Jurnal Biolokus: Jurnal Penelitian Pendidikan Biologi dan Biologi
Vol. 8, Issue 2, December 2025
Pages: 288 – 308

p-ISSN: 2621-3702
e-ISSN: 2621-7538

A Digital Learning Environment (DLE) with STEM and Game-Based Learning (GBL) approaches for fostering scientific literacy among future biology teachers

Amining Rahmasiwi[1]*, Dita Purwinda Anggerlla[1], Triana Atika Zulfa[1], Muhammad Ali[2]
[1]Department of Biology Education, Faculty of Education, Universitas Islam Negeri Raden Mas Said Surakarta
Jl. Pandawa, Dusun IV, Pucangan, Kartasura, Sukoharjo, Central Java, 57168, Indonesia
[2]Department of Life Science, Abasyn University Islamabad Campus, Park Road,
Chak Shahzad, Islamabad, Pakistan
*corresponding author: amining.rahmasiwi@staff.uinsaid.ac.id

ABSTRACT

Scientific literacy is a crucial competency for biology graduates to address 21st-century scientific and educational challenges, as it enables the understanding, evaluation, and application of scientific information in academic and real-world contexts. However, prior studies indicate that prospective biology teachers often exhibit low scientific literacy, particularly in conceptual understanding, problem-solving, and interpretation of experimental data. To address this issue, this study aimed to develop and examine the effectiveness of a Digital Learning Environment (DLE) integrating STEM and Game-Based Learning (GBL) approaches to enhance scientific literacy among prospective biology teachers. The study was conducted at Raden Mas Said State Islamic University Surakarta during the even semester of the 2023–2024 academic year, employing the ADDIE instructional design model. A pre-experimental posttest-only control group design was used during the implementation phase, involving 19 students from the Tadris Biology Program. The developed web-based DLE consisted of mission-based learning modules designed to strengthen general biology concepts, incorporating sequential missions, guiding clues, datasets, conceptual explanations, and Virtual Laboratory tools for online experimentation. Expert validation results indicated that the DLE was feasible, user-friendly, and effective in improving students' scientific literacy. Nevertheless, the study identified several limitations, including technical challenges, students' adaptation to digital learning, a short implementation duration, and a limited sample size, which restricts generalizability. Future studies are recommended to involve larger and more diverse samples, extend the implementation period, apply qualitative methods, and integrate adaptive learning analytics and AI-based feedback to support personalized learning and higher order scientific thinking.

Keywords: Biology education, digital learning environment (DLE), game-based learning (GBL), scientific literacy skills, STEM

INTRODUCTION

The ability to collect, manage, produce, and transfer information is becoming increasingly crucial as society transitions from the industrial era to the information age in the 21st century (Julia & Isrokatun, 2019). This shift has resulted in an overwhelming variety of information sources, making it essential, especially for students, to develop the capacity to critically evaluate and transform information into meaningful knowledge (Kivunja, 2014; Voogt & Roblin, 2012). However, possessing knowledge alone is not sufficient; it must be applied appropriately in real-life situations to make informed decisions about personal and societal issues related to science and technology (Sharon & Baram-Tsabari, 2020). This integrated ability to manage information, convert it into applicable knowledge, and use it for solving everyday problems is referred to as scientific literacy (OECD, 2024).

Scientific literacy is an essential competency required for individuals to adapt to changes in the modern era (Hartono et al., 2023).

This ability involves managing information, transforming it into knowledge, and applying it to make informed decisions about personal and societal issues related to science and technology. In the field of education, scientific literacy is not only crucial for students but also for prospective teachers. According to Haug & Mork, (2021), mastery of scientific literacy has a direct impact on the development of scientific attitudes, such as curiosity, openness to evidence, and reflective thinking. Teachers with strong scientific literacy are better equipped to foster conceptual understanding in students and to facilitate learning that is relevant to real-life contexts (Dragoş & Mih, 2015). Therefore, strengthening scientific literacy should be a key priority in 21st-century education for both learners and future educators.

Biology is a discipline that often requires visualization of complex processes, which can lead to misconceptions in the process (Prayitno & Hidayati, 2022). According to Van Duzor & Rienstra-Kiracofe (2019), DLE provides access to interactive resources and simulations that can help students understand concepts better. Through DLE, students can also access relevant research findings to enrich their learning, while simultaneously reducing cost and time, thereby providing economic benefits and greater convenience Koh & Kan, (2021). This shows that DLE is highly relevant to biology education, as it not only improves conceptual understanding but also provides practical efficiency in the learning process.

In fact, based on several research results related to scientific literacy, it is known that the scientific literacy of Indonesian students, both at the secondary school and tertiary levels, is still relatively low. The latest PISA results in 2022 show that the level of scientific literacy of Indonesian students were ranked 67 out of 81 countries involved (OECD, 2024). Meanwhile, at the tertiary level, students' scientific literacy is generally still relatively low compared to other countries (Nuangchalerm, 2010). Furthermore, research conducted by Adi et al., (2020) towards prospective biology teacher students in Indonesia shows that the scientific literacy of prospective biology teacher students has not reached a satisfactory category. Hartono et al. (2023) shows the same thing, that the results of measuring scientific literacy of prospective biology teachers in Indonesia are still relatively low.

The results of scientific literacy skills measurements of Biology Education students show a consistent trend with previous findings, namely the low level of scientific literacy skills competence among Biology Education students in higher education. With an average score of 40 out of a maximum score of 100, it appears that most of the scientific literacy skills indicators based on Gormally et al. (2012) have not yet reached the expected level for prospective biology teachers. The instrument used in this study refers to the Test of Scientific Literacy Skills (TOSLS) developed by Gormally et al., (2012), which is designed to measure the scientific literacy skills of biology education students with 9 indicators. The scores for each indicator were: 25 for the aspect of identifying valid scientific opinions; 42 for the aspects of conducting effective literature searches and evaluating the accuracy of scientific information; 38 for the aspect of understanding the elements of research design; 53 for the aspect of developing appropriate graphs based on data; 32 for the aspect of analyzing data; 58 in solving problems using quantitative skills, including basic statistics; 37 in understanding and interpreting research results using; and 16 in making inferences and predictions based on quantitative data. In general, these data show that the scientific literacy of Biology Education students is still far from ideal, especially in the aspects of data analysis, inference, scientific information validation, and research design

The low scientific literacy of Indonesian students at the secondary school and college levels is influenced by several factors. According to Siswanto et al. (2023), factors contributing to low scientific literacy include low interest in reading, the use of evaluation tools that do not support the development of scientific literacy, and a lack of mastery in teaching scientific literacy. In addition, other significant factors include the inappropriate selection of learning models, approaches, methods, strategies, learning resources, and assessment tools that are not aligned with the goals of scientific literacy. Factors that are suspected of influencing scientific literacy can be optimized in their application so that they can have a significant impact on the development of students' scientific literacy.

