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# LifeSTEM: An Inquiry-Driven Digital Module for Scientific Literacy in Biology Teacher Education

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**Abstract**

Scientific literacy is a fundamental competency for future biology teachers, yet existing STEM-based digital learning resources rarely address the interdisciplinary demands of biology teacher education. This study developed and evaluated LifeSTEM, an integrated digital learning module that combines plant anatomy, STEM learning, inquiry-based activities, and engineering design tasks to strengthen scientific literacy among pre-service biology teachers. Guided by the ADDIE instructional design framework, the study involved needs analysis, expert validation, iterative module development, and classroom implementation with 30 pre-service biology teachers using a one-group pre-test–post-test design. Data were collected through needs assessment, expert validation, scientific literacy tests, and learner response questionnaires. The findings indicate that the LifeSTEM module achieved high content validity and was positively received by students as an engaging and accessible learning resource. Its implementation substantially enhanced scientific literacy, particularly students' ability to explain scientific phenomena, interpret scientific evidence, and apply procedural knowledge within authentic biological contexts. The integration of inquiry-oriented STEM activities with interactive digital learning promoted meaningful engagement with complex biological concepts while encouraging evidence-based reasoning. This study contributes to biology teacher education by demonstrating how integrated digital instructional design can strengthen scientific literacy through contextual and inquiry-driven STEM learning, providing a transferable framework for preparing future science teachers in technology-enhanced learning environments.

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## INTRODUCTION

Scientific literacy is one of the key performance indicators for measuring the quality of education in a country. In accordance with the findings of the PISA test held in 2022, Indonesia obtained a scientific literacy score of 398 and ranked 68th out of 81 countries (Fayanto et al., 2023). This score shows that the ability of Indonesian students to understand and apply science concepts is still below the international average. This trend has been going on for more than a decade, with Indonesia's scientific literacy score ranging from 382 to 403 from 2006 to 2018, even declining in 2018 with a score of 396 (Yusmar & Fadilah, 2023).

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Numerous reasons contribute to Indonesian students' inadequate scientific literacy, including the limitations of educational infrastructure, the quality of human resources, and learning models that are still teacher-centered (Riani, 2023). In addition, students' tendency to view science as a challenging and dull subject, in addition to the lack of reading habit and writing scientific texts, also exacerbates this condition (Fuadi et al., 2020). In fact, science literacy skills are very important to equip the younger generation to be capable of critical thought, make evidence-based decisions, and actively participate in a technology-based society (Adeoye et al., 2025).

Scientific literacy has been widely recognized as a key competence in science education. Previous studies have shown that STEM-based learning can enhance students' scientific literacy by connecting scientific concepts with real-world problem solving (Alali, 2024; Nurulsari et al., 2023; Pratama et al., 2025; Sole, 2021). However, most existing studies focus on school students, while limited attention has been given to the preparation of pre-service biology teachers through integrated STEM learning modules (Dalimunthe et al., 2025; Jannah et al., 2025).

One of the strategic efforts that can be made by pre-service biology teachers to improve science literacy is through the development of relevant and contextual learning tools, such as electronic modules (e-modules) (Ardiansyah et al., 2024; Dalaila et al., 2022; Prihatiningtyas et al., 2025). Dalaila et al, (2022) created an SSI using an e-Module, which can enhance scientific literacy among high school students. The findings from research and development showed that the SSI-based e-Module developed on immunity is valid, applicable, and utilized for teaching material about immunity, and is also proven to be effective for improving scientific literacy skills of high school students. Prihatiningtyas et al, (2025) evaluated the effects of the STEM Qur'an-Based Flip book e-Module on Senior High School Students' Science Literacy Skills; it was evident from the data collected that this program positively impacted students' Science Literacy. E-modules are digital teaching materials that can contain text, images, animations, and videos, and can be accessed through computer devices and smartphones (Zinnurain, 2021). This module allows for flexible, interactive, and appropriate learning for current technological developments (Patonah et al., 2025; Prasasti & Anas, 2023; Wulansari et al., 2025; Yulando et al., 2019)

Previous Research indicates that students' ability to think critically and solve problems using an interdisciplinary approach can be improved through the use of e-modules developed from a science, technology, engineering, and mathematics (STEM) framework. However, the majority of these studies have been conducted with elementary and high school students. For example, research has Bernica et al, (2022) demonstrated that STEM-based e-modules improved students' science literacy skills, but the study was conducted in the context of general student learning rather than a teacher preparation program. Research examining the use of STEM-based digital modules in the preparation of pre-service teachers remains limited (Hasanah, 2023). Existing studies tend to emphasize the implementation of STEM learning activities, inquiry strategies, or project-based learning approaches rather than the systematic development of structured digital learning modules specifically designed for prospective science teachers (Otaya et al., 2025; Umamah et al., 2025). In addition, many studies emphasize the implementation of STEM learning activities rather than the systematic development of structured digital learning modules. (Indriyani et al., 2024; Yulianti & Masiroh, 2024) noted that many STEM learning resources for pre-service teachers remain content-centered and provide limited opportunities for integrated STEM project experiences. Consequently, challenges remain in designing integrated STEM-based e-modules that effectively support the development of scientific literacy among pre-service biology teachers (Sari & El Islami, 2025). This study differs from previous STEM-based e-module studies by integrating plant anatomy content, engineering design tasks, digital microscopy activities, and scientific literacy indicators specifically for pre-service biology teachers.

In this study, a STEM education-based e-module called LifeSTEM was developed, particularly for plant anatomy learning, because this topic requires students to understand complex and microscopic biological structures through observation, analysis, and interpretation processes that are closely related to STEM competencies. The module is designed to support active learning through an integrative approach that combines science, technology, engineering, and mathematics. In this manner, students are prompted not only to gain knowledge of theoretical principles behind plant anatomy but also to think scientifically, analyze data, utilize modern technologies, and solve problems related to plant biology. Therefore, this study aims to develop and evaluate a LifeSTEM e-

module for plant anatomy learning and to examine its potential contribution to the scientific literacy of pre-service biology teachers.

## METHOD

The ADDIE model serves as the primary framework for analysis, and the current study is classified under the research and development category. The ADDIE paradigm consists of five steps: analyze, design, develop, implement, and evaluate (Branch, 2010). Each stage has an important role to play in forming the basis for the next stage.

