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Augmented reality-assisted biology E-module with PBL-reading concept mapping: Development and its effect on student collaboration

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ABSTRACT

This study aims to develop an Augmented Reality-assisted e-module integrated with a Problem-Based Learning-Reading Concept Mapping (PBL-Remap) to improve students' collaboration skills. This research employed a research and development (R&D) approach using the Lee and Owens model, which consists of five stages: assessment/analysis, design, development, implementation, and evaluation. High school students were involved as trial subjects. At the same time, material experts, media experts, and Biology Education practitioners served as validators to assess the quality and feasibility of the augmented reality-assisted e-module. The research instruments were a validation questionnaire to assess the validity and feasibility, and a collaboration skills observation sheet. The study found that the e-module, supported by augmented reality and integrated with the PBL-Remap model, was valid, practical, and effective in improving students' collaboration skills. Furthermore, the developed augmented reality-assisted e-module was deemed highly valid and practical for use in learning. Thus, the augmented reality-assisted e-module, integrated with problem-based learning and reading concept mapping, is worth implementing as an effective learning innovation to develop students' collaboration skills. We hope that further researchers can expand this research to a wider scope of materials and implementation across other 21st-century skills.

INTRODUCTION

Biology is a science that provides a comprehensive understanding of life phenomena and, at the same time, provides a means for students to investigate ideas and apply them through a systematic thinking process (Fauzi et al., 2021). In general, Biology learning content has characteristics that can stimulate students' cognitive abilities in understanding the material comprehensively (Lestari, 2025). The complexity of biology material, such as body systems, requires students to conduct in-depth analyses of organ structures and the biochemical processes that occur within them. The urgency of studying body systems lies in students' ability to appreciate biological processes and their implementation (Ningsih et al., 2023). Given the abstract and memorization nature of much of the material, teachers need to empower students' potential through 21st-century skills (Rizalia et al., 2024). This approach is expected to simplify complex biological concepts and make them more meaningful for students.

21st-century competencies that students must master encompass a wide range of aspects, from problem-solving and critical thinking to digital literacy and argumentation skills (Ram et al., 2025). Among these skills, collaboration plays a vital role because it involves teamwork in synergizing ideas to address problems (Nahar et al., 2022). Through collaboration, students not only hone their communication skills but also learn to appreciate diversity and make collective decisions for shared goals (Nurhayati & Bahtiar, 2024). This process can be fostered by presenting challenges that require integration of thought, encouraging students to explore concepts more deeply through productive social interactions (Erina et al., 2025; Fitriasih et al., 2025; Mayanti & Widiyatmoko, 2025; Indriyani et al., 2025).

Observations through interviews with high school biology teachers on Sumba Island in July 2025 showed that students' collaborative skills remained at a moderate level. This low achievement is due to insufficient instruction that stimulates collaborative skills and to students' tendency to rely on the teacher as the sole source of information. Furthermore, the availability of teaching materials specifically designed to hone collaborative skills is also inadequate. Therefore, systematic efforts are needed to integrate collaborative skills training into classroom activities to encourage improved student learning.

The use of conventional instructional strategies and limited teaching media that have not been integrated with innovative learning models is a major obstacle to creating a participatory learning ecosystem. This low level of active engagement has a systemic impact on student's ability to collaborate and solve complex problems in Biology (Sholihah et al., 2025) The abstract nature of traditional learning often fails to connect material to real-world phenomena, making it difficult for students to understand the practical relevance of group collaboration (Ayubi et al., 2025). Given this urgency, this research focuses on the development of media-based teaching materials integrated with specific learning models to stimulate collaborative skills and contextual understanding of Biology concepts.

Providing relevant teaching materials is a key strategy in optimizing students' collaboration skills, especially on difficult topics. In the context of learning about ecology and ecosystem interactions, the use of e-modules presents a practical solution that offers time efficiency and ease of access for both teachers and students (Amanda et al., 2025). The main advantage of this digital module lies in its ability to present abstract scientific concepts more concretely and contextually through the integration of interactive features such as audio, video, and images (Alisah et al., 2025). Furthermore, the flexibility of online and offline access and the availability of formative tests make e-modules a comprehensive learning resource for enhancing student understanding (Amanda et al., 2025).