The development of scientific literacy can be optimized through the implementation of the STEM (Science, Technology, Engineering, and Mathematics) approach, which emphasizes the integration of these four disciplines within the learning process. This approach aligns with the indicators of scientific literacy, such as the ability to explain scientific phenomena, design and evaluate scientific investigations, and interpret data scientifically (OECD, 2019). STEM encourages students to think scientifically and analytically (Hidayat et al., 2024), understand scientific concepts contextually, and enhance experimental skills (Sevian et al., 2018). Furthermore, Walsh et al. (2013) emphasize that the STEM approach also cultivates scientific attitudes such as curiosity and environmental responsibility.

However, the application of STEM has not yet been fully effective in boosting students' learning motivation (Julià & Antolí, 2019). To overcome this limitation, Game-Based Learning (GBL) can serve as an effective alternative strategy. GBL provides an engaging, interactive, and contextual learning experience through educational games that not only increase student engagement but also support the achievement of scientific literacy (Li & Tsai, 2013). Qian & Clark, (2016) found that GBL significantly enhances student engagement and deepens their understanding of scientific concepts. Similarly, Voulgari (2020) asserts that GBL strengthens students' ability to interpret data and evaluate scientific information, while also providing authentic simulation-based learning experiences aligned with scientific literacy indicators (Widiyatmoko et al., 2023).

Recent research also highlights the potential of digital game–STEM integration. A 2023 meta-analysis found that digital educational games significantly improve STEM learning outcomes, outperforming traditional approaches effective (Gui et al., 2023). Furthermore, STEM-based interactive e-books and electronic modules have been shown to improve students' scientific literacy in empirical studies (Rustono et al., 2023). For pre-service science teachers, game-based science simulations improve teaching readiness and support deeper conceptual understanding (Sheffield et al, 2024). Despite these advancements, each medium—STEM, GBL, AR/VR games, simulations, and digital STEM e-books—tends to strengthen only certain components of scientific literacy. No single medium fully addresses all the competencies required for future biology teachers. This gap highlights the need for an integrated learning platform that combines the strengths of STEM and GBL within a single digital ecosystem.

Therefore, integrating STEM and Game-Based Learning into a unified digital platform appears to be a strategic solution. A Digital Learning Environment (DLE) offers such potential by merging classroom and laboratory experiences into a digitally supported, interconnected instructional system. The core principles of DLE include interconnectivity, accessibility, affordability, flexibility, and support for meaningful learning experiences (Van Duzor & Rienstra-Kiracofe, 2019). Through DLE, students can experience comprehensive, applicable, and enjoyable learning that enhances scientific literacy holistically. The integration of STEM, GBL, and DLE is particularly important for pre-service biology teachers, as they require both strong scientific competencies and effective digital pedagogy to support future students' scientific literacy.

Integrating STEM, GBL, and DLE simultaneously addresses the limitations of each—providing conceptual depth (STEM), engagement (GBL), and flexible digital access (DLE). This integration has rarely been explored in previous research, especially within the context of biology teacher education, indicating a crucial research gap.

Based on this, the research objectives were formulated to develop DLE media: (1) with a STEM and GBL approach that is valid for use; (2) with a STEM and GBL approach that is practical and feasible for implementation; and (3) to evaluate the effectiveness of DLE media with STEM and GBL approaches in enhancing the scientific literacy of prospective biology teacher students. The novelty of this research lies in the integration of STEM and GBL within a single digital platform specifically designed for the context of teacher education in biology. This combination has been rarely explored in previous studies, particularly in the field of teacher preparation, making it a strategic innovation to strengthen pedagogical and professional competencies as well as scientific literacy skills, which are essential for 21st-century educators.

METHOD

Research design

This research uses the Research and Development type of research with the ADDIE design, which consists of the stages of analysis, design, development, implementation, and evaluation carried out at each stage (Branch, 2009). ADDIE development research steps are as described in Figure 1.

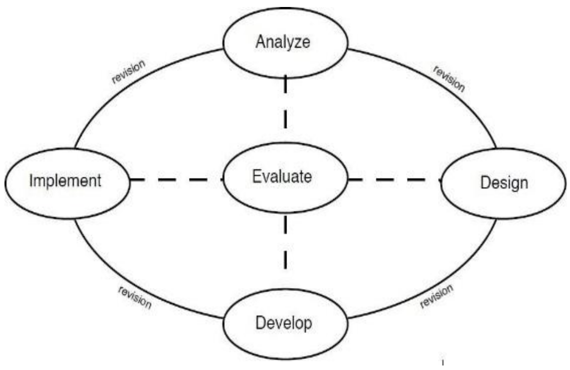

Figure 1. ADDIE development design (Branch, 2009)

Research subject

This study involved 19 Biology Tadris students. The sample was determined using a simple random sampling technique (Creswell, 2016). The use of this technique was justified because the participants were considered homogeneous in terms of their academic ability. This homogeneity was ensured through a placement test conducted at the beginning of the program, which indicated that the students had relatively equivalent academic competencies.