### Analysis

The first step in the study involves finding the needs and circumstances of science literacy among pre-service biology teachers that will serve as the basis for the creation of STEM-based e-modules. In order to accomplish the said objective, a total of 100 pre-service biology teachers underwent a scientific literacy needs assessment. These respondents were individuals who had already finished basic courses in biology and were currently studying in a Biology Education program at a public university in Indonesia. On the other hand, 107 third- and fourth-year pre-service biology teachers participated in the content difficulty analysis, wherein they identified the topics in biology deemed difficult. Semi-structured interviews were also conducted among ten biology education lecturers experienced in teaching biology subjects and creating instructional materials. The scientific literacy instrument consisted of 20 multiple-choice items. Item validity was examined using Pearson product–moment item-total correlation analysis (Çeliker Ercan & Cubukcu, 2021). The average item validity coefficient was 0.298, indicating acceptable item discrimination, while the reliability coefficient (Cronbach's Alpha) was 0.725, demonstrating satisfactory internal consistency. In addition, 10 biology education lecturers participated in in-depth interviews so that qualitative data could be gathered related to curriculum, learning strategies, classroom environments, and the application of technology into the teaching and learning processes.

Participants were recruited using a volunteer sampling technique, a form of non-probability sampling in which individuals voluntarily agreed to participate in the study. The study was conducted within a biology An Indonesian university's teacher education program, where the developed LifeSTEM e-module was evaluated. As part of the needs exploration, lecturers were given the following open-ended questions:

1) What concepts do you think are difficult for students to understand?
2) What concepts are closely associated with STEM?
3) What do you think about the STEM e-module being developed?

Quantitative information derived from the scientific literacy exam results was analyzed descriptively to see the distribution and tendency of students' literacy levels. Meanwhile, qualitative data from the interviews were analyzed using content analysis techniques and a systematic review to identify the main themes underlying the need for effective and applicable STEM e-module development.

**Table 1.** Categories of Students' Scientific Literacy Abilities Results

| Value Range | Category |
|---|---|
| $90 \leq x \leq 100$ | Very Good |
| $80 \leq x < 90$ | Good |
| $70 \leq x < 80$ | Fairly Good |
| $50 \leq x < 70$ | Not Good |
| $0 \leq x < 50$ | Very Bad |

### Design

This stage designs STEM education e-module products based on the results of needs analysis. The design includes product specifications, general and custom descriptions, flowcharts, scripts, and storyboards. The goal is to produce a systematic design of teaching materials that are in accordance with the context of STEM-based biology learning.

**Development**

At this stage, the STEM education e-module was developed based on the previously designed framework. The validation of the product was carried out by five experts in biology and science education who have been involved in STEM-based instruction and the development of teaching materials. These experts are holders of post-graduate qualifications in biology education with many years of teaching and research experience in science education. This process comprised the creation of the module prototype and its user guide, the creation of the expert validation survey instrument, and its validation by the expert panel. An instrument in the form of a Likert scale evaluation instrument, measuring different aspects such as content validity, integration of STEM concepts, instructional design, clarity of language use, and presentation of visuals in the module, was used. Content validity was determined through Aiken's V coefficient.

**Implementation**

The implementation process consisted of 30 pre-service biology teachers, including 24 female (80%) and 6 male (20%) teachers, ranging in age from 19 to 22 years old (M = 20.4 years). The pre-service biology teachers selected were all third-year students who took part in the Biology Education program, having taken some basic courses in biology. In testing the effectiveness of the e-module on enhancing the scientific literacy of pre-service biology teachers, a one-group pre-test-post-test research design was used in the experiment. The treatment was done for two periods of learning. In the first learning session, the students underwent a class discussion of the LifeSTEM e-module and learning activities based on it. In the second learning session, the students did laboratory activities related to the lesson. To ensure consistency during the implementation, several control variables were maintained, including the same instructor, learning objectives, instructional materials, and duration of learning sessions for all participants.

**Evaluation**

The evaluation stage aimed to assess both the quality of the educational procedure and how well the e-module enhances scientific literacy. The analysis employed a mixed-method approach, consisting of quantitative analysis of Test results for scientific literacy before and after the STEM-based curriculum was implemented, as well as a qualitative examination of pre-service biology teachers' reactions. Based on the evaluation results, revisions were made to improve the final version of the product.

## RESULTS AND DISCUSSION

**Analyze**

This stage successfully identified the science literacy profile of pre-service biology teachers, along with qualitative data on curriculum implementation, instructional strategies, and learning technologies employed by lecturers, as well as an analysis of the difficulty level of biology content. The needs analysis revealed that the science literacy levels of pre-service biology teachers vary considerably. The results of the scientific literacy needs assessment were analyzed to identify the strengths and weaknesses of pre-service biology teachers across different scientific literacy indicators. The distribution of achievement for each indicator is presented in Figure 1.

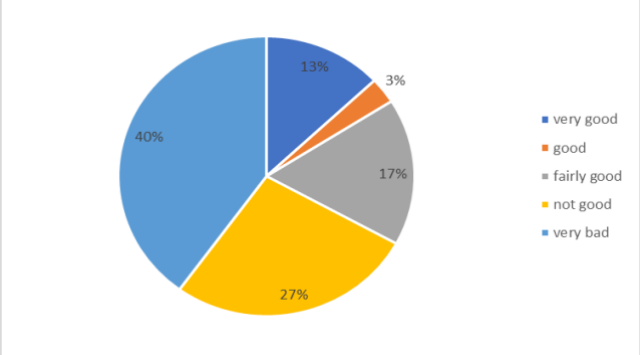



**Figure 1.** Science Literacy Category for Biology Teacher Candidates

Only a small percentage of respondents are already in the very good category, which is 13%, while those who are in the good category are only 3%. This shows that the category of high science literacy is still very limited. Furthermore, for categorization, it is quite 17%, the percentage of categories is very low at 27%, and the category is very low with a percentage of 40% (Figure 1). These results align with earlier research showing that pre-service teachers generally exhibit low to moderate levels of scientific literacy, particularly in applying scientific concepts to real-world contexts and engaging in higher-order thinking (Lederman, 2014; OECD, 2018). For instance, several studies have highlighted that limited exposure to inquiry-based and STEM-integrated learning environments contributes to suboptimal scientific literacy outcomes among teacher candidates (Bybee, 2013; Guthrie et al., 2004). Compared to these studies, the present findings reinforce the urgency of developing innovative instructional approaches, such as STEM-based modules, to systematically improve scientific literacy among pre-service biology teachers. An analysis of content difficulty was conducted to identify biology topics perceived as challenging by pre-service biology teachers. The distribution of difficult topics reported by the respondents is presented in Figure 2.