The integration of Augmented Reality (AR) technology into e-modules has great potential in stimulating students' higher-order thinking skills (Saputra & Octavia, 2024). Through AR, digital objects can be visualized concretely, thus enabling direct interaction between users and virtual information (Dewi, 2020). The use of augmented reality can be accessed through Android and iOS-

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based mobile devices to present 3D objects in real-time by scanning a special code. The main advantage of this technology is its ability to visualize abstract materials and microscopic objects that are difficult for human vision to reach (Maulion & Roleda, 2025). In line with the view of Nst & Ariyanti (2025), AR provides space for students to explore real phenomena and project the implementation of theory in practice. In addition to creating a more attractive and interactive learning atmosphere, the use of this technology has also proven effective in strengthening collaboration skills between students (Sulisetijono et al., 2023).

The integration of the Problem-Based Learning model into learning is a key strategy for empowering students' collaboration skills. PBL facilitates students to work in diverse teams, where each member contributes ideas to generate solutions to specific problems (Mandalika et al., 2024). Collaboration here is not just ordinary group work, but rather a social activity that involves a willingness to make joint decisions to achieve collective goals (Qadariah et al., 2025). Practically, the use of this model has a significant impact on how students communicate and demonstrate respect within group dynamics (Siregar & Pane, 2024; Ervana et al., 2024).

Cooperative learning is an alternative to PBL to encourage active student participation in a supportive and interactive group environment (Ayubi et al., 2025; Xie et al., 2025). One relevant approach in this context is Reading concept mapping (Remap), which emphasizes reading and concept mapping (Zubaidah et al., 2020). Through reading, students can collectively strengthen their knowledge base to formulate solutions to the challenges presented in the discussion (Jauhari et al., 2025).The combination of PBL, which emphasizes solving real-world problems, with Remap, which visualizes relationships between ideas, allows students to understand the material in a more structured manner (Sholihah et al., 2025) .Thus, the combination of the PBL and Remap models provides a comprehensive learning structure, where reading literacy is used to deepen the analysis of the problem being studied.

The novelty of this research is manifested through the synergistic integration of Augmented Reality technology with the Problem-Based Learning-Reading concept mapping (PBL-Remap) pedagogical framework, packaged in the form of a Biology e-module. The fundamental difference from previous studies is that, while previous studies only developed e-modules integrated with the PBL model (Pitorini et al., 2025), developed Augmented Reality-assisted e-modules (Sulisetijono et al., 2023), and applied the PBL learning model to improve students' collaboration skills (Zubaidah et al., 2020)This research will develop an Augmented Reality- assisted e-module integrated with the problem-based learning-reading concept mapping model to improve students' collaboration skills.

Based on the background presented, the focus of this research problem is formulated as follows: What are the design specifications and degree of validity of the development of an Augmented Reality (AR)-based Biology e-module that integrates the Problem-Based Learning-Reading Concept Mapping (PBL-Remap) framework, based on the review of expert validators?; 2) To what extent is the implementation of an AR-assisted e-module integrated with the PBL-Remap model practical in supporting Biology instructional activities from the perspectives of educators and students?; and 3) What is the significance of the effectiveness of using an AR-based e-module integrated with PBL-Remap in optimizing students' collaborative skills when compared to the use of conventional learning media?

Based on this, implementing learning that integrates the PBL-Remap model into the development of an Augmented Reality-based Biology e-module is crucial for optimizing students' collaborative skills. This step is expected to strengthen students' ability to collaborate effectively during instruction. The main focus of this research is to test the effectiveness of the development of a PBL-Remap-integrated Biology e-module in stimulating increased student collaboration skills.

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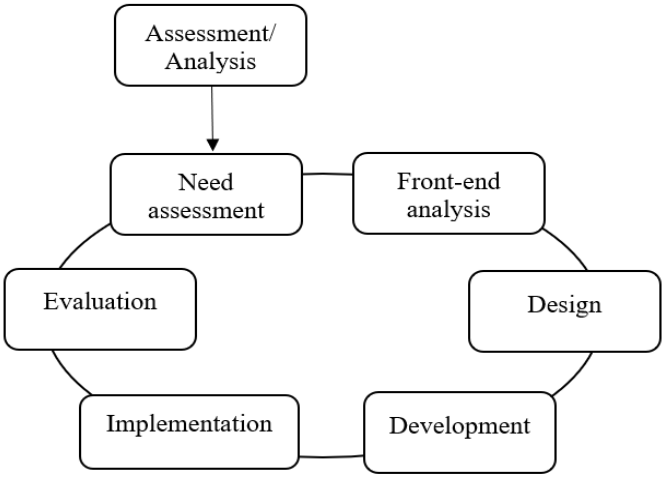
METHODS

This study adopted the development model from Lee and Owens (2004) which consists of the stages of assessment/analysis, design, development, implementation, and evaluation. The stages of the Lee and Owens development model are shown in Figure 1.