Instrument

a. Analysis

At this stage, a learning needs identification was carried out, including the initial conditions of students, the competencies to be achieved, and the problems encountered in developing scientific literacy. The instrument used was a Needs Analysis Questionnaire, designed to collect data from students and teachers regarding the current learning conditions, interest in the STEM and GBL approaches, and existing gaps in scientific literacy.

b. Design

After obtaining data from the needs analysis, this stage involved designing the product (DLE) and determining its instructional specifications. The instrument used was a Product Design Checklist, which was employed to assess the feasibility of the initial media design, the integration of content with the STEM and GBL approaches, and its alignment with the indicators of scientific literacy.

c. Development

At this stage, the digital learning media (product) was developed by integrating the STEM design framework within the Digital Learning Environment (DLE). According to Jolly (2016), the STEM approach based on design thinking consists of six phases. In this study, these phases were adapted into the development of a Digital Learning Environment (DLE) that incorporates STEM and Game-Based Learning (GBL) approaches to enhance the scientific literacy of pre-service biology teachers.

Table 1. STEM design

STEM Phase	Description	Implementation in DLE
Define the Problem	Students are introduced to real problems relevant to biology (e.g., ecology, genetics, evolution).	Students are introduced to real and contextual problems relevant to biology (e.g., ecology, genetics, evolution).
Research and Imagine	Students search for information, read literature, analyze data, and imagine various possible solutions.	Students search for information, read literature, analyze data, and imagine various possible solutions.
Plan	Students design solutions based on their research findings by integrating concepts from science, technology, engineering, and mathematic	Students design solutions based on their research findings by integrating concepts from science, technology, engineering, and mathematics.
Create / Test and Evaluate	Students test their designed solutions through experiments or simulations and evaluate the results.	Students test their designed solutions through experiments or simulations and evaluate the results.
Improve / Redesign	Students refine less effective solutions based on evaluation results.	Students refine less effective solutions based on evaluation results.
Communicatate	Students present their problem-solving results and proposed solutions.	Students present their problem-solving results and proposed solutions.

The developed media was then validated by experts and tested for its practicality by users (teachers and students). The instruments used included: (1) Expert validation sheet, consisting of assessments by media experts, material experts, and instructional experts on aspects such as content feasibility, visual design, and integration of the applied approaches, and (2) Practicality questionnaire, administered to teachers and students to evaluate the ease of use, clarity of instructions, attractiveness of the media, and relevance of the content.

Table 2. Practicality test criteria

Aspects	Description
Ease of Use	How easy is it to use
	The layout and navigation are easy for users to understand.
	Media comes with instructions
Attractiveness	The media has an attractive appearance
	Media allows users to interact
	Innovative content
Involvement	How actively students are involved
	Media increases motivation
	users feel satisfied
Flexibility and Adaptability	Media supports various devices
	Media can be adapted
Completeness of Features	Media has helper features
	These features are easily accessible

(Cota et al., 2014)

d. Implementation

The validated and approved product was then tested in real classroom learning. The instrument used was a Learning Implementation Observation Sheet, which aimed to assess the extent to which the media was utilized according to the planned learning scenario, as well as to observe students' responses during the learning activity

e. Evaluation

The evaluation was conducted to measure the effectiveness of the media in improving students' scientific literacy. The instrument used was a scientific literacy test (pretest and posttest), which was administered to assess the improvement in students' scientific literacy skills.

Table 3. Indicator of scientific literacy

Category of Scientific Literacy Skills	Indicators
Understanding inquiry methods directed toward scientific knowledge	- Identifying valid scientific opinions - Conducting effective literature searches - Understanding elements of research design and their relationship to conclusions
Organizing, analyzing, and interpreting scientific data and information	- Developing appropriate graphs based on data - Solving problems using quantitative skills, including basic statistics

Category of Scientific Literacy Skills	Indicators
	- Understanding and interpreting basic statistical concepts - Considering inferences, predictions, and drawing conclusions based on qualitative data

(Gormally et al., 2012)

Data analysis

Data analysis in this study was conducted in three stages of testing, namely feasibility, practicality, and effectiveness. The following is a description of each test conducted:

a. Feasibility test

The feasibility test was carried out through content validity and construct validity tests with experts. The results of the percentage calculation are then adjusted to the guidelines according to Sugiyono (2020) in Table 4.

Table 4. Validity criteria for validator assessment questionnaire

Percentage (%)	Qualification	Information
85–100	Very Valid	No need to revise
70–84	Valid	Usable with minor revision
50–69	Quite Valid	Require minor revision
< 50	Invalid	Invalid

(Sugiyono, 2020)

b. Practical Test

Learning media that have undergone product validation tests, continued with practicality tests through practicality tests or small-scale trials. The results of this questionnaire were presented as scores converted into percentages. The formula used to analyze the practicality data from the questionnaire is as follows:

$$V = \frac{Tse}{Tsm} \text{ x } 100\%$$

Description:
Tse = number of empirical scores
Tsm = maximum score
V = number of assessment scores
100% = conctant

The interpretation of the respondent data analysis is presented in Table 5.

Table 5. Analysis of respondent data

Percentage (%)	Criteria
68 ≤ X < 100	Highly practical
56 ≤ X < 68	Practical
44 ≤ X < 56	Moderately practical
32 ≤ X < 44	Less practical
20 ≤ X < 32	Impractical

(Utomo et al., 2020)

c. Product effectiveness trial

Field testing was conducted to determine the effectiveness of the application, using a posttest-only control group design. The pre-experimental research design scheme in this study is shown in Table 6.