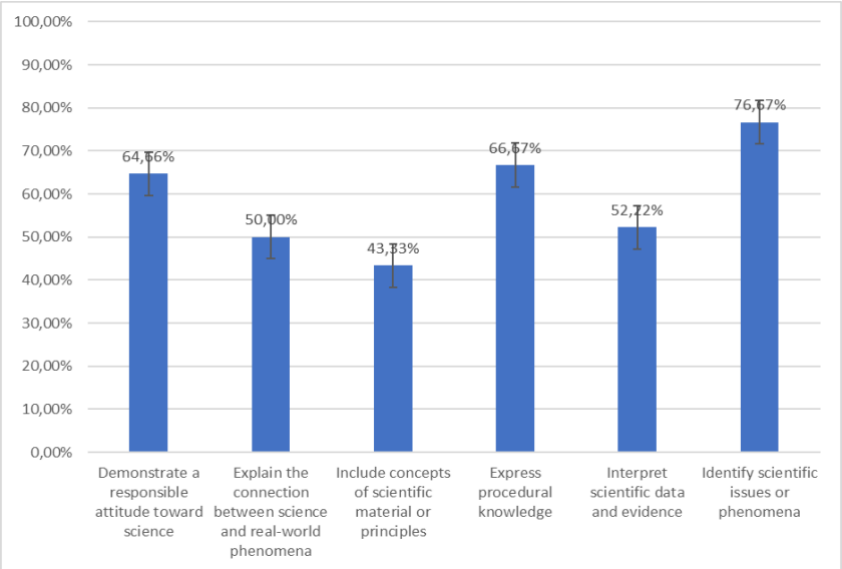



**Figure 2.** Mapping the Science Literacy of Pre-Service Biology Teachers on each Indicator.

Based on the mapping results, the science literacy of pre-service biology teachers showed various achievements in each indicator (Figure 2). The indicator with the highest achievement is the attitude of responsibility towards science (76.67%), followed by mastery of material concepts or scientific principles (66.67%) and the ability to identify scientific issues or phenomena (64.66%). This shows that pre-service biology teachers have good attitude awareness and are strong enough in mastering concepts and identifying phenomena. However, the achievement in the indicators of procedural knowledge (43.33%) and the ability to interpret data and scientific evidence (50.00%) is relatively low, which indicates the need to strengthen the aspects of scientific thinking skills and the application of scientific procedures.

This low procedural knowledge can be explained by the tendency of science learning to focus on mastering content rather than practicing scientific inquiry. Students are often trained to understand concepts rather than to engage in scientific processes such as designing experiments, analyzing data, and disseminating evidence (Ledesma et al., 2019; Osborne, 2014). This creates a gap between knowing science and doing science, where students understand concepts but lack skills in scientific practices (Kind, 2015). This low procedural knowledge is also related to the suboptimal integration of authentic scientific practices into teacher education curricula. Teacher education programs still emphasize theoretical aspects rather than inquiry-based practical experiences and scientific reflection (Capps & Crawford, 2013; Darling-Hammond et al., 2020). Yet, research shows that direct engagement in scientific practices, such as inquiry-based learning and practice-based teacher education, significantly improves the procedural skills and scientific literacy of pre-service teachers (Kang, 2018). Furthermore, digital learning contributes to low procedural knowledge if it is

not pedagogically designed. Technology is often used solely as a means of conveying information, rather than as a means of practicing higher-order thinking skills and scientific practice (Schindler et al., 2017; Selwyn, 2016). However, research shows that the use of digital simulations and virtual laboratories can improve conceptual understanding, but does not automatically improve procedural skills without integrating an inquiry approach (Makransky & Lilleholt, 2018).

Furthermore, the ability to interpret scientific data and evidence is closely related to data literacy and critical thinking skills, which remain challenges in teacher education (García-Carmona, 2020). Therefore, strengthening the framework known as Technological Pedagogical Content Knowledge (TPACK) is crucial so that technology is used not only as a learning medium but also as a tool for developing inquiry, data analysis, and scientific argumentation skills (Mishra & Koehler, 2006; Voogt et al., 2013). These results indicate that more than half of pre-service biology teachers still have low science literacy. Low science literacy among these students is a challenge when it comes to investigating science because it is not just about being literate in terms of reading or writing, but also involves being knowledgeable of and capable of communicating science (Nuangchalerm, 2018). Science literacy is not only related to the ability to understand scientific concepts, but also includes critical thinking skills, evidence-based decision-making, and an understanding of the relationship between science, technology, and society (Maiyanti et al., 2025; OECD, 2019). When pre-service teachers have low science literacy, they tend to have difficulty in meaningfully transferring scientific concepts to students, so learning becomes memorization-oriented and less contextual. As a result, pre-service biology teachers are not encouraged to develop scientific thinking skills, which in the end will hinder the formation of a generation that is able to think scientifically and make evidence-based decisions in daily life (Holbrook & Rannikmae, 2009). Therefore, there is a need for initiatives to improve science literacy by employing novel forms of learning processes since science literacy among prospective science teachers is directly linked to the continuous learning process that has not yet helped develop aspects of science literacy (Sarini et al., 2024). Another strategy to raise pre-service biology teachers' science literacy proficiency is the STEM method (Adi et al., 2020).

The curriculum used by lecturers majoring in Biology Education is the Independent curriculum. Student-centered learning is employed, together with project-based learning (PjBL) and the case approach. This method is widely used because it has been proven to be able to train 21st-century skills such as critical thinking, creativity, and student collaboration (Budiarto, 2023), as well as providing innovation so that learning is interesting and not boring (Farikah et al., 2022). Furthermore, the technology used for learning by Biology Education lecturers comprises digital content, including interactive films, virtual laboratories, and learning management systems (LMS). The integration of technology in teaching planning has the potential to improve the quality and efficiency of learning (Coenders & Verhoef, 2019).

