



Development of AR-assisted socio-scientific issue e-modules on the circulatory system to enhance students' health literacy and critical thinking

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Abstract

Despite the emphasis on integrating critical reasoning and health literacy in 21st-century biology education, current learning practices remain teacher-centered, dominated by low-order assessments, and unsupported by contextual, technology-enhanced materials, creating a gap between curricular expectations and students' actual competencies. This study developed an Augmented Reality (AR)-based e-module with Socio-Scientific Issues (SSI) approach on the circulatory system to enhance health literacy and critical reasoning skills of grade XI students. The urgency arose from findings at SMA Negeri 1 Depok showing teacher-centered biology learning, low health literacy, LOTS-dominated evaluation, and conventional e-modules lacking SSI and AR integration. Using the ADDIE model, the e-module was validated by two experts and a biology teacher, then tested through quasi-experimental non-equivalent control group design with 72 students (36 experimental, 36 control) at SMAN 1 Depok Sleman. Data were analyzed using descriptive statistics and Mann-Whitney test. Results showed the AR-based SSI e-module: (1) integrated SSI features with AR video animation technology, (2) met acceptable validity from expert judgment, (3) was practical for teaching circulatory system, and (4) effectively improved health literacy (N-Gain 0.41) and critical reasoning (N-Gain 0.70) with significant differences between groups ($p < 0.05$). This study transformed biology learning from teacher-centered to student-centered while optimizing productive gadget use to shape critical-thinking Pancasila Student Profiles, opening opportunities for content expansion, advanced AR technologies integration, and sustainable 21st-century biology learning innovation.

Abstrak. Meskipun pendidikan biologi abad ke-21 menekankan integrasi penalaran kritis dan literasi kesehatan, praktik pembelajaran yang berlangsung masih berpusat pada guru, didominasi oleh asesmen berpikir tingkat rendah, serta belum didukung oleh bahan ajar kontekstual berbasis teknologi, sehingga menimbulkan kesenjangan antara tuntutan kurikulum dan kompetensi aktual siswa. Penelitian ini mengembangkan modul e-learning berbasis Augmented Reality (AR) dengan pendekatan Isu Sosial-Ilmiah (SSI) tentang sistem peredaran darah untuk meningkatkan literasi kesehatan dan keterampilan berpikir kritis siswa kelas XI. Kebutuhan mendesak ini muncul dari temuan di SMA Negeri 1 Depok yang menunjukkan pembelajaran biologi yang berpusat pada guru, literasi kesehatan yang rendah, evaluasi yang didominasi oleh LOTS, serta modul e-learning konvensional yang tidak mengintegrasikan SSI dan AR. Menggunakan model ADDIE, e-module ini divalidasi oleh dua ahli dan seorang guru biologi, kemudian diuji melalui desain quasi-eksperimental dengan kelompok kontrol non-ekuivalen melibatkan 72 siswa (36 eksperimental, 36 kontrol) di SMAN 1 Depok Sleman. Data dianalisis menggunakan statistik deskriptif dan uji Mann-Whitney. Hasil menunjukkan bahwa e-modul SSI berbasis AR: (1) mengintegrasikan fitur SSI dengan teknologi animasi video AR, (2) memenuhi validitas yang dapat diterima berdasarkan penilaian ahli, (3) praktis untuk pengajaran sistem peredaran darah, dan (4) secara efektif meningkatkan literasi kesehatan (N-Gain 0,41) dan penalaran kritis (N-Gain 0,70) dengan perbedaan yang signifikan antara kelompok ($p < 0,05$). Studi ini mengubah pembelajaran biologi dari berpusat pada guru menjadi berpusat pada siswa sambil mengoptimalkan penggunaan gadget yang produktif untuk membentuk profil siswa Pancasila yang kritis, membuka peluang untuk perluasan konten, integrasi teknologi AR canggih, dan inovasi pembelajaran biologi abad ke-21 yang berkelanjutan.

A. Introduction

Twenty-first century skills are a set of competencies that are essential for students to face the complexities of life in the era of globalization and digital revolution (Sari & Trisnawati, 2019). These skills include not only academic content mastery, but also the ability to think deeply, communicate, collaborate, and possess rapidly developing information and technology literacy (Mawardi, 2018; Susilawati et al., 2015; Wijaya et al., 2016). One of the fundamental components of 21st-century learning is the 4C concept, in which critical reasoning is closely related to critical reasoning and health literacy (Faradila et al., 2024). When students develop critical reasoning skills, they simultaneously practice critical reasoning to analyze health information, communication to convey evidence-based arguments, collaboration to discuss and broaden perspectives, and creativity to produce innovative solutions to health problems (Lilihata et al., 2024; Rosalino et al., 2024). Therefore, the 4C skills can be comprehensively improved through the integration of critical reasoning and health literacy in biology learning.

Biology education in the 21st-century plays a strategic role in developing students' critical reasoning and health literacy skills. This is because biology material, especially that related to human health, provides an authentic context that gives students the opportunity to critically analyze health information, evaluate scientific claims, and make evidence-based decisions (Aqil, 2017; Aripin & Yulianti, 2018). The development of critical reasoning skills and health literacy in biology learning can be developed through learning strategies, one of which is issue-based learning (socio-scientific issues) (Bruselius-Jensen et al., 2017; Lamanauskas & Augiene, 2019; Sirmayeni, 2023). In this research and development, the aspects studied in critical reasoning skills adopt the indicators developed by Facione (1992), namely 1) explaining, which is related to providing logical statements with concrete evidence, 2) analyzing, which is related to identifying the relationship between information and problems, 3) interpreting, which is related to understanding the meaning of various information, 4) evaluating, which involves assessing the validity of information with valid evidence, and 5) concluding, which involves making conclusions based on hypotheses and relevant information. Meanwhile, the aspect of health literacy refers to indicators developed by Sørensen et al. (2012), namely 1) ability to access information, 2) ability to understand, and 3) self-efficacy.

Through observations of the learning process of students in the classroom and interviews with biology teachers at SMA Negeri 1 Depok from February to April 2025, it was found that the biology learning process remained teacher-centered utilizing a lecture method. A total of 65% of 11th grade students have low learning outcomes because learning has not optimally

developed their critical thinking skills, as seen from the majority of students who are passive during discussions. This has an impact on low health literacy, where 79.1% of students have difficulty understanding health information because learning has not provided a concrete context through relevant health issues. This condition indicates that learning process has not accommodated students' needs in developing their learning potential. Therefore, continuous improvement is necessary to create meaningful learning that can develop students' learning skills, such as critical reasoning and health literacy.

One of the learning skills required in biology education today is critical reasoning. Critical reasoning is one of the dimensions of the Pancasila Student Profile that is emphasized in biology learning. Students with critical reasoning skills are better able to process information objectively, analyze, evaluate, and draw conclusions from various types of information (Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi, 2022). Critical reasoning is one of the higher-order thinking skills that students must master. However, in reality, the learning process is still essentially passive and does not support the development of critical reasoning skills in problem solving (Khoiriyah, 2018). Anisa et al. (2021) also emphasize that one of the reasons for the suboptimal development of critical reasoning skills is the learning process, which fails to stimulate students' interests, talents, and potential optimally. In addition to ineffective learning processes, students' failure in critical reasoning is caused by a lack of learning experience through High Order Thinking Skill (HOTS)-based questions, so that students are not yet accustomed to the types of questions that challenge their analytical and reasoning abilities (Prasetyo & Firmansyah, 2022). Students need critical reasoning in biology to process complex information, analyze scientific data, evaluate perspectives, and draw conclusions when studying body systems, health phenomena, or environmental issues. Without this ability, students only memorize facts without being able to apply them in real contexts such as analyzing the causes of disease, evaluating health information, or making decisions on environmental issues based on scientific evidence. Therefore, a biology learning strategy through contextual issues is needed by applying the SSI model to the circulatory system material.