Figure 1
The stages of the Lee and Owens development model.



Data collection took place during the period of June-August 2025 in four high schools in the Sumba region (a public school in Tambolaka, a private high school Sumba Barat, a private high school in Sumba Tengah, and a public school in Sumba Timur). From the population of grade XI whose equivalence had been tested, 72 students were selected as samples, divided into two classes. A total of 36 students in the experimental class learned using AR-assisted e-modules integrated with the PBL-Remap model, while the other 36 students in the control class used regular e-modules.

This study used a collaborative skills evaluation instrument based on Greenstein (2012) criteria, encompassing elements of productivity, respect, compromise, and team contribution. This assessment was integrated into assignments in an augmented reality-assisted biology e-module. Using the PBL-Remap model, this instrument helps students develop collaborative and social skills to deepen their understanding of the material's concepts more meaningfully.

Validation testing of the Augmented Reality-based biology e-module with the integration of the PBL-Remap model involved collaboration between education practitioners, media experts, and subject matter experts. Material assessment was conducted by academics or practitioners with a minimum educational background of a Bachelor's/Master's degree in Biology/Biology Education who are competent in plant physiology. Meanwhile, media validation was entrusted to a Biology lecturer with a minimum master's degree (S2). The level of validity and practicality of this media was evaluated through data analysis techniques using specific formulas.

The requirements for educational practitioners in this study were biology teachers with a minimum bachelor's degree (S1) in education. Details regarding the validity parameters and practicality of each e-module are presented in Tables 1 and 2, respectively. The success rate of the E-module in stimulating students' collaboration skills was evaluated by comparing pretest and posttest data. The achievement assessment was analyzed using the N-gain test to determine the significance of the score increase before and after the treatment. The classification of the effectiveness of this learning tool refers to the N-gain score criteria presented in Table 3. Collaboration skill scoring criteria can be seen in Table 4.

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Table 1
E-module validity assessment criteria.

Percentage (%)	Criteria
81,00-100,00	Very valid, and ready for immediate use
61,01-81,00	Fairly valid but requires minor improvements
41,01-61,00	Less valid, requires major improvements, not recommended for use
21,00-41,00	Invalid
00,01-21,00	Very invalid

Note: Adapted from Ghazali et al. (2025)

Table 2
E-module practical assessment criteria.

Percentage (%)	Criteria
81-100	Very practical, ready to be implemented without revision
61-81	Practical, with minor revisions
41-61	Quite practical, but requires an in-depth evaluation before use
<40	Less practical, or not suitable for implementation

Note: Adapted from Siregar & Pane (2024)

Table 3
E-module effectiveness criteria based on N-gain.

Score N-gain	Criteria
$g > 0,7$	High
$0,3 \leq g \leq 0,7$	Medium
$g < 0,3$	Low

Table 4
Collaboration skill scoring criteria.

Value Interval	Category
86,26-100	Very high
62,51-81,25	High
43,76-62,50	Moderate
25-43,75	Low

RESULTS AND DISCUSSION

The E-module was developed by integrating the PBL-Remap learning model with augmented reality. This media is structured around three main pillars: a cover, core content focused on instructional activities, and a conclusion that includes the author's biodata. Details regarding the module interface, including learning activity features and developer information, are presented in Figures 2 (a to d). This e-module device is designed to facilitate students' understanding of Ecology material and various forms of interaction in the ecosystem.

E-module Material Expert Validation

The assessment by material experts covers five main indicators: relevance of the material description, general aspects of the material, supporting elements of the presentation, language

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accuracy, and contextual elements. Detailed data regarding the percentage achievement of these validation results are summarized in Table 5. The validation test results by subject matter experts achieved an average score of 96,42%, with the criteria of highly valid. This achievement indicates that the content in the AR-based e-module has met high effectiveness standards, making it suitable for implementation without requiring further refinement.