The analysis of content difficulty was carried out using a questionnaire. The research sample consisted of 107 third- and fourth-year biology teacher candidates. The instruments used have been validated. Students' written responses regarding the difficulties of biology content were described and analyzed qualitatively. The results of the analysis show that there are four materials about what is considered difficult by pre-service teachers. First, the topic of microbial genetics is a microbiology concept that is most often considered difficult by pre-service biology teachers. This shows that there are obstacles in understanding the mechanism of inheritance, the regulation of gene expression, and genetic engineering techniques in microorganisms. In addition, the concept of bacteria and viruses is also widely mentioned, indicating difficulties in understanding their structure, classification, and role in health and disease. Second, there is genetic material. Genetic concepts considered difficult by respondents are the material of molecular genetics, inheritance, and Mendel's laws. In line with the research Fauzi et al, (2021)to dig into data on biology topics that are difficult for students in Indonesia, genetics is the most difficult material. The dominance of these three concepts shows that pre-service biology teachers still have difficulty understanding the basics of inheritance, both at the classical and molecular levels. Further, the concepts of DNA replication, genetic recombination, and gene expression (transcription and translation) also emerged as difficult topics. Furthermore, the third concept that is considered difficult by pre-service biology teachers is the concept of botany, which includes plant physiology, followed by photosynthesis and plant anatomy. This means that pre-service biology teachers do not understand the physiological functions of plants well, such as photosynthesis, respiration, transportation of water and nutrients, and hormonal control. Pre-

service biology teachers also encounter problems in the topic of plant anatomy, including problems in defining plant tissue organization and the link between tissue organization and physiological functions. The fourth concept of zoology that was deemed the most difficult by pre-service biology teachers is invertebrates, followed by animal physiology, animal anatomy, and animal embryology. This shows that pre-service biology teachers have difficulties in comprehending the concept. Then the concept of ecology, which is the concept considered most difficult by pre-service biology teachers, includes biogeochemistry, population dynamics, and energy flow, followed by other topics such as vegetation diversity, community ecology, and ecological niche. This is because it needs mathematical comprehension of population dynamics, density regulation, and interspecific interaction. Meanwhile, energy flows within ecosystems require an integrative understanding of energy transfer from producers to peak consumers, which is often abstract without adequate visualization or modelling.

The findings from this study brought out the need to create learning aids that combine content, pedagogy, and technology (TPACK). This led to the encouragement of the transformation of the process of utilizing technology in such a way that it allows learning not just about the content, but also allows for a deeper and more meaningful process of learning. It should be noted that previous international research has shown how the TPACK framework is critical to meaningful technology integration (Aumann et al., 2024; Stinken-Rösner et al., 2023). In addition, research has shown that pre-service science teachers still experience challenges in integrating technology, pedagogy, and content knowledge effectively in learning practices, indicating the need for innovative and technology-oriented instructional tools (Oye & Salleh, 2012). In addition, this analysis also strengthens the urgency of relevant evaluation innovations in order to prepare pre-service biology teachers to face the challenges of 21st-century education.

## Design

As such, the designing phase yielded the development of a systematic prototype of the LifeSTEM e-module, learning about plant structure, and comprising sections of introduction, exploration, engineering design challenges, and reflection. The design of the e-module is depicted using storyboards detailing the learning process, instructional strategies, media use, and assessments. The storyboards describe how the students will interact by observing plant structure and making connections between structure and function to solve problems. To facilitate a systematic learning experience, the LifeSTEM e-module was designed with several instructional components that integrate science, technology, engineering, and mathematics within plant anatomy learning. The detailed design specifications of the module are presented in Table 2.

**Table 2.** Design Specifications of the LifeSTEM E-Module

| Aspect | Description |
|---|---|
| Development Platform | The e-module was developed using Canva-based interactive design to support visual and multimedia integration |
| Curriculum Basis | The module is aligned with Outcome-Based Education (OBE), ensuring alignment between learning outcomes, activities, and assessments |
| Target Users | Pre-service biology teachers |
| Content Focus | Plant anatomy (epidermis, cortex, xylem, phloem, stomata) |
| Learning Structure | Organized into X units consisting of introduction, exploration, STEM activities, engineering design tasks, and reflection |
| STEM Integration | Science: plant tissue concepts; Technology: digital visualization/virtual tools; Engineering: design-based tasks; Mathematics: data analysis and comparison |
| Learning Approach | STEM integrated with Engineering Design Process (EDP) |
| Scientific Literacy Focus | Explaining phenomena, interpreting data, and applying knowledge in real-world contexts (aligned with OECD) |
| Media Components | Images, diagrams, videos, interactive elements |
| Assessment Design | Formative and summative assessments embedded in each unit |
| Storyboard Output | Detailed storyboard outlining learning flow, activities, media, and assessment |

STEM integration is deliberately incorporated in every unit: science involves scientific ideas centered on the organization of plant tissue, such as epidermis, cortex, xylem, and phloem; technology includes the employment of digital microscopy or simulated technologies; engineering encompasses engineering problems that students will solve concerning plant adaptation; and mathematics comprises data comparisons and measurements. This design corresponds to the scientific literacy skills needed for explaining scientific phenomena, analyzing data, and applying them to real-life situations.

Furthermore, the technology aspect is emphasized in the use of light microscopes for more detailed observations. Then, the use of digital cameras for documentation and cell measurement can be more accurate. The engineering aspect includes making a simple microtom aid when it is difficult to make thin, flat slices of plant tissue with just a razor. Students designed simple microtomes out of foam, cork, or straw that can hold the stem/leaf sample from shifting as it slices and slices more consistently. The preparation is easier to observe. The mathematics aspect is focused on observing cells using a microscope equipped with an ocular scale to calculate the size of cells/tissues with the micrometre scale. Results from tissue thickness ratio measurements (e.g., xylem and phloem ratio). In addition, to calculate the density of stomata or trichomes per unit area. The data obtained is used for quantitative data analysis (e.g., average cell diameter, comparison between species, simple statistical tests).

The competencies that must be mastered are mainly related to understanding the structure and function of plant tissues. One of the CPMK in this course is that students are required to be able to identify plant tissues through microscopic images, analyze their functions scientifically (Science), and relate them to the application of observation technology (Technology). The inventory and preparation of these assignments is very helpful to determine the order of presentation of the material, learning activities, the relevance of each topic to STEM elements, and the tasks that will be created and done by students. The next step after the assignment inventory is completed is to formulate a performance goal that describes the specific abilities expected of pre-service biology teacher students after using this e-module. This goal includes the ability to understand the concept of plant anatomy, interpret anatomical images through a scientific approach, and apply STEM principles in the context of biology learning. The formulation of these performance goals is the basis for determining the content, interactive activities, and learning media in the e-module. This goal also determines the evaluation tools presented in the e-module.

**Development**

The STEM education e-module is developed according to the design that has been made. The initial product was validated by five biology/science education experts to assess the feasibility and quality of the module. The steps include product creation and user guides, preparation of media assessment instruments, validation by a team of experts, and further revision based on expert input. The results of the research at this stage are: STEM e-modules, assessment instruments, and the results of validation of e-modules by validators.