Based on interviews conducted from February to April 2025 at SMA Negeri 1 Depok, it was found that students lacked critical reasoning skills despite the school having implemented an independent curriculum. This was due to several factors: first, the lack of active student participation during learning meant that they were unable to express their understanding critically and creatively. Second, daily and semester evaluations are still dominated by LOTS

questions, so students are not yet accustomed to working on HOTS questions. Third, the lecture method that is applied results in student activities being limited to taking notes, memorizing concepts, and doing exercises in workbooks based on textbooks with limited images. This condition has serious academic implications for the achievement of critical thinking in the Pancasila Student Profile, where students are not yet able to process objective information, analyze perspectives, evaluate arguments, and draw logical conclusions, which should be the main objectives of the independent curriculum. Therefore, there is a need for innovation in biology learning that can foster critical reasoning through contextual material based on health issues relevant to biology learning.

In addition to critical reasoning skills, learning that relies solely on books and notes is not sufficient to build students' literacy in biology. One literacy skill that has not been optimally integrated into learning practices is health literacy. According to Nutbeam (2000), health education can essentially be implemented through biology learning in the classroom and has the potential to become a goal in achieving 21st-century learning requirements. In fact, low levels of individual health literacy are often influenced by low educational attainment in schools (Lee et al., 2010). In addition, other factors such as domicile, patterns of access to information, developments in information technology, age, race, education, and economic level can have an impact on the level of individual health literacy (Batubara et al., 2020; Gazmararian et al., 2005; Magnani et al., 2018).

Individual health literacy skills are influenced by how they access and process health information for application in real life. However, observations at SMA Negeri 1 Depok revealed a crucial gap: low health literacy among students was caused by biology lessons that did not integrate contextual material and relevant SSI, resulting in knowledge, skills, and attitudes that were not optimally correlated to develop these competencies. These findings are in line with Cornett (2009), theoretical solution, which states that low health literacy can be improved through oral, written, and photonovela communication strategies integrated into education an approach that is absent in learning at SMAN 1 Depok. Bruselius-Jensen et al. (2017), reinforce the argument that biology learning is an optimal medium for improving students' health literacy. The implications are significant: biology education must become a strategic platform for equipping students with the ability to access, understand, and apply health information in real life from choosing a healthy diet, understanding medical information, to responding to public health issues scientifically. Without this integration, students lose the opportunity to develop critical competencies that determine the quality of their future health decisions.

Based on the above explanation, it is evident that health literacy requires critical reasoning as a cognitive engine for processing information, thinking, and making decisions to optimize health literacy. This phenomenon indicates a causal relationship between critical reasoning and health literacy, where health literacy is a manifestation of the application of critical reasoning, therefore without critical reasoning skills, health literacy cannot develop optimally. Thus, to support health literacy and critical reasoning, it is necessary to apply learning with relevant contexts, especially in biology learning. In other words, biology learning can be a bridge between biological science and health issues that occur in society, allowing knowledge skills and attitude skills to demonstrate their interrelationship through health literacy in biology learning. In addition, biology learning has the potential to have an impact when integrated with health issues through SSI as a contextual learning framework, which is expected to improve students' critical reasoning and health literacy skills.

Socio-scientific issues are a learning strategy that can bring about real and relevant contextuality in everyday life (Mayasari & Paidi, 2022; Sari et al., 2022). This learning strategy encourages students to play an active role in stimulating intellectual, moral, and ethical development, as well as awareness of the relationship between science and their surroundings (Laksono et al., 2022; Rohmawati et al., 2018; Subiantoro, 2017). Socio-scientific issues-based learning facilitates students in developing problem-solving skills on the issues being studied as well as finding sources of information to answer questions and pros and cons that arise. Individuals who are accustomed to accessing health information can increase the amount of information obtained, thereby influencing individual knowledge and understanding in making decisions and assessing the health information obtained (Roiefah et al., 2021).

One health issue with a high mortality rate is cardiovascular and blood vessel disease caused by smoking. Preliminary studies show a strong correlation between smoking and an increased risk of heart disease due to habits and the influence of the living environment (Gallucci et al., 2020; Keates et al., 2017). Learning with SSI, which presents controversial issues from various perspectives within the community, thereby sparking both pros and cons, can provide new learning experiences for students. This can support students' critical reasoning and health literacy skills through the SSI learning process by paying attention to aspects of SSI, such as science, culture, ethics, economics, and the environment.

The relationship between the circulatory system and issues such as smoking and cardiovascular disease has great potential in science education, particularly biology. Cardiovascular disease, which is the leading cause of death in Indonesia (26.3% of deaths), can be used as an authentic context to raise

controversial issues such as the impact of modern lifestyles on heart health, disparities in access to cardiovascular health services between urban and rural areas, the controversy surrounding tobacco use and public health policies, and ethical dilemmas in blood donation and transfusion (Gallucci et al., 2020; Keates et al., 2017). Through these issues, students not only learn about the anatomy and physiology of the heart and blood vessels, but are also trained to critically analyze health information, evaluate various perspectives, and make appropriate decisions based on scientific evidence relevant to their daily lives (Subiantoro, 2017).

Recognizing the challenges in learning biology in school, such as low critical reasoning skills and health literacy among students, it is essential to implement gradual and continuous improvements in learning. One way to do this is by utilizing technology and information media that are already familiar to users. Observations show that 100% of students in phase F at SMA Negeri 1 Depok use gadgets in classroom learning to search for information that supports their learning process. However, the use of gadgets in the learning process has a negative impact on student learning activities. This condition is caused by teachers not yet utilizing gadgets as a specific learning medium, so it is not uncommon for students to use gadgets to search for answers from sources that are not relevant. Based on this, the researcher was motivated to utilize mobile devices as a medium and teaching material that can be used as an innovation in classroom learning. One of the media and teaching materials that can support learning by utilizing mobile device technology is the e-module.

The use of e-modules in biology learning, particularly in the subject of the circulatory system, generally focuses on mastering anatomical and physiological concepts, such as blood, circulatory organs, and disorders of the circulatory system, using a conventional approach that only transfers knowledge without integrating SSI relevant to students' lives (Isnaini & Rahayu, 2023). These modules have not developed students' critical reasoning and health literacy skills through authentic problem contexts involving scientific, social, and ethical dimensions, even though research shows that SSI based biology learning can improve health literacy (Puspita, 2022). There is a gap between conventional modules and 21st-century learning needs that emphasize higher-order thinking skills. Therefore, it is necessary to develop SSI e-module on the circulatory system to improve students' critical reasoning and health literacy skills, bridging science content with contemporary health issues so that students not only understand concepts but are also able to analyze, evaluate, and make appropriate health decisions based on scientific evidence.