Figure 2

Augmented reality-assisted biology e-module with PBL-Remap: (a) E-module cover view, (b) Display of student learning activities, (c) The author's biodata, and (d) AR-assisted biology e-module display featuring barcode scanning.

(d)

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Table 5
Results of e-module analysis by experts.

	Aspect	Score obtained	Maximum score	Percentage	Category
1	Suitability of material	34	40	97,14%	Very Valid
2	Material	40	40	100%	Very valid
3	Supporting presentation	37	40	93,50%	Very valid
4	Language appropriateness	74	80	92,50%	Very valid
5	Contextual appropriateness	15	15	100%	Very valid
	Mean Total			96,42%	Very valid

Based on the data in Table 5, the criteria for an appropriate e-module according to (Alisah et al., 2025) Include aspects of learning independence, clarity of learning targets, ease of language in delivering the material, and appropriate assessment strategies. To achieve the standard of material accuracy, an e-module must integrate educational facts, straightforward concepts (not open to multiple interpretations), and coherent procedures (Ayunda et al., 2024). Validation by experts is essential to ensure the suitability of the material content to the curriculum demands. Through this validated media, students can be guided to master collaboration skills, including working together effectively and respectfully in a diverse team to achieve common goals. Activities in the module that are designed with a problem orientation will encourage students to investigate concepts in more depth (Afelia et al., 2023).

Validation by Media Experts of Augmented Reality-Assisted E-module
The media validation process for this e-module focused on six essential parameters: component completeness, content layout, media characteristics, language quality, and product suitability. Detailed data on the validation percentage achieved by the media experts is summarized in Table 6.

Table 6
Results of validation percentage analysis by e-module media experts.

	Aspect	Score obtained	Maximum score	Percentage	Category
1	Component Completeness	10	10	100%	Very Valid
2	Content Design	65	70	92,85%	Very valid
3	Characteristics				
	a. Self-Instructional	48	50	96%	Very valid
	b. Self-Contained	4	5	80%	Very valid
	c. Stand-Alone	5	5	100%	Very valid
	d. Adaptive	10	10	100%	Very valid
	e. User-Friendly	9	10	90%	Very valid
4	Language Suitability	42	45	93,33%	Very valid
5	Suitability	14	20	70%	Very valid
	Mean Total			84,80%	Very valid

The results of the validation test by experts on the AR e-module showed a figure of 84,80% with a very valid predicate, as shown in Table 6. This reflects that the e-module is very practical and ready for use in the field after several minor improvements were made.The quality of learning can be effectively improved through e-modules that have complete components, starting from the

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introduction, material description, and feedback instrument. According to the standards put forward (Afelia et al., 2023).

A good e-module must be structured, free from conceptual ambiguity, and have a correct procedural flow. The testing process by material expert validators is a key step to validate the accuracy of the content contained in the media. In addition to the content, the development of this e-module focuses on equipping students with collaboration skills, one of the pillars of 21st-century skills. By presenting challenges that require teamwork, students are trained to share ideas and engage in meaningful social activities, thereby obtaining a more comprehensive and in-depth understanding of Biology concepts.

In developing biology e-modules, the module's functional and characteristic aspects are the main foundations for ensuring learning effectiveness. Referring to the opinion of (Wijayanto et al., 2023), e-modules must meet the criteria of self-instruction that encourages student independence (Ayunda et al., 2024), as well as being self-contained, which ensures the completeness of the material in one media package (Hastuti et al., 2020). In addition, the stand-alone nature ensures that the module does not depend on external references (Talan et al., 2022), while the adaptive and user-friendly aspects ensure that the module is flexible and comfortable to use by students (Koray & Bilgin, 2023) The integration of these characteristics aims to make the learning process run more systematically and help students achieve an in-depth understanding.

Validation by Expert Practitioners of E-module Assisted by Augmented Reality

Biology education practitioners' assessment of this e-module covered several crucial aspects, such as material presentation techniques, visual appeal, and user accessibility and comprehension of the content. Detailed data regarding the validation results are summarized in Table 7. The developed Biology e-module achieved a high level of validity with a practicality percentage of 93,00%. The main advantage of these tools lies in their ability to encourage student learning independence through systematic and interactive methods (Pitorini et al., 2025). Indicators of this tool's success include engaging visualizations, motivating content, and easy-to-understand navigation (Delita et al., 2022). By presenting relevant and easy-to-use material, this tool not only simplifies the learning process but also hones students' higher-order thinking skills (Dewi, 2020).