This e-module basically uses Canva as an application to design its appearance. Canva has an easy-to-use interface with a variety of attractive templates that make it easy for users to design e-modules quickly and professionally. Additionally, Canva provides access to diverse visual elements to enrich the look of the e-module. At the end of the module is converted to PDF. This module is equipped with learning videos to make it easier for pre-service teachers to understand the content. Some of the videos in this e-module are taken from YouTube (the source listed), and some are made by themselves. Video creation using the Wondershare Filmora app. Furthermore, to make this module more interesting and add some interactive elements, the PDF format module is edited using the flipbuilder application (flip pdf corporate). Once all parts of the e-module are complete, to make it easier to access by all devices, the e-module is uploaded to the internet (website-based) and can be accessed at the following link: https://modul-spt2.github.io/Modul_SPT2/

**E-module Assessment Instrument**

The STEM e-module validation instrument was prepared based on [4] with modifications including 30 questions covered in seven aspects of assessment, namely curriculum aspects, suitability of material content, suitability of the use of learning modes, language, display of STEM e-

modules, use of STEM e-modules, and attractiveness of STEM e-modules. The curriculum aspect is measured through indicators of material suitability with the Merdeka curriculum. Furthermore, the aspect of the suitability of the material content includes three indicators, namely the suitability of the content of the material in the STEM e-module, the suitability of the supporting material in the STEM e-module, and the suitability of the material with the development of bioinformatics science. In terms of the suitability of the use of learning models, there are two indicators assessed, namely the use of STEM learning models and the suitability of learning models in improving the science literacy of pre-service biology teachers. The linguistic aspect is assessed through two indicators, namely the use of language according to Indonesian rules and the use of easy-to-understand sentences. The next aspect is the aspect of the display of the STEM e-module, consisting of four indicators, namely the completeness of the e-module content, the presentation of illustrations in the form of images, and the selection of colours and graphic elements, as well as the use of designs and fonts. In terms of the use of STEM e-modules, the indicator evaluated is the ease of using STEM e-modules. Finally, the attractiveness aspect of the STEM e-module is assessed through the feature indicators used in the STEM e-module.

**Results of e-module validation**

The e-module validation aims to see the quality of the e-module based on the feasibility aspects in the e-module assessment instrument. The results of the e-module validation are as figure 3.

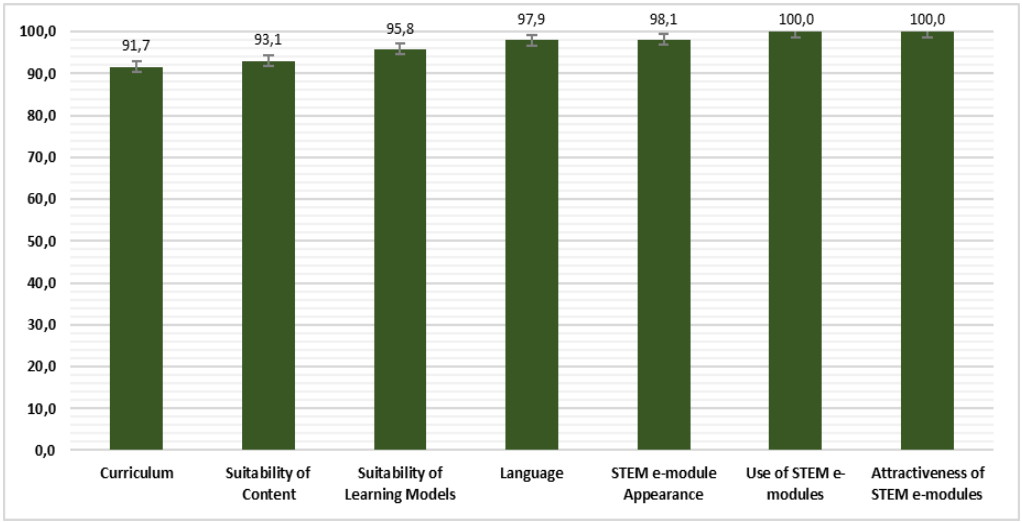



**Figure 3.** Mapping of the Results of the Validation of the STEM E-Module

Based on the results of validation by experts in Figure 3, the developed e-modules obtained very high scores on every aspect of the assessment. In the curriculum aspect, the e-module obtained a percentage of 91.7%, which shows that the content in this e-module is in accordance with the independent curriculum. The second aspect is the aspect of the suitability of the content of the material, which received a score of 93.1%, indicating that the material presented is relevant and in accordance with the development of plant anatomical content. Furthermore, the third aspect is the suitability of the use of learning models; the percentage of 95.8% shows that the presentation of material in e-modules is appropriate to support the implementation of STEM. Then, in the linguistic aspect, the e-module obtained a score of 97.9%, which means that the language used is easy to understand, communicative, and in accordance with the rules of the Indonesian language. Furthermore, the display aspect of the STEM e-module received a very good assessment with a score of 98.1%, because the visual presentation on the e-module is attractive, systematic, and easy for users. Finally, in terms of using the STEM e-module and the attractiveness of the STEM e-module, obtaining a percentage of 100% shows that this e-module is very easy to use with interesting features. Overall, the score achievement in each aspect of validation shows that the e-module developed has met the criteria of being very valid and feasible to be used as a STEM-based learning resource. To strengthen the validity analysis, the content validity was also calculated using Aiken's V

(Nurjanah et al., 2023), resulting in a coefficient of 0.922. This value indicates a very high level of content validity, confirming that the developed e-module is highly appropriate and feasible to be used as a STEM-based learning resource.

Based on expert input, there are several aspects of the Plant Anatomy STEM e-module product. Based on expert assessments related to the curriculum aspect, it is necessary to adjust the material to the objectives of the plant anatomy course because the learning outcomes of the course are still too low for the student level, and the material presented related to leaves, roots, and stems is made more in-depth by using references from various articles in reputable journals. In addition to the in-depth content of the material, the material presented is more contextual, accompanied by literacy questions and HOTS questions. In terms of the suitability of material content, practices, and mini projects are very good, but the development of the material must be strengthened by providing additional info or examples of material analysis. Supporting materials such as learning videos and image illustrations are attractive, clear, and good, but it is also recommended that the image illustration be accompanied by a description explaining the content of the image. The presentation of case studies in practice questions should remain related to the material presented; if not discussed in the e-module, reinforcement articles can be given to be read independently by students.