The use of e-modules provides an effective solution because teaching materials integrated with technology can accommodate adaptive and flexible independent learning (Pachler et al., 2014). E-modules are electronic learning resources containing materials, methods, limitations, and evaluations that are organized in an attractive and systematic manner to achieve competencies in accordance with the curriculum (Sa'diah et al., 2022). Their advantages lie in their ability to motivate students through systematic displays, facilitate independent problem solving, and be accessible without space and time limitations. However, conventional e-modules have significant limitations: their content generally only contains static material with simple visuals such as 2D images and videos that lack context. This weakness is crucial in biology learning, which requires the visualization of abstract and complex concepts and connections to real health issues. Therefore, innovation is needed through the integration of contextual visual elements based on SSI and 3D/Augmented Reality (AR) technology. This integration is not merely an aesthetic enhancement, but a fundamental transformation that allows students to visualize biological concepts interactively, explore contextual health issues, and develop health literacy through immersive and meaningful learning experiences.

One contextual element that is suitable for biology learning is SSI, which can make e-modules more relevant and contextual. However, conventional e-modules are currently still limited to presenting static material with simple 2D visuals, making them less than optimal for visualizing abstract biological concepts and providing an immersive learning experience. To overcome these limitations, it is necessary to integrate AR in the form of animated videos that combine digital elements in real-time with the real environment into SSI-based e-modules. Socio-scientific issue-based e-modules supported by AR can increase learning engagement, foster independence, enthusiasm, interactive experiences, and facilitate meaningful theoretical concept understanding (Basit et al., 2023). The integration of SSI and AR significantly contributes to improving students' health literacy and critical thinking skills: SSI trains students to analyze scientific social issues, evaluate various perspectives, and make evidence-based decisions, while AR strengthens conceptual understanding through interactive visualizations that allow students to see biological objects in real life, thereby creating meaningful learning experiences that equip students with essential competencies to make appropriate health decisions in the future.

Based on this explanation, it is necessary to develop media and teaching materials in the form of augmented reality-based e-modules on SSI in the subject of the circulatory system to enhance students' health literacy and critical reasoning skills.

B. Material and method

The development of AR-based SSI e-modules in this study uses a Research and Development (R&D) model that aims to develop teaching products in the form of media and teaching materials to improve effective learning in schools. The development design used in this study employs the ADDIE development model, known by its acronym for the phases of Analyze, Design, Development, Implementation, and Evaluation. ADDIE is also the most widely used R&D model used in the creation and development of teaching materials (Robert et al., 2024). The ADDIE model is designed to design instructional models and evaluate each stage of development. This procedure will be repeated until the appropriate instructional model is found to achieve the set objectives (Welty, 2007). The procedure for implementing the ADDIE model R&D is presented in the following Figure 1.

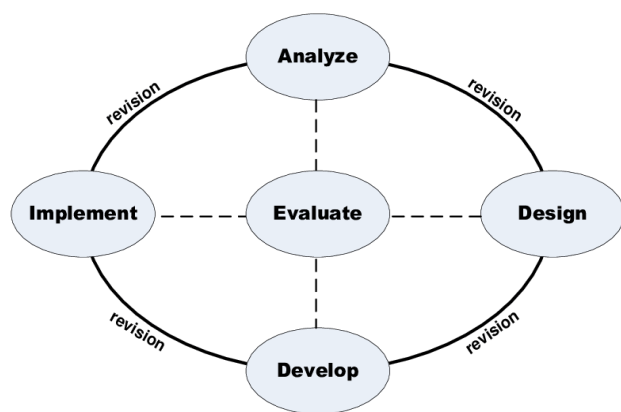


Figure 1 ADDIE model R&D procedure (Branch, 2009)

Research and development of AR-based e-learning modules for SSI began with an analysis phase focused on identify and analyze problems in biology learning. Researchers identified problems, school needs, and potential solutions through open interviews with biology teachers, observations using learning observation sheets, and distribution of questionnaires using a Likert scale to 11th grade students in phase F from February to April 2025. The analysis covered three aspects, namely needs, curriculum, and student characteristics. The needs analysis identified the use of teaching materials (textbooks and exercise books), learning approaches, and materials that were obstacles. The curriculum analysis examined the competencies of the Merdeka Curriculum at SMA Negeri 1 Depok so that the development of media was in line with the learning objectives. The student characteristics analysis understands the emotional conditions and external factors that influence student motivation. The analysis results form the basis for designing effective learning by adjusting the content, display, and AR features provided in the SSI E-module to suit student needs, particularly to develop an AR-based SSI e-module that

is expected to improve student understanding and engagement in biology learning.

Based on the results of the analysis phase, researcher designed a product by creating an AR-based SSI e-module concept. The design includes three main components, namely a product concept with a user-friendly learning and navigation framework, learning materials tailored to the characteristics of SSI and AR technology for an interactive learning experience, and learning tools in the form of critical reasoning tests and health literacy questionnaires. The design was outlined in a storyboard as a visual blueprint and technical-pedagogical guide as the basis for product development.

The AR design process in the E-Module for circulation system material begins with identifying learning objectives, followed by developing content that includes visual and interactive information. The selection of AR applications, such as Unity Hub, enables the creation of 3D models of circulation system components that can be integrated with learning content. AR product specifications include interactive 3D models, text and audio information, and interaction features that allow users to zoom in and rotate models. These AR-based modules offer a more immersive interactive experience and 3D visualization that facilitates understanding, unlike conventional modules that are static and less engaging, thereby increasing student engagement and creating a more immersive learning experience.

The development phase realizes the product design according to the storyboard into a product ready for implementation. This phase includes (1) the preparation and editing of AR-based SSI e-module products that are fully realized and ready to be assessed for feasibility by expert judgment (media experts, subject matter experts, and biology teacher practitioners). (2) Validation by expert judgment by providing assessments and input as a reference for revision and to determine the feasibility of the product before limited testing and implementation. (3) Revision of the product based on the suggestions and input from expert judgment to improve the shortcomings in the developed product, and (3) Limited trials to determine feasibility conducted by two expert judges and product readability by one biology teacher and 36 students in phase F at SMA Negeri 1 Depok using a readability questionnaire.

The field test was the implementation stage using the AR-assisted SSI e-module, which had undergone expert assessment validation, revision, and limited trials. The implementation was carried out in phase F of grade XI at SMA Negeri 1 Depok using two classes, namely the experimental class and the control class, each consisting of 36 students. This trial used a quasi-experimental method with a pre-test post-test non-equivalent control group design. The sampling in this study was predetermined, because only two classes in grade XI phase F were science classes, while

the other classes were social studies classes. The selection of these two classes involved one class as the experimental group that received treatment with the developed product, while the other class served as the control group with different treatment.

The research began with a pre-test to determine students' critical reasoning skills and initial health literacy, and ended with a post-test to measure their final abilities and the effectiveness of the product. The assessment guidelines for measuring critical reasoning used a test instrument in the form of a 10-item essay, while health literacy was measured using a non-test instrument in the form of a questionnaire with a 1-4 Likert scale. In addition, the learning process was observed using a validated instrument to assess the effectiveness of the product on students' critical reasoning and health literacy abilities in the subject of the circulatory system. In addition, observations of the learning process were carried out using validated instruments to assess the effectiveness of the product on students' critical reasoning and health literacy skills in the subject of the circulatory system.