Table 6. Posttest only control group design research design

Pretest	Treatment	Posttest
Y1	X	Y1

Description:
Y1 = Pretest Score
Y2 = Posttest Score
X = Treatment

The data were analyzed using the N-Gain Test to determine the extent of students' improvement in Scientific Literacy, using the following formula:

$$\text{N-Gain} = \frac{\textit{Posttest score} - \textit{pretest score}}{\textit{maximum score} - \textit{pretest score}}$$

Table 7. N-Gain score category

N-Gain Score	Category
g > 0,7	High
0,3 ≤ g ≤ 0,7	Moderate
g < 0,3	Low

(Hake, 1998)

Table 8. N-Gain interpretation criteria

Percentage (%)	Interpretation
< 40	Ineffective
40-55	Less Effective
56-75	Moderately Effective
>76	Effective

(Hake, 1998)

RESULTS AND DISCUSSION

1. Analyze stage

At this stage, a comprehensive analysis is conducted on the learning process, student characteristics, and the media and instructional materials that have been used so far. The needs analysis identified several weaknesses in the learning media, including: 1) the use of conventional media such as PowerPoint files, PDFs, and printed modules, which do not fully utilize the potential of digital technology; as a result, the learning experience is less interactive and does not adequately support 21st-century learning needs; 2) the media and instructional materials used are still fragmented between printed and digital formats without integration that supports blended learning, leading to suboptimal student engagement and conceptual understanding; 3) the media have not been able to connect learning materials with real-world contexts, especially in applying the STEM approach that holistically integrates science, technology, engineering, and mathematics, resulting in less than optimal scientific literacy and critical thinking skills among students; 4) the learning media have not been designed in a flexible digital format that is easily accessible anytime and anywhere, making it difficult for students to review materials and engage in independent learning outside of class hours.

Based on the limitations of the learning media that are commonly used, a needs analysis was conducted to determine the types of learning media required by students for biology learning. The results of this needs analysis are presented in Figure 2.

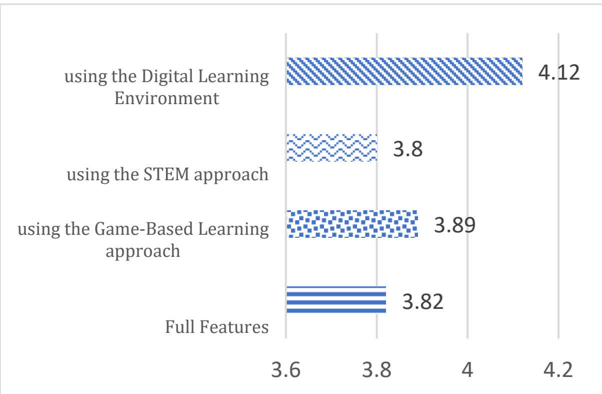

Figure 2. Analysis of media-related needs

The results of the analysis show that each component has an average above 3.8. These results indicate that each component needs development. Biology education students choose DLE learning media as a learning media because it is related to the needs and characteristics of biology studies (Score 4.1).

Based on the results of the students' needs analysis regarding biology learning media, as shown in Figure 2, it was found that the most needed aspect was the use of a Digital Learning Environment (DLE), with an average score of 4.12. This finding indicates that students perceive conventional learning media—such as PowerPoint, PDF materials, and printed modules—as insufficient in providing an interactive learning experience and less effective in supporting 21st-century learning. Through the use of DLE, students can access various digital learning resources in a more interactive and flexible manner (Noskova et al., 2021), thus supporting the development of scientific competencies, such as explaining phenomena scientifically and interpreting data critically (Marty et al., 2013).

Subsequently, the use of a game-based learning (GBL) approach obtained a score of 3.89, indicating that students need a more enjoyable and motivating learning experience. GBL encourages students to actively engage in the learning process through problem-solving and decision-making (Adipat et al., 2021), thereby contributing to their engagement with scientific issues and fostering positive attitudes toward science (Shapiro & Squire, 2011).

The STEM approach received a score of 3.8, emphasizing that students desire more challenging learning experiences through interdisciplinary problem-solving. This approach contributes to the application of scientific concepts in real-world contexts, as students are trained to integrate knowledge of science, technology, engineering, and mathematics in everyday life situations (Winarni et al., 2022).

In addition, the media completeness feature obtained a score of 3.82, indicating that students expect learning media equipped with comprehensive components such as text, audio, video, and digitally integrated interactive features. Media with complete features can enhance scientific literacy in terms of conceptual understanding, thinking skills, and attitudes toward science, as it allows students to learn more comprehensively from multiple sources (Harmatiy, 2020).

Overall, these results indicate that students need digital learning media based on Digital Learning Environment (DLE), STEM, and GBL with complete and integrated features to enhance scientific literacy holistically. By integrating these three aspects, the developed learning media can address the limitations of conventional media while promoting mastery of scientific literacy encompassing knowledge, scientific competencies, and attitudes toward science (Genç, 2015).

Research by Nilyani et al. (2023) has proven that the STEM approach is effective in improving students' scientific literacy; however, it still presents certain limitations, particularly regarding low learning motivation. To address this issue, it is necessary to integrate Game-Based Learning (GBL), which can increase students' motivation and engagement in the learning process. In this context, the Digital Learning Environment (DLE) serves as a platform that integrates the STEM and GBL approaches, allowing them to complement each other and optimally enhance students' scientific literacy.

When linked to the indicators of scientific literacy proposed by Gormally et al. (2012), DLE plays an essential role in supporting the ability to understand the scientific inquiry process by facilitating students in identifying valid scientific opinions, conducting effective literature searches, and understanding elements of research design through access to interactive simulations and digital resources. The STEM approach contributes to skills in organizing, analyzing, and interpreting scientific data—such as creating graphs from data, solving problems using quantitative skills, and interpreting basic statistics—as students are trained to integrate biology concepts with technology, mathematics, and engineering in real-world problem-solving contexts. Meanwhile, GBL emphasizes skills in making inferences, predictions, and conclusions based on qualitative data through game scenarios that encourage students to make evidence-based decisions. The integration of DLE, STEM, and GBL is therefore expected to strengthen biology pre-service teachers' scientific literacy, both in mastering scientific inquiry methods and in managing and interpreting scientific data critically.

Evaluation of analyze stage

Based on the results of the needs analysis, it can be concluded that students perceive conventional learning media such as PowerPoint, PDF, and printed modules as having limitations, as they are less interactive, not fully integrated, and have yet to support 21st-century learning effectively. This is reflected in the findings showing that all aspects obtained average scores above 3.8, indicating that each component still requires further development. Students thus require the development of DLE-based learning media that integrate the STEM and GBL approaches with comprehensive features. DLE functions as the main platform that connects concept-integration learning (STEM) with motivational enhancement (GBL), thereby optimally improving students' scientific literacy. Referring to the scientific literacy indicators by Gormally et al. (2012), the combination of DLE, STEM, and GBL supports students' abilities to understand the process of scientific inquiry, organize and interpret scientific data, and make evidence-based inferences and conclusions. This integration holds significant potential to strengthen biology pre-service teachers' mastery of scientific literacy in terms of knowledge, scientific competencies, and attitudes toward science.