In the aspect of the suitability of using the learning model, it is better to include a guide on the steps for implementing the learning model, and practice case-based questions should be added at the end of each submaterial. In the linguistic aspect, the use of language is in accordance with the rules of the Indonesian language, but the use of punctuation must be correct and include a glossary of biological terms. In the aspect of the display of the e-STEM module, it is recommended that the text presented uses the appropriate font type and size, is not excessive, and does not use many typefaces to be consistent and professional. The images and videos presented are in accordance with the material discussed, but each image should be given an explanatory statement. In terms of using e-modules, STEM modules are very good and easy to use because they can be accessed using smartphones, laptops, or computers. In terms of the attractiveness of the STEM e-module, the features used are very interactive and can be operated easily, and there is a feedback feature that can be used by students to express their opinions about the Bima e-module.

The results of input from the expert team are then revised to correct the product's weaknesses before entering the implementation stage. Revisions cover aspects of content. This revision is important because it ensures that the product has in-depth and contextual content. This is because contextual learning can develop students' science literacy by highlighting various scientific contexts and issues in the surrounding environment (Sari et al., 2024; Wahab et al., 2023). In addition, the addition of interactive features is also a point in improving the e-module so that this e-module becomes more effective, attractive, and meets user needs. Once the revision is done, the next step is to conduct a retest (advanced validation) or final product implementation to ensure that all improvements are optimized before they are officially disseminated or used.

**Implementation**

Implementation is a stage of preparing for the use of the STEM education e-module, then the product is tested and assessed. The steps are preparing teachers, preparing students, testing products, using product assessment instruments, assessing student competencies, and making revisions as needed. At this stage, the implementation of the validated e-module is carried out through a trial on 30 samples of pre-service teachers. The trial process began with the provision of a pre-test to the respondents. Furthermore, learning activities are carried out using the STEM e-modules that have been developed. The next day, post-test and response tests were carried out. The pre-test is used to find out the initial science literacy ability, and then the post-test is carried out to find out the science literacy of pre-service biology teachers after being given the STEM e-module. The results of the science literacy pre-test and post-test are shown in Figure 4.

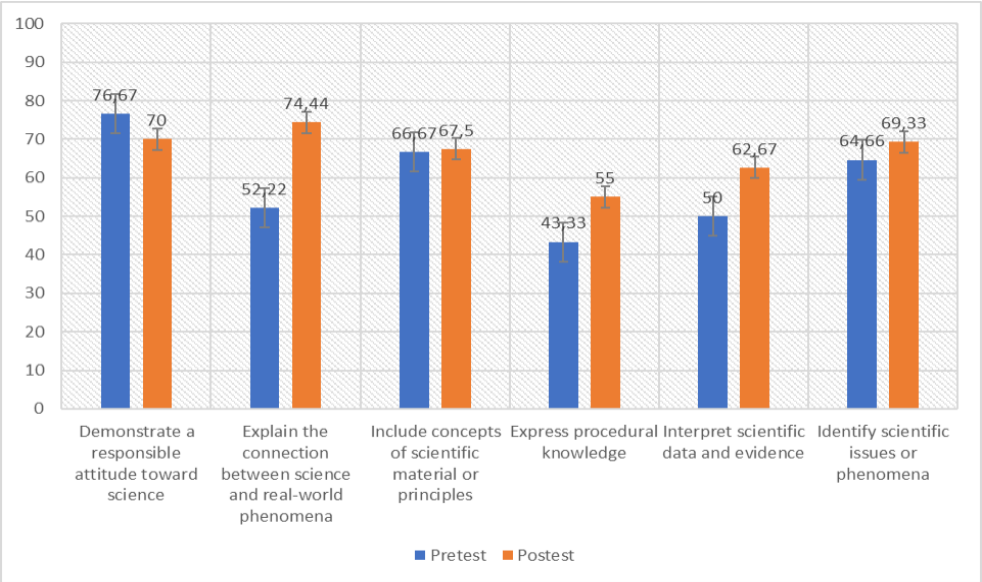



**Figure 4**. Pre-test and Post-test Results of Literacy Ability of Pre-Service Teachers.

From Figure 4, the variation in pre-service biology teachers in terms of science literacy indicators can be seen. The Wilcoxon signed-rank test found a significant difference between the pre-test and post-test results ($p = 0.011$). In order to measure the effect size, a formula of $r=Z/\sqrt{N}$ was used. As a result, the effect size obtained was 0.57. It can be said that an effect size with this number belongs to a large effect based on Cohen's criteria. despite the relatively low average N-gain score. The average score improved from 58 (SD = 18.70) in the pre-test to 66.67 (SD = 18.25) in the post-test, implying a general improvement in the scientific literacy of students. The magnitude of effect (r-value) was computed, with an obtained effect size of 0.57, considered a large effect. Thus, the implementation of the LifeSTEM e-module significantly influenced the enhancement of scientific literacy among prospective biology teachers. Further examination through N-gain revealed varying results depending on the indicators, with their N-gains of 0.13, 0.25, 0.21, 0.03, 0.47, and −0.29, respectively, with an average N-gain of 0.13, classified as low improvement. Although some indicators had a moderate level of improvement, others had a negative N-gain, which implied a reduction in performance. Overall, the findings imply that the effect of the intervention is significant; however, the improvement in particular aspects of scientific literacy was not evenly distributed and may require further refinement of the instructional design.

The pre-test results, the dominant aspects of science literacy of pre-service biology teachers were the attitude of responsibility towards science (76.67%) and identifying scientific issues (64.66%). Other aspects, such as the ability to explain the relationship between science and real phenomena and procedural knowledge, are still low. After learning, the aspect with the highest improvement was the ability to explain the relationship between science and real phenomena (up 22.22%), interpreting scientific data, and expressing procedural knowledge, which also increased significantly. This increase is in line with Asrizal et al, (2023) findings that STEM learning can improve students' science literacy skills in various aspects, including concept understanding, data interpretation, and introduction to the latest science issues. The results also noted that there was a slight decrease in the aspect of responsibility attitude (down 6.67%), which can be an input for the evaluation of attitude and character development strategies in biology learning. Overall, the results of the post illustrate that there has been positive progress in the science literacy profile of pre-service biology teachers, especially in the aspects of critical thinking and problem solving related to real phenomena. However, continuous efforts to strengthen attitudes and consistency in each science literacy indicator need to be a major concern in the education strategy of pre-service biology teachers in the future.

Furthermore, learning activities are carried out using the STEM e-modules that have been developed. The module is applied to the Plant Development Structure course with learning using a mini project to identify local plant tissues. The STEM aspect is included in learning, and the Engineering aspect is carried out by the respondents by making a transverse slice, colouring it with

tissue dye, and then placing it on the glass object. Furthermore, the respondents conducted microscopic observations to identify the main network and document it; this stage contains science and technology aspects. In the Mathematics aspect, respondents took measurements such as cell diameter and number of stomata, and presented the measurement results in the form of simple tables or graphs.