The evaluation phase is the final stage in the ADDIE model to measure the effectiveness and efficiency of the developed product and ensure that learning objectives are achieved and that the methods, media, and materials are appropriate. Evaluation consists of formative and summative evaluations. Formative evaluation is conducted at each stage of development to assess validity, feasibility, and provide feedback on the AR-based SSI e-module through expert

judgment assessments in the fields of media and material, biology teacher practitioners, and responses from 11th grade students in phase F. Summative evaluation assesses the overall effectiveness of the AR-based SSI e-module on the circulatory system material in improving students' critical reasoning and health literacy skills using critical reasoning test instruments and health literacy questionnaires after implementation.

The data collection techniques used in this Research and Development study employed test techniques in the form of critical reasoning pre-tests and post-tests, while non-test techniques consisted of observation, interviews, and questionnaires. The data collection instruments used consisted of critical reasoning ability tests, health literacy questionnaires, interview guides, expert judgment validation sheets, practicality questionnaires by biology teachers, readability questionnaires by students, and learning implementation observation sheets. The feasibility assessment of the AR-based SSI e-module was carried out by expert judgment, while the practicality assessment of the AR-based SSI e-module was carried out by biology teachers and the readability response of phase F students. The scores for the feasibility and practicality assessment instruments for the AR-based SSI e-module obtained through quantitative calculations were then interpreted based on assessments using a 1-4 Likert scale, then interpreted based on the assessment system and criteria in the following Table 1.

Table 1 Score interpretation

Formula	Score interval	Criteria
$M_i + 1.5 S_{bi} < \bar{X} \leq M_i + 3.0 S_{bi}$	$3.25 < \bar{X} \leq 4.00$	Very good
$M_i + 0 S_{bi} < \bar{X} \leq M_i + 1.5 S_{bi}$	$2.50 < \bar{X} \leq 3.25$	Good
$M_i - 1.5 S_{bi} < \bar{X} \leq M_i + 0 S_{bi}$	$1.75 < \bar{X} \leq 2.50$	Less
$M_i - 3.0 S_{bi} < \bar{X} \leq M_i - 1.5 S_{bi}$	$1.00 < \bar{X} \leq 1.75$	Very less

The effectiveness of the AR-based SSI e-module was determined from the results of pre-tests and post-tests on students' health literacy and critical reasoning skills. Health literacy was measured using a questionnaire with a Likert scale that had four answer options, namely SA = Strongly Agree, A = Agree, D = Disagree, and SD = Strongly Disagree. The students' answer choices were converted into scores, with positive questions assigned SA = 4, A = 3, D = 2, and SD = 1. Negative statements were assigned SA = 1, A = 2, D = 3, and SD = 4. The data obtained from the measurement of students' health literacy skills was ordinal data. Critical reasoning was measured using an essay-type test consisting of 10 questions administered at the beginning and end of the learning process, both in the experimental and control classes.

The effectiveness of AR-based SSI e-modules in improving students' health literacy and critical reasoning was analyzed using the normalized gain (N-Gain) score technique with the Formula 1 (Hake,

1999). The N-Gain score obtained is then interpreted based on the criteria in the Table 2.

$$g = \frac{S_f - S_i}{S_{max} - S_i} \dots \dots \dots \text{Formula 1}$$

Description:

g = Normal (standard) gain value
 S_f = Post-test score
 S_i = Pre-test score
 S_{max} = Maximum score

Table 2 N-Gain score criteria

Gain size (g)	Interpretation
$(g) \geq 0,70$	High
$0,30 \leq (g) < 0,70$	Medium
$(g) < 0,30$	Low

Before determining parametric or non-parametric statistical tests, prerequisite tests are needed to ensure that assumptions such as normality

and data homogeneity are met. Normality tests are conducted to determine the normal distribution of data in the experimental and control classes using the Kolmogorov-Smirnov test. The data is declared to be normally distributed if the significance value is > 0.05 . For samples < 50 , the interpretation uses the Kolmogorov-Smirnov test significance value. Meanwhile, the homogeneity test uses Box's M Test to test the similarity of variance between of the experimental and control classes. The data is considered homogeneous if the significance value is > 0.05 .

After the prerequisite tests were met, hypothesis testing was carried out to determine whether the AR-based SSI e-module that was developed had successfully facilitated students' health literacy and critical reasoning skills between the experimental and control groups after implementation. If the data obtained met the prerequisites of normality and homogeneity, then the MANOVA test was continued with the help of the SPSS 26 statistics application. This study used the non-parametric Mann-Whitney test because the data obtained were not normally distributed. The following are the testing hypotheses in this research and development:

- H0 There was no significant difference in the improvement of students' health literacy and critical reasoning skills between the experimental class and the control class simultaneously.
- Ha There was a significant difference in the improvement of students' health literacy and critical reasoning skills between the experimental class and the control class simultaneously.

C. Results and discussion

The product designed and developed in this study is an augmented reality-based E-Module on socio-scientific issues in the subject of the circulatory system, with the aim of improving the critical reasoning and health literacy of students in phase F. This product was developed as a website and mobile application, requiring a stable internet connection for operation. Meanwhile, the learning activities in the SSI E-LKPD are based on the SSI approach, which consists of presenting socio-scientific issues (issues oriented), analyzing socio-scientific issues (issues analyze), clarifying issues and making decisions (clarify issues and make decisions), discussing and evaluating (discuss and evaluate), and reflecting. The development of AR-based SSI E-Modules is based on the ADDIE development model, which consists of five stages. The five stages of the ADDIE model are described in Table 3.

Table 3 ADDIE development procedure (Branch, 2009)

Phase	Activities	Achievements
Analyze	- Conduct open interviews and preliminary observations at schools regarding issues in biology learning. - Analyze the needs of students and teachers in biology learning. - Develop a work plan (design).	Identifying the root causes of problems in biology learning through needs analysis in schools and identifying priority needs for biology learning in accordance with school conditions.
Design	- Designing learning media contained in storyboards. - Creating the necessary research instruments, such as expert judgement assessment questionnaires, health literacy questionnaires, critical thinking test questions, and learning observation sheets.	The AR-assisted SSI E-Module is designated as an innovative learning medium that is in line with the SSI learning design, and there are research instruments for development and evaluation of assessment in the AR-assisted SSI E-Module.
Develop	- Creating AR-assisted SSI E-Module products. - Validating products through 2 expert judgement. - Conducting limited trials. - Revising the product.	The quality of the product can be continuously improved through revisions and is ready for implementation. At this stage, it is also possible to determine the validity and practicality of the product through expert judgment.
Implement	Conducting limited trials on grade 11 students in phase F who have studied the circulatory system material.	Has the potential to improve students' critical thinking and health literacy in biology learning.
Evaluate	Evaluating AR-assisted SSI E-Module products based on implementation data.	Determines the validity, effectiveness, and practicality of the product in achieving the expected learning objectives. At this stage, the feasibility of implementing the product on a wider scale is also determined.

The analysis stage was carried out using two methods, namely directly in the field and based on a systematic literature review to identify learning needs and find the causes of problems in biology learning to achieve learning objectives. This analysis was based on

actual field conditions with a specific focus on biology learning media through structured interviews with biology teachers at SMA Negeri 1 Depok. Table 4 are the results of the analysis of potential problems found in the field.