Effectiveness Test Results of AR-Assisted E-module Integrated with PBL-Remap Model

Students' collaboration skills were measured using six test items, which then served as the basis for assessing the effectiveness of the e-module. Data obtained from the pretest and posttest scores were further processed using the N-gain test to determine the significance of the improvements. The findings related to the effectiveness of this teaching tool, as shown in the N-gain test results, are presented in Table 8. Based on the data in Table 8, a significant increase in scores from the pretest to the posttest is evident. This learning effectiveness is reinforced by the N-gain score of 0.70, which is considered high. Based on the N-gain test data presented in Table 8, it was found that the use of e-modules had a significant positive impact on improving students' collaboration skills compared to conventional methods in the control class. Overall, the experimental class demonstrated more consistent scores across all collaboration indicators.

The experimental class experienced an impressive increase in average scores. The highest increase was seen in the "Responsibility and Contribution" indicator, where the score jumped from 56.09 to 78.98. This indicates that the interactive structure of the e-module successfully stimulated students' sense of ownership of group assignments. Cumulatively, the experimental class's N-gain values ranged from 0.35 to 0.38, which falls into the moderate category. This figure was consistently higher than the control class, which mostly ranged from 0.31 to 0.34. For the "working productively" indicator, the experimental class excelled with an N-gain of 0.38, compared to only 0.32 for the control class. Interestingly, for the "Mutual Respect" indicator, the control class had a slightly higher N-gain (0.38) than the experimental class (0.36). This suggests that while e-modules

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excel in technical aspects and contribution, affective aspects such as respect can still thrive in conventional face-to-face interactions.

Table 7
Results of validation percentage analysis by biology education practitioner experts.

	Aspect	P	Category
1	Articulation of learning content	100%	Very Valid
2	Visual appeal aspect	100%	Very Valid
3	Efficacy of using electronic modules		Very Valid
	a. The e-modules contain instructions.	100%	Very Valid
	b. The font type and size of the e-module text are clear.	80%	Very Valid
	c. The learning content in this e-module is detailed.	100%	Very Valid
	d. The language used is clear and easy to understand.	100%	Very Valid
	e. Visual elements in e-modules facilitate students' learning activities.	80%	Very Valid
	f. The presented problem illustrations relate to real phenomena in everyday life.	100%	Very Valid
	g. Integration of e-modules in learning can be implemented by students very smoothly	100%	Very Valid
4	The level of readability and clarity of content in the developed e-module		Very Valid
	a. The language used in the e-module can be understood by students.	80%	Very Valid
	b. The content of the material presented aims to improve students' collaboration skills.	80%	Very Valid
	c. Integration of material in e-modules strengthens students' cognitive domains and academic success.	80%	Very Valid
	d. practice questions according to the content of the material	80%	Very Valid
	e. The integration of images in the e-module strengthens the explanation of concepts.	80%	Very Valid
	f. Evaluation indicators aim to measure learning outcomes	100%	Very Valid
	g. The content supports the student learning process.	100%	Very Valid

Table 8.
N-gain test Results of collaboration skills between two groups.

Collaboration skills indicators	M Pre Exp.	M Post Exp.	N-gain Exp	M Pre Ctrl	M Post Ctrl	N-gain Ctrl
Working productively	66,21	79,92	0,38	53,78	66,29	0,32
Mutual respect	74,03	84,61	0,36	46,64	60,27	0,38
Compromise	55,11	73,52	0,35	52,84	65,47	0,31
Responsibility and contribution	56,09	78,98	0,37	60,38	70,63	0,34

Note: M = Mean, Exp = Experiment class, Ctrl = Control class, Pre = Pretest, Post = Post-test.

The significant gap in posttest scores between the experimental class (average range 73-84) and the control class (60-70) demonstrates that digital media interventions are more effective in

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visualizing collaborative elements. E-modules likely facilitate independent learning, indirectly forcing students to be more active in compromising and contributing to group discussions. This finding aligns with the notion that learning media can create a more dynamic environment.

Table 9
Results of pretest and posttest scores for each aspect of collaboration skills.