2. Design stage

Based on the needs analysis, it is necessary to design a media that can accommodate scientific literacy of DLE learning media with STEM and GBL approaches. The stages in designing learning media are described as follows:

a. *Design of learning media components*

The first stage involves designing the core components of the media to be developed, including: 1) Competency Achievement, aligned with the learning outcomes of the General Biology course according to the Indonesian National Qualification Framework (KKNI) level 6, to ensure relevance to the higher education standards for future biology teachers; 2) Learning Content, delivered through game-based learning, covers key topics such as the organization of life, the structure of genetic material, basic concepts of evolution, and relevant biological issues; 3) Assessment, conducted through interactive tests embedded in each mission within the game, allowing for real-time measurement of competency achievement; 4) Virtual Laboratory, designed as a supporting tool to help students understand the content and complete missions in the game, thereby enhancing the integrated practical learning experience.

b. *Design of learning structure and STEM-based games*

This stage is central to the development of DLE-based instructional media that integrates STEM and GBL approaches. The learning structure is designed based on the design thinking model in the STEM approach, as proposed by Jolly (2016), which includes: 1) Define the Problem, Learners are introduced to real-world, contextual problems relevant to biological topics such as ecology, genetics, or evolution. These problems are presented through narratives or interactive simulations within the game to help students understand and define the core issues to be addressed; 2) Research and Imagine, After understanding the problem, learners are encouraged to conduct research by reading provided materials, analyzing data from the virtual lab, and exploring available resources. This phase also engages students in creative thinking to imagine various possible solutions; 3) Plan, based on their research, students design solutions. In the game environment, this phase is facilitated through strategic planning activities that align with scientific, technological, engineering, and mathematical principles; 4) Test and Evaluate, the designed solutions are tested through simulations or virtual experiments in the game. Learners evaluate the effectiveness of their solutions based on qualitative and quantitative results; 5) Redesign, following evaluation, learners are allowed to improve less effective solutions. This process supports continuous improvement and fosters reflective and critical thinking skills; 6) Communicate. At the end of each mission, learners are asked to communicate their problem-solving outcomes through reports, presentations, or digital portfolios available on the platform. This stage aims to develop students' scientific communication skills effectively.

c. *Design of Learning Technology and Platform*

The third stage involves determining the appropriate technologies and platforms to support the implementation of the learning media, such as educational game applications, interactive simulations, or virtual learning environments. The selection is aligned with the GBL concept and STEM approach to ensure flexibility, affordability, and accessibility in digital learning

Evaluation of design stage

The design stage, which integrates the Digital Learning Environment (DLE) with STEM and Game-Based Learning (GBL) approaches, demonstrates significant potential in supporting the development of students' scientific literacy.

In the Define the Problem phase, the presentation of real-world biological problems through narratives and simulations within the game-based DLE trains students to identify scientific questions and relate them to everyday life contexts. Subsequently, the Research and Imagine phase encourages students to conduct digital literature searches, analyze virtual lab data, and explore available resources—strengthening their scientific literacy indicators, particularly the ability to understand scientific inquiry methods and evaluate the validity of information sources.

In the Plan phase, the integration of STEM principles into strategy-based problem-solving requires students to combine knowledge of science, technology, engineering, and mathematics, aligning with the scientific literacy skill of applying scientific concepts to real-world problems. The Test and Evaluate phase, conducted through simulations and virtual experiments within the DLE, helps students develop the ability to interpret both quantitative and qualitative data while fostering critical thinking skills. The Redesign phase provides opportunities for students to reflect and improve their solutions, consistent with scientific literacy indicators related to maintaining an open-minded scientific attitude toward revision and verification.

Finally, the Communicate phase, through digital reporting and presentation, encourages students to develop scientific communication skills, which form an essential component of scientific literacy. The use of a DLE platform that supports flexible access across devices further enhances student engagement and motivation, as emphasized in the GBL approach, making the learning process more interactive, adaptive, and contextual.

In conclusion, the integration of DLE, STEM, and GBL not only produces innovative learning media but also effectively addresses the demands of developing holistic scientific literacy for pre-service biology teachers.

3. Development stage

This stage is the development stage of DLE media with the STEM and GBL approaches. The prototype media designs developed include: 1)developing instructional materials according to the lecture material in the RPS, and indicators of Scientific Literacy; 2) compiling materials according to learning outcomes that are adjusted to the STEM approach and its supporters, namely Vlab and AR: 3) compiling evaluations (questions or exercises in games) to hone students' science competencies; 4) Developing media designed based on instructional materials (materials, data, questions, Vlab, and AR); 5) developing questionnaires used to measure product validity and research subject responses; 6) developing instruments in the form of questionnaires to measure digital literacy and tests to measure Scientific Literacy; 7) validating STEM and GBL-based DLE media that have been developed. Table 9 is the result of the feasibility test by experts on the media that has been developed before being revised.

Table 9. Expert validation results for DLE media development before revision.

Rated aspect	Percentage (%)	Criteria
Technical feasibility	61	Quite Valid
Correctness and accuracy of language	60	Quite Valid
Software engineering	83	Valid
Quality of interaction	87	Highly Valid
Average	73	Valid

Table 9 presents the media validation results, which show a reasonably valid average percentage. However, some components exhibit less valid results, particularly in terms of technical feasibility and language correctness. The suggestions given by the validator in terms of technical feasibility are: 1) apply consistent design guidelines across all displays; 2) ensure animations have high resolution and clear visual quality; 3) consider the proportion of visual element placement to fit a balanced layout; 4) use clear and descriptive button labels to describe their functions adequately. Furthermore, suggestions related to language correctness include improving sentences to avoid convoluted language, selecting the right words or phrases to convey messages, avoiding lengthy and complex sentences, and arranging sentences more simply.