Table 4 Analyze potential problems found in the field

No	Current biology learning media	Required biology learning media
1	Biology lessons in schools still use printed books and worksheets, PowerPoint presentations, and e-books from the independent curriculum available on the Ministry of Education and Kemendikbud website.	There is a need for innovative learning media in the form of interactive e-modules based on technology that display clear visualizations with images and animated videos that are easy for students to understand.
2	Teachers' use of media does not take into account student characteristics, making it difficult for students to understand and visualize material that requires visualization and in-depth understanding, such as the mechanism of blood circulation.	An interactive augmented reality-based e-module is needed, containing several elements to support different learning styles, such as engaging narrative text, easy-to-understand images, audio explanations of biology material, contextual learning videos and animated learning videos, and augmented reality that presents the mechanism of the circulatory system with the aim of attracting students' attention and interest in learning biology.
3	There are no assignments that develop and improve students' health literacy and critical reasoning skills in a manner that is consistent with biology learning.	An e-module is needed that includes health issues relevant to the circulatory system material as a real-life case analysis assignment presented in the form of a narrative text related to circulatory system disorders. Students will then engage in group dynamics through role-playing related to the case and the roles assigned to develop and improve students' health literacy and critical reasoning skills.

Table 5 Description of the product design developed

Parts of the developed product (in Indonesian)	Descriptions
	Cover page display
	Instruction page display

Parts of the developed product (in Indonesian)	Descriptions
INFORMASI E-MODULE  ELEMEN Pemahaman Biologi Pada akhir fase F, siswa memiliki kemampuan mengaitkan hubungan antara struktur dan fungsi organ di dalam sistem peredaran darah manusia yang terjadi di dalam sistem peredaran darah antara sistem organ dalam tubuh untuk menerapkan prinsip ilmiah dan observasi, menerapkan prinsip penemuan, dan mengaitkan mekanisme evolusi dengan proses terjadi keterkaitan dan keterkaitan biologis organisme menerapkan prinsip penemuan dan penemuan, serta menerapkan proses bioteknologi modern. ELEMEN Keterampilan Proses Menganalisis, menginterpretasikan dan mengaitkan, menerapkan dan melakukan penemuan, menerapkan dan melakukan data dan informasi, menggunakan dan melakukan, serta menggunakan hasil. vi INFORMASI E-MODULE INFORMASI UMUM Kelas/Fase : XI Fase F Topik : Sistem Sirkulasi Alokasi Waktu : 10 JP Profil Pelajar Pancasila : Beriman kepada Tuhan YME, Berakhlak Kritis, Mandiri, Gotong Royong, Kreatif, Kolaborasi Pendekatan Pembelajaran : Socioscientific Issue Sarana Prasarana : E-Module, E-LKPD, Internet, Gadget  CAPAIAN PEMBELAJARAN Pada akhir fase F, peserta didik memiliki kemampuan mengaitkan keterkaitan struktur organ pada sistem sirkulasi dengan fungsinya serta kelainan atau gangguan yang muncul pada sistem sirkulasi. TENTANG SOCIO-SCIENTIFIC ISSUES Socio-scientific Issues (SSI) merupakan isu yang didasari oleh konsep atau masalah ilmiah yang menjadi pertimbangan di kalangan masyarakat dan memiliki dampak sosial, etis, dan lingkungan. Mengapa SSI diterapkan pada pembelajaran Biologi melalui E-Module? Pendekatan SSI yang diintegrasikan pada pembelajaran dapat mengatasi kesulitan siswa dalam mengaitkan relevansi antara pengetahuan biologi yang dimiliki dengan permasalahan kehidupan sehari-hari sehingga pembelajaran menjadi lebih kontekstual. SSI yang diintegrasikan pada pembelajaran dapat memotivasi siswa dalam meningkatkan kemampuan belajar dan berakhlak berkeadilan. SSI menjadi sangat penting digunakan karena dapat menjadi penghubung permasalahan yang nyata di masyarakat dan sebagai tantangan peserta didik dalam mengaitkan konsep ilmiah. vii	E-Module information page display
BIO ISSUE I Mari menganalisis isu yang disajikan pada artikel berikut! "MEROKOK dan Pembuluh Darah: Keterkaitan yang Perlu Diperhatikan" Merokok telah lama dikenal sebagai faktor risiko utama penyakit serius, termasuk penyakit jantung dan stroke. Salah satu alasan utama dibalik dampak merokok yang merugikan adalah pengaruhnya terhadap pembuluh darah, yang merupakan jaringan vital dalam sistem kardiovaskular. Ada banyak zat kimia dalam rokok dan asap rokok yang dapat merusak jantung dan pembuluh darah penggunaannya. Dua zat yakni nikotin dan karbon monoksida mengganggu kemampuan sistem kardiovaskular untuk berfungsi dengan baik. Paparan terhadap nikotin dan karbon monoksida mengubah jantung dan pembuluh darah dengan cara yang meningkatkan risiko penyakit jantung dan kardiovaskular. Nikotin menyebabkan pembuluh darah menyempit, yang mengurangi jumlah darah yang mengalir ke organ-organ. Siring waktu, penyempitan konstan menghasilkan pembuluh darah yang kaku dan kurang elastis. Pembuluh darah yang menyempit mengurangi jumlah oksigen dan nutrisi yang diterima oleh sel-sel. Karbon monoksida mengikat hemoglobin, molekul dalam darah yang membawa oksigen. Ketika karbon monoksida terikat pada hemoglobin, oksigen tidak dapat terikat. Hal ini mengurangi jumlah oksigen yang disampaikan ke seluruh sel. 5 BIO ISSUE II Mari menganalisis isu yang disajikan pada artikel berikut! "Apa yang Terjadi pada Tubuh saat Berhenti MEROKOK?" Merokok dalam jangka waktu yang lama bisa meningkatkan risiko seseorang terkena penyakit kronis, mulai dari jantung, penyakit paru obstruktif kronis (PPOK), hingga kanker. Sebuah studi tahun 2021 menunjukkan hubungan antara merokok dengan kecemasan dan depresi. Saat berhenti merokok, tubuh mulai pulih, dan manfaat kesehatan langsung terasa. Keputusan berhenti merokok juga jadi sangat menantang jika seseorang sudah kecanduan nikotin dalam rokok. Kandungan zat ini menyebabkan seseorang jadi cepat marah, sedih, hingga insomnia. Sejumlah perubahan yang akan terjadi pada tubuh secara bertahap jika seseorang mulai berhenti merokok. Melansir WebMD, di Jam pertama saat seseorang mulai berhenti merokok, denyut dan tekanan darah mulai turun dan kembali normal. Pada tahap ini, tangan dan kaki juga akan menghangat dan masuk ke suhu normal. Kemudian dalam waktu delapan jam setelah berhenti merokok, jumlah nikotin dan karbon monoksida dalam darah mulai berkurang hampir setengahnya. Biasanya ditandai dengan napasan yang mulai terasa nyaman. 22	Bio issues page display
BIO ANALYZE Berdasarkan artikel sebelumnya, jawablah pertanyaan berikut sesuai dengan analisa pemahaman kamu! - Berdasarkan artikel sebelumnya, dikatakan bahwa salah satu faktor utama penyakit jantung dan stroke adalah merokok yang dapat menghambat kerja pembuluh darah. Menurut pendapatmu, bagaimana kebiasaan rokok dapat menjadi boomerang terhadap penyakit jantung? Dan apakah seorang perokok yang sudah menemukan hidup sehat dapat terbebas dari penyakit jantung? - Menurut pendapatmu, bagaimana seseorang dapat kecanduan merokok? Apakah hal tersebut dipengaruhi oleh kandungan dalam rokok atau hanya trend yang menunjukkan bahwa seseorang sudah cukup dewasa untuk merokok? - Menurut pendapatmu, apakah seorang perokok yang berhenti merokok dalam beberapa waktu dapat memiliki pembuluh darah normal dan terhindar dari gejala-gejala yang mampu memicu penyakit kardiovaskular? 7 BIO ANALYZE Berdasarkan artikel sebelumnya, jawablah pertanyaan berikut sesuai dengan analisa pemahaman kamu! - Berdasarkan artikel sebelumnya, dikatakan bahwa aktivitas merokok dapat menyebabkan penyakit kronis seperti jantung hingga kanker. Menurutmu, bagaimana hal tersebut dapat terjadi dan memengaruhi mekanisme peredaran darah? - Apakah kecemasan dan depresi yang memengaruhi kebiasaan merokok? Atau apakah faktor lain seperti sosio-ekonomi (pendidikan, pekerjaan, dan tingkat kemiskinan) memengaruhi pada hubungan tersebut? - Saat seseorang memutuskan berhenti merokok, beberapa perubahan dalam tubuh mulai dapat dirasakan. Menurutmu, jika seseorang berhasil sepenuhnya dalam melepaskan diri dari kebiasaan merokok apakah dapat memiliki sirkulasi peredaran darah seperti orang normal tidak perokok? Kemukakan gagasamu! 24	Bio analyze page display