School Name	Indicators	Experiment Class		N-gain	Control Class		N-gain
		Pre **(M± SD)**	***Post*** **(M ± SD)**		***Pre*** **(M ± SD)**	***Post*** **(M ± SD)**	
Waingapu 1 State Senior High School	Working productively	67.93 ± 12.99	82.46 ± 9.88	0.39 ± 0.33	45.37 ± 12.67	58.96 ± 14.39	0.25 ± 0.20
	Mutual respect	77.90 ± 9.69	86.81 ± 10.38	0.38 ± 0.46	45.62 ± 7.15	57.03 ± 12.30	0.20 ± 0.21
	Compromise	55.31 ± 10.77	72.56 ± 10.35	0.35 ± 0.24	57.62 ± 16.96	68.09 ± 16.38	0.28 ± 0.29
	Responsibility and contribution	55.00 ± 10.54	76.25 ± 9.46	0.44 ± 0.22	65.45 ± 15.67	73.93 ± 13.56	0.26 ± 0.31
Central Sumba Private Christian High School	Working productively	63.96 ± 14.47	76.93 ± 8.92	0.30 ± 0.26	62.03 ± 12.60	71.65 ± 12.49	0.25 ± 0.13
	Mutual respect	74.62 ± 11.12	84.84 ± 8.21	0.41 ± 0.29	45.78 ± 7.08	61.40 ± 10.09	0.28 ± 0.19
	Compromise	55.31 ± 9.99	72.96 ± 17.52	0.37 ± 0.42	51.25 ± 9.91	65.15 ± 10.81	0.26 ± 0.23
	Responsibility and contribution	55.15 ± 10.35	80.46 ± 10.99	0.56 ± 0.24	59.37 ± 11.48	71.56 ± 12.91	0.29 ± 0.29
Waikabu-bak Private Christian High School	Working productively	63.75 ± 9.06	79.68 ± 12.04	0.45 ± 0.28	44.21 ± 10.08	62.18 ± 8.79	0.29 ± 0.24
	Mutual respect	65.71 ± 12.45	78.40 ± 8.91	0.33 ± 0.28	47.18 ± 6.94	60.31 ± 9.66	0.24 ± 0.18
	Compromise	55.00 ± 10.54	73.50 ± 19.75	0.40 ± 0.47	55.00 ± 10.54	67.40 ± 17.36	0.23 ± 0.46
	Responsibility and contribution	55.00 ± 10.54	79.53 ± 11.21	0.53 ± 0.24	60.00 ± 11.70	69.37 ± 12.87	0.23 ± 0.27
State Senior High School 1 Tambolaka	Working productively	69.18 ± 14.58	80.59 ± 12.20	0.37 ± 0.30	63.50 ± 13.74	72.37 ± 13.65	0.26 ± 0.24
	Mutual respect	77.87 ± 9.86	88.40 ± 9.65	0.47 ± 0.40	47.96 ± 6.33	62.34 ± 11.07	0.26 ± 0.21
	Compromise	54.84 ± 10.35	75.06 ± 12.06	0.42 ± 0.27	47.50 ± 7.40	61.25 ± 13.44	0.25 ± 0.20
	Responsibility and contribution	59.21 ± 9.68	79.68 ± 10.92	0.48 ± 0.29	56.71 ± 10.96	67.65 ± 10.99	0.24 ± 0.21

Note: Pre = Pretest, Post = Post-test, M = Mean, SD = Standard Deviation

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Improvements in the "compromise" and "responsibility" aspects indicate that e-modules go beyond simply transferring text to a screen and serve as a managerial tool for group work. The detailed comparison of scores for each collaboration skill indicator is summarized in Table 9. Overall, students' collaborative skills experienced a significant increase, as indicated by the N-gain scores. The responsibility and contribution aspects were the indicators with the most prominent increase, while the productive collaboration aspect recorded the least increase. With an average N-gain categorized as moderate, we conclude that the use of AR-assisted biology e-modules integrated with PBL-Remap was successful in effectively improving students' collaborative skills. Based on the data in Table 9, there are crucial findings regarding the effectiveness of e-modules in improving students' collaboration skills at four high schools in Sumba. The data show that all collaboration indicators in the four schools for the experimental class consistently achieved high criteria with an N-gain range of 0.30 to 0.56. In contrast, the control class in all schools only achieved low criteria with an N-gain range of 0.20 to 0.29. This proves that the determining factor in improving collaboration skills lies not in the school location or initial student input, but rather in the learning media intervention used.