**Evaluation**

At the evaluation stage, it will be carried out to determine the effectiveness of the STEM e-module in improving science literacy. The analysis methods used are mixed, quantitative, and qualitative methods. The quantitative method was analyzed based on the results of the science literacy pre-test and post-test, and the qualitative method was analyzed based on the results of interviews and student reflections after using the STEM e-module. The results of the study show that the development of plant anatomy STEM e-modules is very valid and feasible to be used as a STEM-based learning resource to improve the science literacy of pre-service biology teachers.

According to the Wilcoxon test, the STEM E-Module's implementation on the anatomy of the plant yields positive results in developing science literacy in biology teacher candidates. The distribution of pre-test and post-test scores showed that they were not normally distributed; therefore, Wilcoxon's test was conducted to identify whether or not there was a statistically significant difference between the two scores. The results of the Wilcoxon test revealed an Asymp. Sig. (2-tailed) value of .0011 (<.05), indicating that there was a significant difference in the means of the two groups of scores. Each of the significant differences between the pre-test and post-test scores was noted to have a low pre-test score, while the post-test score for both groups, one-high and one-low, revealed a higher degree of overlap between the pre-test and post-test scores; thus, these findings illustrate a significant difference between the two means of scores and that science literacy skills for preservice biology teachers had improved substantially due to using the STEM e-modules on the anatomy of plants. Figure 5 is a comparison of average science literacy scores for preservice biology teachers from the pre-test and post-test.

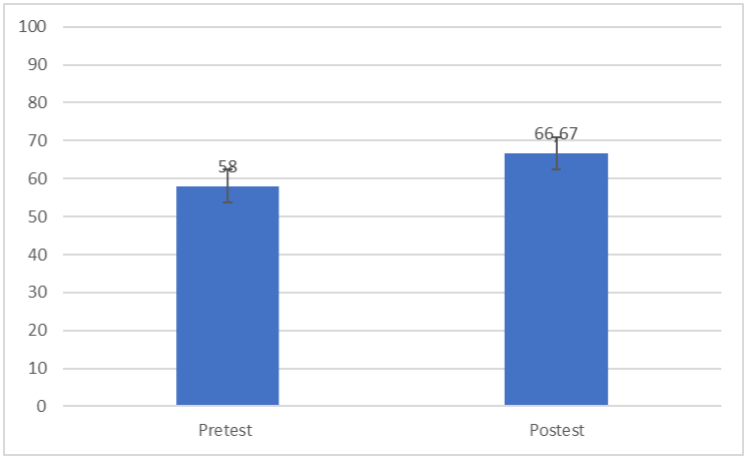



**Figure 5.** Average Pre-test and Post-test Scores of Science Literacy Candidates for Biology Teachers.

Analysis is also carried out on each science literacy indicator; six science literacy indicators are assessed, including identifying scientific issues or phenomena, interpreting scientific data and evidence, stating procedural knowledge, making material concepts or scientific principles, explaining the relationship between science and real phenomena, and showing an attitude of responsibility towards science. Based on the results of statistical test analysis for each indicator item, it was found that in the first indicator, between the pre-test and post-test values, both sig values were obtained. In the Shapiro test, the Wilk is 0.25 (pre-test) and 0.002 (post-test). Both had a value of less than 0.05 (<0.05), so the data of both were not normally distributed, and then the Wilcoxon Test was carried out to compare the two mean values. The result of the Wilcoxon test showed that the value of Asymp. Sig. (2-tailed) was 0.266 ( >0.05), so the average value of the two datasets did not have a significant difference. Although the values of the two datasets look different, statistically, the values are not

significantly different. The average score of indicator 1 for the pre-test is 6.466, and for the post-test is 6.933, although numerically there is a difference (higher post-test score), but statistically it is still considered not significantly different for the indicator to identify issues or scientific phenomena.

In the second indicator, namely interpreting data and scientific evidence, the results of the Wilcoxon Test were obtained with a value of 0.020 ( <0.05 ). This means that the two average scores between the pre-test and post-test have significant differences. To find out the higher and lower values, it can be seen from the mean value. The pre-test has an average score of 5,000, and the post-test has an average score of 6,266. The scores of the pre-test and post-test are seen to have differences, and the post-test score is higher than the pre-test. Based on statistical tests, the two have significant differences. In the third indicator about declaring procedural knowledge, based on the results of the Wilcoxon Test, a value of 0.070 ( >0.5 ) was obtained, which means that the average value of the two samples (pre-test and post-test) did not have a significant difference. This can be considered the same or no change from pre-test to post-test. The average pre-test score is 4,333, and the post-test score is 5,500. The two are considered to have no statistically significant difference. In the fourth indicator about making material concepts or scientific principles, based on the results of the Wilcoxon Test, a value of 0.862 ( >0.05 ) was obtained. This means that the average pre-test and post-test scores of the two do not have a significant difference. The average pre-test score of 6.667 and the post-test score of 6.750 were considered to have no significant difference according to the statistical test. In the fifth indicator explaining the relationship between science and real phenomena, the results of the Wilcoxon Test were obtained as 0.006 ( <0.05), meaning that there was a significant difference between the pre-test and post-test scores. The average pre-test score for the fifth indicator was 5,222, and the post-test score was 7,500. The difference between the two is considered to be significantly different based on the results of statistical tests. The post-test score is higher than the pre-test score, so it is considered that the use of the STEM e-module has a good influence on the development of this fifth indicator. In the sixth indicator of showing responsibility towards science, the results of the Wilcoxon Test showed a value of 0.593 ( >0.05 ). This means that the average value of the two data sets (pre-test and post-test) does not have a significant difference. The pre-test score for the sixth indicator is 7.667, and the post-test score is 7.00. The difference between the two is statistically not significantly different.

Interestingly, although the average normalized gain fell within the low category (0.13), the intervention produced a large effect size (r = 0.57). This discrepancy suggests that the LifeSTEM e-module generated meaningful changes across participants, but the magnitude of improvement varied considerably among scientific literacy indicators. Previous studies have noted that effect size reflects the overall strength of change, whereas N-gain is highly sensitive to baseline scores and ceiling effects (Hake, 1998). Therefore, the large effect size indicates that the module had substantial educational value, even though improvements were not uniformly distributed across all literacy dimensions.