Parts of the developed product (in Indonesian)	Descriptions
	Issues activity page display

Based on the Table 4, contextual learning needs to be developed through the SSI approach and the integration of AR-based interactive learning media with multimedia elements (text, images, audio, video) to support students' learning needs. This media displays the circulatory system mechanism and is equipped with contextual issues about heart health through e-modules to develop students' health literacy and critical reasoning in learning biology.

The design stage includes the preparation of learning tools such as ATP and teaching modules, the design of AR-based SSI e-module storyboards using the Canva platform and Unity Hub application, and the formulation of critical reasoning research instruments and health literacy questionnaires. The e-module prototype was designed using the Canva platform in three parts, namely (1) an introduction containing the cover, instructions for use, and a concept map; (2) content containing activities based on social science issues; (3) conclusions containing evaluations, a glossary, and references. The research instruments were designed to measure product feasibility through two expert assessors, practicality by one biology teacher, and readability by one class of grade XII students in phase F using a 1-4 scale questionnaire and qualitative assessment in the form of suggestions for improvement.

Furthermore, in the development stage, the AR-assisted SSI e-module was realized in accordance with the prototype and storyboard. The product was developed using Canva and converted to Heyzine Flipbook, while the AR application used Unity Hub with animated video content about the human circulatory system. These three tools were chosen to create an integrated learning ecosystem, with Canva for engaging visual content design, Heyzine Flipbook for an interactive digital reading experience, and Unity Hub for immersive AR features, all designed to increase student engagement and conceptual understanding. AR technology with a single marker is placed on each sub-material as a marker, where the

provided marker only needs to be clicked to access the AR animated video. This product was verified by two expert assessors, one biology teacher, and one grade 12 study group to achieve implementation feasibility standards. Table 5 is an overview of the AR-assisted SSI e-module product that has been developed.

Continued in the implementation stage by testing the product that had been verified by experts and practitioners through a quasi-experimental design with unequal pre-test and post-test control groups of 72 students from two 11th grade classes at SMAN 1 Depok. This was aimed at measuring the effectiveness of the product on health literacy and critical thinking skills.

Evaluations are carried out at each stage of the development of the AR-based SSI e-module. The analysis and planning stages were evaluated based on input from the supervising lecturer. The development stage was evaluated through expert validation, practicality tests by biology teachers, and small-scale trials with students to determine the product's feasibility. The implementation stage was evaluated after face-to-face learning in the experimental class to review improvements in students' health literacy and critical reasoning skills. Once deemed feasible, development continued with the publication of scientific articles.

As shown in Table 6, the circulatory system material in the AR-based SSI e-module has met the CP and TP with conceptual accuracy, contextual problems to hone critical reasoning, and in-depth health literacy. The average assessment score of 3.8 (very good) indicates that the media is suitable for use, but there is a need to improve SSI issues that are more viral and pose dilemmas.

According to Table 7, the AR-based SSI e-module is of excellent quality in terms of appearance, operation, and design, with an average score of 3.54. Suggested improvements include citing YouTube video sources or using links, as well as using Calibri/Arial fonts.

Table 6 Results of material feasibility assessment by expert judgment

Assessment aspects	Score	Category
Material	3,82	Very good
Presentation	3,81	Very good
Contextuality e-module with SSI topics	4	Very good
Language	3,5	Very good
Average	3,8	Very good

Table 7 Results of media suitability assessment by expert judgment

Assessment Aspects	Score	Category
Display quality	3.13	Good
Software engineering & ease of operation	3.83	Very good
Design & illustration quality	3,67	Very good
Average	3.54	Very good

Table 8 Feasibility by practitioners

Assessment Aspects	Score	Category
Learning	3,63	Very good
Materials/content	4	Very good
Language	3,67	Very good
Display	3,83	Very good
Average	3,78	Very good

Table 9 Health literacy results

Description	Experimental class		Control class	
	Pretest	Posttest	Pretest	Posttest
Min-value	1	2	0	0
Max-value	1	3	2	3
Mean	1	2.08	0.92	1.86

As shown in Table 8, the AR-assisted SSI e-module meets the requirements in all four aspects (learning, material, language, display) with a score of 3.78 (very good) from biology teachers and is recommended for wide distribution independent of space and time constraints. This assessment is reinforced by the results of media and material expert validation (Tables 4-5), which show that the AR-assisted SSI e-module meets the eligibility standards from technical, pedagogical, and content aspects with a very good category. The content aspect received the highest score (4.00) compared to other aspects, indicating that the integration of the circulatory system material with contextual SSI issues and alignment with the Merdeka Curriculum successfully met the learning substance requirements optimally. Meanwhile, the technical and pedagogical aspects received slightly lower scores (3.75-3.80), indicating minor room for improvement in optimizing the user interface and interactivity of AR features, although they remain in the excellent category. The difference in scores between aspects reflects that the main strength of the e-module lies in the quality of content and relevance of material, while the user experience through AR technology can still be further optimized in the next iteration. The consistency of positive assessments from experts and practitioners indicates

that the AR-assisted e-SSI module is feasible and practical for implementation in learning, especially for circulation system material. These findings are in line with the research by Azrai et al. (2023), which shows that AR learning can improve students' critical thinking skills and encourage active participation, as well as Saputra and Octavia (2024) which proves that AR-based e-modules can facilitate student literacy well. Therefore, AR-based SSI e-modules are practical for application in teaching human circulatory system biology.