The success of the e-module assisted by augmented reality integrated with the problem-based learning-reading concept mapping model in achieving high criteria in all schools indicates that this medium is able to minimize psychological barriers in collaboration. In depth, the increase in the compromise aspect, which is stable at the N-gain figure of 0.35-0.42 in the experimental class, indicates that digital technology helps students in negotiating ideas in a more structured manner. Integrating the PBL-Remap model into an AR-assisted e-module has proven effective in strengthening students' collaborative skills. This finding corroborates a previous study by (Sulisetijono et al., 2023), which demonstrated a significantly higher increase in collaborative skills in the experimental group compared to the control group. Overall, this research data confirms that the use of this innovative learning medium positively contributes to the development of students' collaborative competencies.

The structure of the PBL-Remap model is specifically designed to hone students' collaborative skills (Sulisetijono et al., 2023) Through a series of activities such as problem orientation, group discussions, concept mapping, and solution evaluation, students are trained to work productively, develop a sense of responsibility, and respect the contributions of teammates. The use of an AR-based e-module further optimizes this process by presenting contextual cases visually and interactively (Erina et al., 2025). The synergy between PBL, which encourages collective problem identification, and the Remap model, which helps organize thought patterns, creates an immersive learning experience that motivates students to actively participate in groups. PBL fosters critical thinking and shared responsibility by positioning students as active problem-solvers, whereas the Remap model strengthens conceptual understanding by helping them organize and visualize the connections between ideas. Together, these two approaches form a complementary framework that not only enhances students' cognitive engagement but also cultivates collaborative skills essential for meaningful and sustained group learning.

The PBL-Remap learning model requires students to brainstorm and negotiate ideas when developing a collective concept map (Zubaidah et al., 2020). This interactive process indirectly hones students' ability to respect each other's opinions, be open to constructive criticism, and be good listeners to their peers. This aligns with previous research that emphasized the importance of problem-based learning methods in fostering mutual respect and social intelligence in the educational setting. Improved group consensus-building skills were evident when students designed their final concept maps. Significantly, many groups were now able to manage conflicts of understanding within the team without relying on teacher intervention. Through the Remap approach, all members were required to map the hierarchy and correlations between key concepts. This process fostered in-depth discussion and cognitive compromise, as students had to reconcile differing interpretations to reach a valid, shared understanding. Furthermore, the PBL

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model's requirement to produce a single, final solution served as a reinforcing factor for students practicing their compromise skills (Ayubi et al., 2025).

There was a decrease in cases of free-riding (students who did not contribute). Peer assessments showed a consistent increase in individual contributions. Students felt more responsible for their assigned portion of the assignment, as successful problem-solving in AR/PBL depended heavily on mastery of the mapped concepts (Remap). The PBL-Remap integration implicitly instilled both collective and individual responsibility. PBL placed responsibility for problem-solving, while Remap placed responsibility for understanding and mapping key concepts. The interactive AR e-module served as an engaging and focused tool, fostering student ownership of the assignment.

CONCLUSION

The Biology e-module developed in this research, which integrates Augmented Reality (AR) technology with the Problem-Based Learning-Reading Concept Mapping (PBL-Remap) model, has been proven valid, practical, and effective in optimizing students' collaborative skills. This e-module emphasizes the alignment between content design, AR-based visualization, and the PBL-Remap syntax, which is specifically structured to support collaboration across problem orientation and solution evaluation. Through the integrated features of the e-module, students are required to actively discuss, negotiate concepts, and build cognitive compromises to collectively construct a valid concept map (Remap). Integrating AR into the e-module further strengthens engagement by presenting contextual problem simulations in a visual, interactive way, which encourages students to take initiative in sharing roles and improves overall group productivity. These findings reinforce the notion that problem-based learning, when supported by well-designed digital media, is effective in fostering social intelligence and mutual respect in academic settings.

The developed e-module can therefore serve as a reference for educators in designing innovative learning media to strengthen students' 21st-century skills across various biology topics. For future development, we recommend expanding the AR-assisted e-module to cover a broader range of biology topics, particularly those involving abstract or microscopic concepts, and integrating it with other innovative learning models to examine its adaptability across different instructional contexts. Further research is also encouraged to involve larger and more diverse samples, enhance AR features through 3D simulations, gamification, or real-time collaborative tools, and provide adequate training for educators to ensure that the implementation of AR-based e-modules aligns with pedagogical objectives and optimally supports the development of students' 21st-century skills.

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