The STEM components in the developed DLE media are as follows: 1) Science: the media presents general biology content (for example, topic related to basic scientific concept), this is indicates that the science element is represented within the content; 2) technology: media is delivered online an allows digital interaction; 3) mathematics: the media include element of mathematical activity in form of graphing data analysis; 4) engineering design thinking by trains students to designing conceptual solution, testing idea via digital simulation, improving iterative based on automatic feedback.

The following image shows the revised media based on validator input.

Figure 3. Initial View

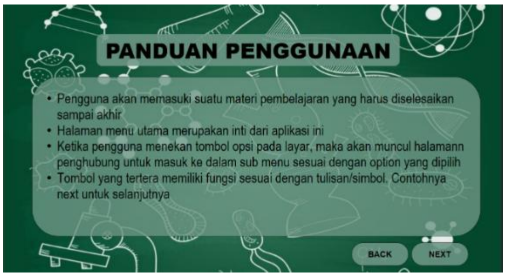

Figure 4. Usage Guide

Figure 5. Main Menu

Figure 6. Mission Menu Display

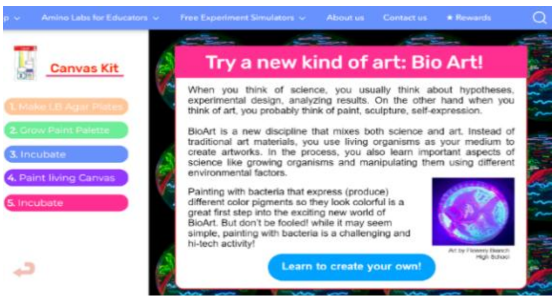

Figure 7. Example of Vlab Display

Expert validators then retested the revised media. The results are shown in Table 10.

Table 10. Expert validation results after revision

Rated aspect	Percentage (%)	Criteria
Technical feasibility	96	Highly Valid
Correctness and accuracy of language	95	Highly Valid
Software engineering	100	Highly Valid
Quality of interaction	94	Highly Valid
Average	96	Highly Valid

The developed DLE media after validation showed an average percentage of 96%, indicating that the media is highly valid. The same results are also shown in every aspect.

In addition to the media aspect, validation was also carried out in terms of material content. The results of material validation by expert validators in the field of biology are shown in Table 11.

Table 11. DLE media material validation results

Rated aspect	Percentage (%)	Criteria
Suitability of material to learning outcomes	80	Valid
Accuracy of Material	100	Highly Valid
Encouraging curiosity	100	Highly Valid
Suitability of presentation	98	Highly Valid
Language Eligibility	92	Highly Valid
Average	94	Highly Valid

The results of the validation showed an average percentage of 94%, which means that the media developed has met the criteria of highly valid. The same results are also presented in percentage scores for each aspect, including the suitability of the material to learning outcomes, accuracy, encouragement of curiosity, presentation feasibility, and language feasibility, which collectively demonstrate the results of a very valid category.

The learning outcome aspect determines the expected results of the learning process, such as skills or knowledge that students must acquire. Materials that are in accordance with learning outcomes ensure that students develop the expected knowledge and skills according to the established standards (Mosha, 2012). In terms of material accuracy, it is very important and influences the quality of the learning process. Accurate material ensures that the information conveyed to students is correct and in accordance with the facts (Suskie, 2018). In the aspect of encouraging curiosity, it is proven that the media developed can stimulate curiosity and can make students more involved in learning because of their interest in following lessons and participating in activities. According to June et al. (2014) by encouraging curiosity, learning media can stimulate students to think more deeply and critically about the material. This helps them to not only receive information, but also analyze and evaluate it (June et al., 2014). Furthermore, in terms of feasibility, proper media presentation ensures that information is delivered in a clear and easily understood manner by students. This avoids confusion and misunderstandings that can interfere with the learning process. Ip et al. (2019) stated that well-presented learning media can attract students' attention and increase their interest in the material. Attractive and interactive designs can make learning more enjoyable and motivating (Ip et al., 2019). Meanwhile, in terms of language feasibility, it shows a percentage of 92% in the very valid criteria. The validator suggests that the material presented is contextual, supported by Vlab and AR, which train students' skills and understanding. This is in line with Ratamun & Osman (2018), who state that VLab is effective in improving understanding and skills in the science process. In addition, Dilmen & Atalay (2021) also support that AR can improve understanding and skills.

Practicality Test

The media implementation stage begins with a practicality test. The practicality of the STEM and GBL-based DLE media developed is assessed based on the responses obtained from 15 biology education students at UIN Raden Mas Said Surakarta. The results are described as follows: Student responses can also be seen based on the questionnaire given. There were 19 students who filled out the questionnaire, the results of the questionnaire responses were then analyzed as described in Table 12.

Table 12. Biology education student questionnaire results

Aspects	Average score
Ease of Use	4.70
Attractiveness	4.70
User Engagement	4.63
Flexibility and Adaptability	4.82
Feature Completeness	4.74
Average	**4.72**
Percentage	**94.36%**
Conclusion	**Very practical**

The results of the questionnaire responses from 19 students can be concluded as practical, with a percentage of 94.36%. The results of the analysis obtained from the questionnaire filled out by students show that they responded well to STEM and GBL-based DLE media.

The results of the practicality test showed that students and lecturers provided positive feedback on their experiences, indicating that the media had effectively met their needs. This is because the media is designed to be easy to understand and operate, so that students can quickly adapt without much technical assistance. Learning media that is easy to operate will be more efficient to use, so that learning will be more effective (Lin et al., 2017).

In addition, integrating interactive elements into learning makes students more engaged and happy during the learning process. Quiz features in the form of games and simulations allow students to actively participate. Interactive learning media can attract students' attention and make them more motivated to learn (Sahronih et al., 2019). By applying GBL principles, students not only learn theory but also engage in fun activities, which increase their motivation and involvement in the learning process.

This media is also designed to be accessible on various devices such as computers, tablets, and smartphones, so that students can learn anytime and anywhere. The flexibility of the media provides an opportunity for students to learn independently and manage their own study time, according to their own pace (Howard & Scott, 2017; Zainuddin & Perera, 2018).