As presented in Table 9, the average posttest score for health literacy in the experimental class (2.08) was higher than that of the control class (1.86). The experimental class experienced an increase from a pretest score of 1 to a posttest score of 2.08, while the control class increased from 0.92 to 1.86. This significant difference indicates that the intervention using AR-based SSI e-module with debate roleplay contributed more effectively to improving students' health literacy compared to conventional learning methods. The higher achievement in the experimental class can be attributed to several factors: (1) AR visualization enabled students to interact with 3D representations of complex biological concepts (e.g., circulatory system), which enhanced their conceptual understanding as the foundation of health literacy; (2)

SSI integration exposed students to real-world health issues, allowing them to access, process, and evaluate contextual health information critically; (3) debate roleplay activities facilitated active engagement where students analyzed multiple perspectives, evaluated evidence-based arguments, and made informed health decisions core competencies of health literacy. The combination of immersive visualization through AR, contextual learning via SSI, and argumentative practice through debate roleplay created a synergistic learning environment that not only increased knowledge acquisition (as reflected in the 2.08-fold increase from

the pre-test) but also developed practical skills in applying health information to real-life situations, which is the ultimate goal of health literacy education.

Further analysis used N-Gain to measure the effectiveness of learning by comparing the increase in initial and final scores. This analysis aimed to determine the effect of the SSI e-module with roleplay debate activities on socio-science issues related to the circulatory system on the improvement of students' health literacy. The N-Gain results are presented in Table 10.

Table 10 Health literacy N-Gain score results

Class	N-Gain	Interpretation	
Experimental	0.41	$0.30 \leq (g) < 0.70$	Medium
Control	0.24	$(g) < 0.30$	Low

Table 11 Critical reasoning results

Description	Experimental class		Control class	
	Pretest	Posttest	Pretest	Posttest
Min-value	0	47.5	0	5
Max-value	55	93	63	70
Mean	31.44	79.86	25.67	29.08

Table 12 N-Gain critical reasoning scores

Class	N-Gain	Interpretation	
Experimental	0.70	$(g) \geq 0.70$	Medium
Control	0.003	$(g) < 0.30$	Low

Based on Table 10, the N-Gain of the experimental class (0.41) was higher than that of the control class (0.24). The experimental class was in the medium category, while the control class was in the low category. These results prove that the implementation of AR-based SSI e-modules has an effect on improving students' health literacy. In the N-Gain score category, learning improvement is divided into three levels: high (≥ 0.70), medium (0.30-0.70), and low (< 0.30). The experimental class with an N-Gain of 0.41 (medium category) proved to be superior to the control class with an N-Gain of 0.24 (low category), indicating that the AR-assisted SSI e-module was 71% more effective. The superiority observed in the experimental class was due to the AR-assisted e-module's ability to provide interactive visualization, active and contextual learning, increased learning motivation, and differentiated learning tailored to individual student needs. This proves that the integration of AR technology in biology education, particularly in the subject of the circulatory system, has a significant impact on improving students' health literacy. This finding is in line with the research by Arizen and Suhartini (2020), which proves that SSI-based learning improves students' science literacy because the SSI stages train argumentation skills in

explaining scientific phenomena, interpreting data, and making decisions based on literacy results.

According Table 11, the average critical reasoning posttest score for the experimental class (79.86) was higher than that of the control class (29.08). The experimental class experienced a significant increase from a pretest score of 31.44 to a posttest score of 79.86, while the control class only increased from 25.67 to 29.08. Based on Table 12, the N-Gain value of the experimental class (0.70) is higher than that of the control class (0.003). The experimental class is in the medium category, while the control class is in the low category. These results prove that the application of AR-assisted SSI e-modules has a positive impact on improving students' critical reasoning skills in phase F. Based on the N-Gain score criteria, the high category (≥ 0.70) indicates highly effective learning, the medium category (0.30-0.69) indicates moderately effective learning, and the low category (< 0.30) indicates ineffective learning. The experimental class with the AR-SSI-based e-learning module achieved an N-Gain of 0.70 (medium category), which was much higher than the control class, which only achieved 0.003 (low category). This advantage was due to the integration of AR technology, which created interactive learning with concrete visualizations, as well as the Socio-Scientific Issues approach, which trained

students to analyze contextual problems, evaluate information, and formulate critical solutions, thus proving to be more effective in improving the critical reasoning of phase F students, especially on the subject of the circulatory system in the experimental class. Results prove that the application of AR-assisted SSI e-modules has an effect on improving the critical reasoning of phase F students. Manunal (2024) proved

that learning using SSI-based electronic modules improves critical reasoning dimensions through contextual issues, because students are trained to analyze problems, evaluate sources, and formulate solutions. Sitanggang et al. (2024) also stated that learning with SSI modules stimulates learning skills through issues to strengthen students' understanding.

Table 13 Results of normality tests for the experimental and control classes

Desc	Class	Kolmogorov-Smirnov ^a		
		Statistic	Df	Sig.
Health Literacy	Pretest C. Experiment	.214	35	.000
	Posttest C. Experiment	.231	35	.000
	Pretest C. Control	.153	36	.032
	Posttest C. Control	.157	36	.025
Critical Reasoning	Pretest C. Experiment	.144	36	.058
	Posttest C. Experiment	.150	36	.040
	Pretest C. Control	.143	36	.061
	Posttest C. Control	.296	36	.000

Table 14 Results of the homogeneity test for the experimental and control classes

Test of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Health Literacy	Based on Mean	10.981	3	138	.000
	Based on Median	6.503	3	138	.000
	Based on Median and with adjusted df	6.503	3	85.304	.001
	Based on trimmed mean	9.881	3	138	.000
Critical Reasoning	Based on Mean	1.615	3	140	.189
	Based on Median	1.652	3	140	.180
	Based on Median and with adjusted df	1.652	3	113.612	.181
	Based on trimmed mean	1.733	3	140	.163

Table 15 Results of the Mann Whitney test for health literacy and critical reasoning

Test Statistics ^a		
	Health Literacy	Critical Reasoning
Mann-Whitney U	216.500	37.500
Wilcoxon W	846.500	703.500
Z	-4.768	-6.888
Asymp. Sig. (2-tailed)	.000	.000

Table 16 Spearman correlation test results

			Health Literacy	Critical Reasoning
Spearman's rho	Health Literacy	Correlation Coefficient	.734**	1.000
		Sig. (2-tailed)	.000	.
		N	72	72
	Critical Reasoning	Correlation Coefficient	1.000	.734**
		Sig. (2-tailed)	.	.000
		N	72	72

Based on Table 13, the health literacy and critical reasoning data in both classes had a significance value of < 0.05 , indicating that the data were not normally distributed. The consequence of this abnormal data distribution is that parametric statistical tests (such as the Independent Sample t-test) cannot be used because they violate the

assumption of normality, which is a key prerequisite for parametric tests. Therefore, the analysis of the differences between the two groups must use the Mann-Whitney U test as a robust alternative to the violation of the normality assumption, so that the analysis results remain valid and reliable even though the data are not normally distributed.

Subsequently, a homogeneity test was conducted using the Levene test in IBM SPSS Statistics 26 to confirm the basic assumptions of parametric statistical analysis. Decision criteria: data is homogeneous if the significance is > 0.05 , and not homogeneous if < 0.05 . According to Table 14, health literacy data has a significance value of < 0.05 , indicating that it is not homogeneous, while critical reasoning data shows a significance value of > 0.05 , indicating that it is homogeneous. Because health literacy data is not homogeneous, further analysis uses nonparametric statistics with the Mann-Whitney test to avoid violating the homogeneity assumption required for parametric tests, which could lead to biased results and increased Type I error rates (Creswell & Creswell, 2018; Pallant, 2020). Creswell and Creswell (2018) emphasizes that Mann-Whitney U test provides more robust and valid inferences for non-homogeneous data because it does not assume equal variances and is less sensitive to outliers, while Pallant (2020) argues that nonparametric tests analyze rank-ordered data rather than raw scores, thereby reducing the impact of variance heterogeneity on statistical conclusions. Therefore, the Mann-Whitney test is employed for health literacy data to ensure accurate comparison between groups, while independent t-test is used for critical reasoning data that meets parametric assumptions.

