying the problem stage, students are faced with phenomena or learning objects. This process reflects Piaget's approach which sees students as active individuals who construct their own knowledge through direct experience and interaction with the learning environment. In this process, students use digital literacy skills to identify problems based on data and information obtained digitally. Students also develop critical skills in distinguishing valid information from misinformation in the digital environment. According to Gustavson et al., (2016) & Pambudi and Windasari (2022), problems identified by students will make students more motivated in finding the right solution by integrating information and communication technology using digital media to solve problems.

The third stage, constructing the solution, where students are guided to find ideas for solving problems through AR-assisted e-modules and through direct observation of fruit and seed morphological structure practicums. Students use AR to help design accurate digital information-based solutions that are appropriate to the problems faced. Students are more skilled in accessing, managing, and utilizing AR-assisted e-modules to support learning. According to Köhler (1947), visual media helps students see patterns and relationships as a whole so that understanding arises through insight. In the constructing the solution stage, students are invited to develop solutions to previously identified problems. This process is often carried out through group discussions, collaboration, and joint exploration that reflects the principle of scaffolding in Vygotsky's theory, namely providing temporary support that helps students develop high-level thinking skills (Vygotsky, 1978).

When supported by AR technology, students can interact directly with three-dimensional visual objects, such as fruit and seed structures, in a more concrete and contextual way. These interactive visualizations act as cultural tools that are very important in Vygotsky's view, because they can strengthen the thinking process, help cognitive mediation, and deepen the construction of solutions. According to (Chiu et al., 2022), students operate technology adequately to solve their own problems, such as connecting digital devices or solving problems by reading online manuals or watching videos/animations. The constructing the solution stage is carried out by students to explore their knowledge in proposing several solutions to the problems given in the previous stage. At this stage, students conduct investigations and make causal relationships between problems and solutions (Mahanal & Zubaidah, 2017).

The fourth stage, solving the problem, is the stage where students solve problems through solutions that have been designed. Students apply solutions using digital technology, such as accessing AR software contained in the e-module to determine the effectiveness of their solutions. The solving the problem stage in the RICOSRE learning model is closely related to Robert Gagné's cognitive learning theory. In his theory, Gagné explains that learning consists of nine learning events (Nine Events of Instruction) that reflect the internal cognitive processes of students, from gaining attention to demonstrating performance (Gagné et al., 1992).

At the solving the problem stage, students are in a phase where they must demonstrate the understanding and skills that have been built through the previous stages, such as identifying problems and building solutions. This is in line with the "eliciting performance" step in Gagné's theory, which is when students begin to apply knowledge in real contexts to solve tasks or problems (Gagné et al., 1992). This process improves digital-based problem-solving skills. This process improves digital-based problem-solving skills. According to Yustina et al. (2022), students' ability to think critically and creatively in answering problems and solutions related to everyday life requires learning strategies in finding information in the current digital era which requires digital literacy skills. According to He et al. (2018), during the problem-solving stage, students can develop a number of skills, including information gathering, classification, analysis, scientific reasoning, and decision-making accuracy.

The fifth and sixth stages, namely reviewing the problem solving and extending the problem solution, are stages where students carry out discussion activities and class presentations in group activities and reconsider the suitability of solutions to be applied to other similar problems. The reviewing the problem-solving stage in the RICOSRE learning model is closely related to David Kolb's learning theory, especially in the Reflective Observation stage in Kolb's learning cycle. After students experience and try to solve problems through concrete experiences, students enter the reflection phase to review the process, strategies, and results of problem solving that have been carried out. In this stage, students analyze what worked, what didn't, and why it happened, which is the core of reflective observation (Kolb, 2015). Thus, the reviewing stage helps students internalize experiences, strengthen understanding, and form the basis for developing concepts and future applications, as described in Kolb's experiential learning cycle.

Extending the problem-solving stage in the RICOSRE learning model is closely related to David Kolb's learning theory, especially in the Abstract Conceptualization and Active Experimentation phases in his learning cycle. At this stage, students are encouraged to develop and reapply the solutions that have been found in new contexts or problems, which is a concrete form of applying concepts more broadly and flexibly. In Kolb (2015), after students reflect on previous experiences (Reflective Observation), they begin to form a deeper conceptual understanding (Abstract Conceptualization), then test it in new situations (Active Experimentation). Students respond and conclude the suitability of the problems and solutions that have been carried out during the learning process. These two stages of RICOSRE provide opportunities for students to learn from everyday life experiences while their digital literacy skills are developed through the process of contextual problem solving (Hardianto et al., 2024). According to Feola (2016), students can apply the knowledge gained during learning as a reference in creating appropriate solutions to problems that occur in the surrounding environment.

CONCLUSION

The results concluded that the e-module on the morphological structure of fruits and seeds based on the RICOSRE model assisted by AR significantly improves students' digital literacy. This is evidenced by the increase in students' digital literacy scores across the social-emotional, cognitive, and technical dimensions, as shown by the results of the One-Way ANCOVA test (sig. < 0.05). In light of these findings, it is recommended that the development and use of AR-assisted e-modules be expanded to other courses in biology education, such as plant anatomy, cell biology, and ecology, to enhance student engagement and digital competencies. Educational institutions should also provide continuous training for educators to strengthen their capacity in designing and implementing technology-based learning. Furthermore, the successful adoption of such modules requires the strengthening of digital infrastructure, including internet access and supporting devices. Finally, the integration of AR-based learning models into the formal curriculum should be considered to ensure sustainability and broader impact in higher education.

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