The availability of features such as simulations, interactive exercises, and instant feedback helps students understand concepts better and accelerates the learning process. The availability of these features makes students interested in using media. The right learning media can support learning success (Gašević et al., 2016).

This media integrates relevant STEM concepts with Basic Biology material, helping students better understand the relationships between disciplines. The STEM approach can enhance critical and analytical thinking, which is important in solving real-world problems (Rizaldi et al., 2020).

Evaluation of develop stage

The developed media has gone through a validation process by learning from media experts. The display design has been crafted to be both interactive and visually appealing, featuring animations that harmonize with the material, high-quality images in a carefully selected color palette and size, and strategically placed buttons that enhance navigation. In addition, the text used is easy to read, and the images maintain their quality when enlarged. By utilizing these advantages, DLE media can provide an effective, enjoyable, and satisfying learning experience for users, in addition to having gone through validation by material experts. Evaluation related to the results of media expert validation is described as follows: the material presented in DLE is very appropriate to the learning outcomes that have been set for the General Biology course. Each topic and subtopic reflects the competencies that students must achieve. The material in DLE media is arranged with a level of difficulty that is appropriate to the abilities and levels of understanding of students. The material begins with basic concepts before moving on to more complex concepts. DLE media is designed to encourage active student involvement through the use of interactive elements such as simulations and games that are relevant to learning outcomes.

4. Implementation stage

The learning process using the Digital Learning Environment (DLE) based on the STEM and Game-Based Learning (GBL) approaches was designed to be implemented in four to six class sessions, each lasting 2 × 50 minutes. The implementation was carried out gradually through stages of media orientation, problem presentation, exploration and inquiry, solution design, virtual experimentation, evaluation, reflection, and scientific communication, as described below:

a. Orientation and introduction to the media

In this initial stage, students were introduced to the DLE equipped with features such as interactive simulations, a virtual laboratory, game missions, and an automatic assessment system. This orientation aimed to familiarize students with the platform's interface, features, and learning flow to ensure smooth participation during the learning process.

b. Problem presentation (define the problem)

Each session began with the presentation of a contextual STEM-based problem derived from biological topics such as ecology, genetics, or evolution. The problems were delivered through game narratives or interactive simulations within the DLE. This activity encouraged students to identify problems, formulate hypotheses, gather information, analyze data, and draw conclusions.

c. Exploration and inquiry (research and imagine)

Students were assigned to read digital materials, conduct literature searches, and analyze data obtained from the virtual laboratory. The DLE supported inquiry-based learning by providing access to databases, interactive modules, and game-based activities. At this stage, the scientific literacy indicator developed was the ability to identify and explain scientific phenomena through information gathering and understanding biological concepts.

d. Solution design (Plan)

Students designed STEM-based solutions through game activities, often working in small groups to foster collaboration. This stage aimed to develop the scientific literacy indicator related to evaluating and designing scientific investigations, including formulating hypotheses, creating experimental designs, and selecting appropriate procedures.

e. Virtual experimentation and evaluation (test and evaluate)

Students tested their designed solutions through virtual experiments in the DLE. The experimental results were compared with theoretical references to train scientific data analysis skills. The scientific literacy indicator developed at this stage was the ability to interpret scientific data and evidence, enabling students to compare experimental results with theory and draw logical scientific conclusions.

f. Reflection and revision (redesign)

Students reflected on their experimental results. The DLE provided discussion features and automatic feedback to help students improve less effective solutions. This stage strengthened the scientific literacy indicator related to evaluating scientific investigations by identifying weaknesses in experimental design and revising solutions based on data and feedback.

g. Scientific communication (communicate)

Students presented the results of their problem-solving activities in the form of digital reports, class presentations, or DLE-based portfolios. The DLE's assessment system provided real-time, constructive feedback. At this stage, the scientific literacy indicator developed was the ability to communicate scientific phenomena and research findings using clear scientific language supported by empirical evidence.

h. Final evaluation and feedback

Each session concluded with an interactive game-based quiz to assess competency achievement. The lecturer conducted a summative evaluation to measure the effectiveness of the media and students' engagement throughout the learning process. This final stage emphasized the scientific literacy indicators related to integrating scientific knowledge to explain phenomena, interpret results, and evaluate overall understanding comprehensively.

Effectiveness test

The effectiveness test in this study was conducted to determine the effectiveness of DLE Media with the STEM and GBL Approaches in improving the scientific literacy of Tadris Biology students at UIN Raden Mas Said Surakarta.

Table13. The mean results of N-gain test

Aspect	Average pre-test Value	Average posttest Value	N-gain	N-gain Category
Scientific Literacy	39	85	0.75	High

Figure 8 shows that, based on the analysis of the average scores of scientific literacy indicators, the indicators that experienced the highest improvement were A5 (developing appropriate graphs based on data) and A2 (conducting effective literature searches). Indicator A5 increased from 8 in the pretest to 19 in the posttest, while indicator A2 rose from 7 to 18. This finding indicates that after the learning intervention, students became more skilled in visually presenting data and more effective in searching for and utilizing scientific literature as the basis for their studies.