The Mann Whitney test results show a p-value of $0.00 < 0.05$ for both variables (health literacy and critical reasoning), meaning that there is a significant difference between the experimental and control classes (see Table 15). It can be concluded that the implementation of the AR-based SSI e-module has a proven effect on improving the health literacy and critical reasoning of phase F students. These findings are in line with the research by Subandi et al. (2024), which shows that AR-based health education is more effective in increasing knowledge than conventional methods, with significant differences between groups ($p < 0.05$). Meanwhile, research by Sung et al. (2024) also shows that the SSI approach is effective in improving students' critical thinking skills in science learning with a Mann-Whitney test result of 0.00001, which is significant because $p < 0.05$. The combination of AR and SSI in this e-module creates optimal learning synergy to develop both competencies simultaneously through interactive visualization and exploration of contextual health issues.

The results of the Spearman correlation test showed a p-value of $0.000 < 0.05$, indicating a correlation. The strength of the relationship was classified as strong with a correlation value of 0.734 (see Table 16). This value indicates a strong positive relationship between the two variables, meaning that the higher the students' health literacy, the better their critical reasoning skills in biology learning, and vice versa.

The AR-based e-module with the SSI approach has a significant effect on students' health literacy through the presentation of relevant health issues that encourage in-depth literacy exploration. Students are confronted with real problems such as the effects of smoking on the circulatory system, motivating them to seek additional information and understand the socio-scientific context. Nursyada et al. (2025) show that students in issue-based learning tend to explore literacy more broadly. AR visual elements play a crucial role in arousing curiosity through interactive visualizations of circulatory system disorders and the effects of smoking.

The implementation of AR in e-modules uses marker-based scanning to display interactive animated videos comparing normal organs and those affected by smoking, atherosclerosis simulations, and animations of the accumulation of harmful substances in the circulatory system (Cheng & Tsai, 2019), while SSI implementation is carried out through the presentation of authentic cases of cardiovascular disease prevalence, tobacco control policy dilemmas involving health versus economic perspectives, and scenario-based discussion activities to analyze multi-stakeholders and construct evidence-based arguments (Sadler et al., 2016; Zeidler et al., 2019), with these two elements integrated synergistically where AR visualization serves as an initial stimulus that triggers investigation through the SSI framework to develop students' health literacy and critical reasoning.

These findings are also in line with Balqis and Raksun (2024) prove that the use of images and videos helps students understand complex concepts more effectively. Socio-scientific issue-based learning enables critical discussion of health issues from a social and ethical perspective. Rifa'i and Subiantoro (2022) show that participation in socio-science discussions improves health literacy because students are trained to think critically and make decisions based on information. One of the statements made by students who achieved the highest scores in health literacy and critical reasoning was when students were able to explain in detail the mechanism of blood vessel endothelial damage and chronic inflammation, leading to plaque buildup that narrows the artery lumen and reduces oxygen supply to the heart, as well as linking this to economic impacts and social and ethical dilemmas in society.

AR-based e-modules with an SSI approach effectively improve critical reasoning skills by presenting complex socio-scientific issues that encourage analysis from various perspectives and consideration of socio-scientific impacts. When faced with open-ended questions such as the health effects of smoking, students are encouraged to think critically and evaluate information from various sources. Septiningrum et al. (2021) prove that issue-based learning improves critical reasoning skills because students are trained to question assumptions and

make decisions based on evidence. The visual elements of AR in e-modules play an important role in arousing students' curiosity through interactive visualizations of health issues such as the impact of smoking on the circulatory system. Students not only witness the real consequences, but also reflect on the impact of individual actions on public health. Ramadhani et al. (2025) stated that students build knowledge through direct experience and reflection, so that AR elements can stimulate the critical reasoning process.

Socio-scientific issue-based learning encourages discussion and argumentation about the issues at hand, training students to evaluate arguments, consider different points of view, and develop evidence-based solutions. Masing and Aminatun (2022) show that students who engage in critical socio-science discussions experience a significant increase in critical reasoning skills. Thus, AR-based SSI e-modules not only increase knowledge about health issues, but also strengthen critical reasoning and decision-making skills in a broader social context.

D. Conclusion

The results of research and development of AR-assisted SSI e-modules on the subject of the circulatory system have undergone comprehensive validation covering three main aspects, namely feasibility, practicality, and effectiveness. In terms of feasibility, this module has been validated by experts and proven to meet the established validity standards, even exceeding the feasibility threshold for implementation in biology learning. This expert validation included an assessment of the instructional design, the suitability of the content to the curriculum, the integration of AR technology, and the relevance of the socio-scientific issues raised in the e-module. In terms of practicality, the module received positive responses from both teachers and students in phase F, indicating that the module is highly useful and easy to operate in an actual learning context. This practical assessment shows that the module is not only theoretically valid but also feasible to be applied in a classroom learning setting.

The effectiveness of the module was measured through a quasi-experimental design by comparing the learning outcomes of the experimental group using the AR-assisted SSI e-module with the control group using the STAD cooperative model. The results of the study showed a statistically significant increase in the two main dependent variables. First, students' health literacy improved with a N-Gain value of 0.41, which is in the medium category, indicating that students experienced an improvement in their conceptual understanding of health issues in the circulatory system, such as cardiovascular disease risk factors, healthy lifestyles, and prevention of circulatory system disorders. Second, students' critical reasoning skills showed a more substantial increase with an N-Gain value of 0.70, which falls into the high category.

This increase in critical reasoning skills reflects that students are able to analyze controversial health issues in greater depth, evaluate various perspectives, and construct more solid scientific arguments. This success can be attributed to four main components of the integrated module: (1) an interactive interface with AR technology that visualizes the structure and function of the circulatory system in three dimensions and immersively, (2) systematic navigation that facilitates structured learning and appropriate scaffolding, (3) an SSI framework that presents controversial and contextual issues to stimulate cognitive engagement, and (4) a discussion platform that encourages scientific argumentation through role-playing and debate. The integration of these four components creates a learning environment that not only presents factual information but also develops higher-order cognitive skills through the exploration of authentic issues relevant to students' lives.

Thus, the AR-assisted SSI e-module has been proven to be valid, practical, and effective in improving students' health literacy and critical reasoning skills in the subject of the circulatory system. This module has met the eligibility standards based on expert validation, demonstrated high practicality based on positive responses from teachers and students, and produced significant learning effectiveness with an increase in health literacy of N-Gain 0.41 (medium category) and critical reasoning skills of N-Gain 0.70 (high category) in the experimental group compared to the control group. The success of this module shows that the integration of AR technology with a social-scientific issue-based learning approach can be an innovative solution in improving the quality of biology learning, particularly in developing students' health literacy and critical reasoning skills, which are essential in the digital age and in facing various contemporary health issues. This research makes an important contribution to the development of technology-based learning media that focuses not only on content mastery but also on the development of higher-order thinking skills that are essential for 21st-century learning.

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