**Response of Biology Teacher Candidates to Plant Anatomy STEM E-Module**

Pre-service Biology Teachers or students who are accustomed to using the Plant Anatomy STEM e-module showed positive responses toward its implementation. This is reflected in the average response score of 83.5, which falls into the good category, indicating that the developed e-module is well accepted and considered effective as a learning resource. Pre-service biology teachers feel that the material presented in the STEM e-module is easy to understand, especially on the concept of plant anatomy, the e-module also helps in understanding the use of microscopes or other technologies in the concept of plant anatomy, solving problems in case studies in daily life, practicing questions in it can improve the understanding of science literacy, some attractive illustrations and videos are in accordance with plant anatomy material, and overall the language and sentences used are in accordance with the rules of Indonesian writing that are good and easy to understand. However, several things need to be improved to improve the quality of the e-module that is being developed, including that in the aspect of presenting the material it needs to be made more systematic using points not just paragraphs to make it easier to understand the core of the material, add space for reflection and feedback so that learning is more meaningful and interesting, in the quiz section you can be given more interesting answer feedback such as voices, So that when the answer is correct or incorrect, the respondent can appreciate it, so that this module can reach all people who have limitations, it is better to provide deaf-friendly features such as screen reading features.

In terms of design or presentation of display illustrations, the layout, elements, and colours should be made more cohesive and attractive, and material in the form of explanation stages should be presented in the form of diagrams or plots to be more concise and systematic. In terms of ease of use, the STEM e-module should be used offline so that readers can access it easily without having to be in a condition of needing a signal. It is better to provide a search feature or a link back to the homepage, so that it is easier for readers to find or reread previous information. In terms of attractiveness, add sound effects for each slide and background to make it more exciting to read and interesting. Pre-service biology teachers consider the STEM e-module to be very good for understanding plant anatomy material, integrated with science, technology, engineering, and mathematics, so that it can improve science literacy and problem-solving skills, presenting material clearly, interestingly, and not boring to read.

Overall, pre-service biology teachers rated the STEM e-module as excellent in helping them understand plant anatomy material integrated with science, technology, engineering, and mathematics. This finding corroborates previous research that STEM-based learning can improve scientific literacy and problem-solving skills through the integration of concepts with real-world contexts (Bybee, 2013; Thibaut et al., 2018; Triplett et al., 2023). Findings from this research show that the development in science literacy was not achieved equally across all the indicators, especially procedural knowledge and data analysis. Nonetheless, the findings are consistent with and add weight to previous studies showing that digital learning would be more effective in enhancing conceptual knowledge rather than procedural knowledge when it lacks an inquiry-oriented approach. The current research is unique from previous studies in that it focuses on testing the impact of the STEM e-module on a sample of pre-service biology teachers (pre-service teachers). Previous studies had focused largely on school pupils. The importance of this finding lies in the fact that pre-service teachers will play a critical role in implementing STEM learning in the future (Darling-Hammond et al., 2020). This research offers some fresh perspectives whereby digital STEM learning is seen to be dependent on more than just the inclusion of STEM subject content. The factors include the instructional design as well as the interactivity. This proves that what matters is not the technology itself, but how the technology has been pedagogically designed to assist scientific work and literacy (Schindler et al., 2017; Spencer, 2024; Voogt et al., 2013).

The significance of this paper includes the findings that despite STEM-based digital modules increasing the science literacy among participants, this influence is uneven with regard to different indicators, especially procedures and data interpretation. Contrary to earlier works stating positive effects from using this technology generally, the current research reveals certain weaknesses of its implementation for the benefit of pre-service biology teachers. Also, it stresses that effectiveness is more related to design, interactivity, and usability rather than technology per se.

This research also contributes to the development of online education and educational technology by designing a LifeSTEM e-module, a digital STEM-based learning resource for biology trainee teachers. Using STEM – science, technology, engineering, and mathematics in the form of electronic modules is a way in which educational technology can facilitate effective learning experiences (Bond et al., 2021; Hodges et al., 2020). In the case of online learning, the LifeSTEM module enables learners to access instructional content individually, participate in inquiry-based learning, and acquire scientific literacy through technology-enhanced learning approaches. In previous research, digital learning systems in STEM education have been found to promote engagement and self-directed learning among learners (Lai & Bower, 2020). In addition, the creation of this module helps in the increasing use of technology innovation in the field of e-learning in higher education, especially for teacher training programs in biology, by encouraging the application of e-learning technologies that blend scientific principles with real-world problem solving. The educational technology literature has also indicated the importance of online and technological learning environments as enablers of active learning and 21st-century skills such as critical thinking and teamwork (Martin et al., 2020; Rapanta et al., 2021). Thus, the present study not only adds to research in STEM education but also to the wider area of online learning and educational technology by illustrating the use of digitally enhanced materials as a way of facilitating significant learning in pre-service teachers.

## LIMITATION

The limitations of this study include the use of a sample that is relatively small in size and not very diverse, potentially limiting the applicability of the study findings. Using only quantitative information might have missed out on how the students perform when it comes to procedural abilities and reasoning. The differences shown when analyzing the improvements made by the students in different scientific literacy measures imply that there is a need for the development of the e-module used.

## CONCLUSION

The successful implementation of the LifeSTEM e-module has incorporated the key concepts of STEM-based education into biology courses to promote scientific literacy among pre-service teachers. As the results show, the module in question is reliable and appealing since it enables pre-service teachers to learn in a meaningful way by linking scientific concepts with the real world and developing the skill of evidence-based reasoning. Despite the effectiveness observed, the findings reveal that the increase in scientific literacy is uneven concerning the four indicators studied, with pre-service teachers demonstrating significant progress only in conceptual understanding and identification of scientific problems, whereas procedural knowledge and data interpretation remain weak. Thus, even though the LifeSTEM e-module is an effective tool for scientific literacy promotion, the results are rather mixed because of its partial efficiency that needs further improvement in terms of fostering high-level scientific skills. In other words, it could be said that STEM-based digital materials have the potential to promote scientific literacy. The implication of this study highlights the importance of embedding E-STEM learning in teacher education, not only to improve conceptual understanding but also to strengthen procedural and analytical competencies. It is recommended that teacher education institutions adopt and further develop LifeSTEM-based modules by incorporating more inquiry-based activities, data interpretation tasks, and interactive feedback features to ensure more balanced improvements across scientific literacy indicators.

## AUTHOR CONTRIBUTION

IDL, DR, and IR were responsible for questionnaire development and manuscript preparation. EA, RS, DENF, and MEH helped prepare the paper. IJS helped with the development of the text, data coding, and analysis. The published version of the work was examined, approved, and approved by all authors.

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