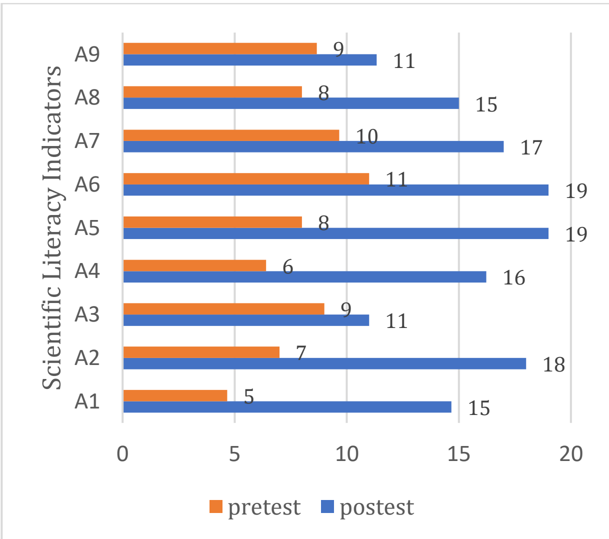

Figure 8. Comparison of Scientific Literacy

Description:

A1: Identifying valid scientific opinions
A2: Conducting an effective literature search
A3: Evaluating the truth of scientific information
A4: Understanding the elements in research design
A5: Developing precise graphs based on data
A6: Analyzing data
A7: Solve problems using quantitative skills including basic statistics
A8: Understanding and interpreting research results using
A9: Perform inferences and make predictions based c quantitative data

Meanwhile, the indicators with the lowest improvement were A3 (evaluating the validity of scientific information) and A9 (making inferences and predictions based on quantitative data). Indicator A3 increased only from 9 to 11, and indicator A9 also rose from 9 to 11. This suggests that although some progress occurred, students' critical thinking skills in evaluating scientific information, as well as their inference and prediction abilities based on data, remain relatively weak compared to other indicators.

From the data above, it can be seen that the experimental group tends to be superior in indicators related to scientific thinking skills and data analysis, such as analyzing data, evaluating scientific information, and understanding research design. This shows that the STEM and GBL-based learning approach packaged in learning media in the experimental group has a positive impact on developing students' 21st-century skills. STEM-based learning integrated into digital media can improve critical thinking skills (Irfana et al., 2022) and scientific (All et al., 2016) needed to optimize students' Scientific Literacy (Wahyu et al., 2020). In addition, science-based educational games that use simulations and virtual experiments in DLE learning media provide students with the opportunity to observe scientific phenomena and conduct experiments virtually. This gives students the opportunity to see the results of scientific concepts directly, which can improve their understanding and scientific literacy (Bortnik et al., 2017; Husnaini & Chen, 2019).

In the experimental group, data analysis skills were the highest. STEM-based media often involve interactive and practical data processing. Students are given the opportunity to be trained to process data independently and critically, improve data analysis skills through virtual labs, thus facilitating students to optimize data analysis skills in scientific literacy (Nechypurenko et al., 2019).

While the lowest indicator in the experimental class is Conducting effective literature searches, although not much lower, the experimental group got the lowest score in conducting literature searches. This could happen because the focus of the STEM and GBL learning methods is more towards direct application and data analysis, so that literature is less emphasized in the learning process.

In contrast, the control group demonstrated superiority in more theoretical aspects, such as literature searches and basic quantitative skills. This suggests that traditional learning methods are more effective in providing a strong theoretical foundation (Simonson et al., 2011), especially in the context of quantitative and statistical skills and literature searches.

However, the Control Group tends to have weaknesses in making inferences and predictions based on quantitative data, which is shown by this indicator having the lowest score in the control class. Inferences and predictions require in-depth analytical skills needed to optimize scientific literacy, which seem to be less facilitated in the learning methods used in the control group. The control group in this study used the presentation discussion method. Based on research Fajrie & Fauzia (2021), presentation discussion methods can improve communication skills, but (Yasin (2022) research shows that presentation discussions can improve information literacy. This is not in line with the research results, which can be caused by the structure and quality of the discussion, only focusing on delivering information verbally without any deeper exploration of scientific concepts, so that in-depth skills related to science are not developed. Presentation discussions that only emphasize theoretical understanding or presentation of facts without critical evaluation or application are not sufficient to improve competence (Bender, 2023), especially in scientific literacy. This is supported by the opinion of Snow and Dibner (2016) that scientific literacy not only includes the ability to understand and use information, but also to think scientifically, apply scientific concepts, understand, and carry out scientific methods.

Evaluation of implementation stage

The evaluation of the implementation phase revealed that learning through the Digital Learning Environment (DLE) based on STEM and Game-Based Learning (GBL) successfully provided a more interactive, collaborative, and student-centered learning experience. Each stage from media orientation, contextual problem presentation, literature exploration, solution design, virtual experimentation, reflection, to scientific communication was carried out as planned and effectively facilitated the development of students' scientific literacy.

The analysis results indicated a significant improvement in scientific literacy skills, particularly in the indicators A5 (developing graphs based on data) and A2 (conducting effective literature searches), demonstrating that the media effectively enhanced students' data analysis and scientific information utilization skills. However, weaknesses were observed in A3 (evaluating the validity of scientific information) and A9 (making inferences and predictions based on quantitative data), which showed relatively lower improvement.

These findings suggest that while the integration of STEM and GBL successfully promotes practical and analytical skills, higher-order critical thinking and scientific prediction abilities still require further reinforcement. Additional strategies—such as emphasizing reflective discussions, engaging students in deeper literature studies, and providing explicit guidance in evaluating the validity of scientific information—are recommended to strengthen these aspects.

CONCLUSION

The learning media developed through the integration of the Digital Learning Environment (DLE) with STEM and Game-Based Learning (GBL) approaches has successfully passed expert validation and field testing, demonstrating that it meets the eligibility criteria in terms of design quality, content relevance, and alignment with learning objectives. The media has proven to be practical and user-friendly, both for lecturers and students, as it can be implemented effectively in classroom settings without requiring complex technological infrastructure. Furthermore, the results of the implementation phase indicate that the developed media is effective in enhancing the scientific literacy of Tadris Biology students at UIN Raden Mas Said Surakarta, as evidenced by the significant differences between the experimental and control classes.

However, this research has several limitations. The study was conducted within a relatively short duration and involved a limited number of participants, which may affect the generalizability of the findings. In addition, the assessment of higher-order scientific literacy indicators, such as evaluating the validity of scientific information and making inferences or predictions based on quantitative data showed only modest improvement, suggesting that these aspects require deeper exploration.

Future research is recommended to involve a larger and more diverse sample, extend the duration of implementation to observe long-term effects, and incorporate qualitative evaluations such as student interviews or reflective journals to gain deeper insights into learning processes. Further development could also integrate adaptive learning analytics and AI-based feedback systems within the DLE to personalize learning experiences and strengthen students' critical and reflective scientific thinking.

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