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STEM-Based E-Module Integrated with Virtual Scanning Electron Microscope (SEM): An Innovative Learning Material for Science Learning in Secondary School

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Abstract: This study aims to develop a STEM-based e-module integrated with a Virtual Scanning Electron Microscope (SEM) as an innovative solution in science learning. This study employed the research and development method, utilizing the ADDIE model, which comprises five main stages: analysis, design, development, implementation, and evaluation. The study involved seventh-grade students in secondary school as the research subjects. The developed e-module was validated in content, language, and presentation, including a practicality test through readability responses and an effectiveness test using a quasi-experimental design. The results indicated that the developed e-module had high validity, practicality, and effective use. Expert validation categorized the e-module as feasible, specifically, the material component obtained a score of 82.67, the language aspect was rated at 88, and the presentation dimension reached 87.3. While the readability test demonstrated its practicality, meaning that the e-module is easy to use, engaging, and interactive, with the majority rating it as "very practical". Furthermore, its implementation in learning was proven to enhance students' achievement, as reflected by N-Gain scores ranging from medium to high, along with a large effect size, with an average value of 0.75 within the "high" category. Therefore, this developed e-module can be considered a relevant instructional innovation to support 21st-century science learning.

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Introduction

In the Education Era 4.0, the learning process is colored by learning innovations, one of which is through the integration of technology into the stages of teaching and learning activities. Learning innovation is an urgency to improve the effectiveness, results, and quality of the teaching and learning process (Andani et al., 2023; Susilawati et al., 2024; Utomo, 2023). Innovation in learning is not solely targeted at academic achievement but also optimizes the mastery of 21st-century skills, including the ability to think critically in solving problems, creativity in generating new ideas, collaborative skills in working together effectively, and essential technological literacy in facing the challenges of the digital era (Dewi & Arifin, 2024; Herlinawati et al., 2024). The integration of learning design that is in harmony with the dynamics of the times has the potential to present an interactive, contextual learning process and is able to provide an increase in motivation and academic achievement of students (Chukwuemeka & Garba, 2024; Yaseen et al., 2025). This integration includes the use of online platforms, learning analytics, and artificial intelligence that facilitate the active participation of students while linking learning materials so that they are more contextual and meaningful (Balalle, 2024; Mduwile & Goswami, 2024; Schmidt et al., 2025).

Virtual laboratories can be positioned as innovative learning media that support the teaching and learning process. Virtual laboratories as an alternative solution to optimize the learning quality in the 21st century, which requires the integration of technology in education (Abdelmoneim et al., 2022; Sapriati et al., 2023; Sriadhi et al., 2022). Its use is able to facilitate students exploring concepts more applicably, in-depth, and contextually. It has an impact not only on the abstract theory that students understand, but also on the ability to connect with real practices that strengthen critical thinking, problem-solving, and mastery of science literacy more comprehensively (Asare et al., 2023). The advantage of virtual laboratories lies in their flexibility, without being bound by time or location limits. Through structured simulations, students can gain experiences similar to the practice of using physical equipment in real laboratories, so that the limitations of facilities and infrastructure are no longer obstacles in achieving practicum competencies (Flowers, 2024; Kashaka, 2024). The use of virtual laboratories not only facilitates the learning process but also enriches the learning experience of students through support for technical skill development as well as increased understanding of material that they may not have encountered before (Herráez, 2022). The use of virtual laboratories allows the process to take place more efficiently and in a more targeted manner, while making learning activities more effective.

Learning process can be integrated with the learning approach, namely STEM, which plays an important role in nurturing 21st-century challenges (Minarti et al., 2023; Noris et al., 2022; Trisnaningsih et al., 2021). STEM helps students to prepare and face the challenges of education in this era (Fajrina et al., 2020). It needs STEM to be integrated into the learning process to reach the educational goals (Astawan et al., 2023; Khalid et al., 2024). Through the application of the latest technology, students can hone their skills in solving complex problems. In this context, the application of virtual laboratories that are integrated with STEM approaches is able to increase the flexibility and effectiveness of learning, enrich the learning experience, and contribute to significantly improving students' academic achievement. STEM-based virtual laboratories are a strategic means of integrating theory and practice contextually to make learning outcomes effective (Dodevska et al., 2025).

The results of observations show that the use of microscopes in science learning in the biology topic in secondary school is still limited to the use of light microscopes. Meanwhile, the introduction of more advanced microscopes, like electron microscopes, only occurs at the theoretical knowledge level, without providing hands-on practice opportunities. Interviews conducted with Science Learning Teacher (MGMP) participants informed that the implementation of the learning enrichment program in some schools is still not optimal. The follow-up to the learning evaluation so far has been more focused on the implementation of remedial programs for students with low learning outcomes, while enrichment programs are often not implemented systematically. In some cases, enrichment activities are only carried out by asking students to independently read the material or subsequent learning topics, without any assistance or structured learning strategies. This condition indicates the need for alternative enrichment programs that can be implemented effectively by teachers (Tan et al., 2020).

The enrichment program has a strategic role in deepening understanding of concepts, expanding the skills mastered, and developing the Higher Order Thinking Skill (HOTS) (Postrado & Aliazas, 2024). Enrichment is not only designed as a supplement in learning but also as a means of developing students' academic abilities that have exceeded the minimum competency standards (Direktorat Pembinaan Sekolah Menengah Atas, 2017). Through involvement in enrichment programs, learners not only gain the opportunity to explore more deeply the material they have learned but also expand their skills and knowledge through

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relevant additional experiences and challenges. The novelty contribution of this research lies in the application of Virtual SEM as the main medium in the development of STEM e-module in science learning, which is still very limited in its application in educational practice. This research not only produces innovative products but can also be a model for the development of relevant technology-based teaching materials to be applied in various educational contexts.

Research Method

This research used the research and development (R&D) method with the ADDIE model (Branch, 2009) in five stages: analyze, design, development, implementation, and evaluation. Each stage of development is carried out based on needs, accompanied by evaluation at the end of the stage before moving on to the next stage. This mechanism aims to ensure that each development step is carefully designed so that the ADDIE model becomes more systematic and comprehensive, and has a clear basis for consideration. Therefore, the application of this model is seen as effective and structured in optimizing the quality of results in each stage of development (Nababan, 2020).

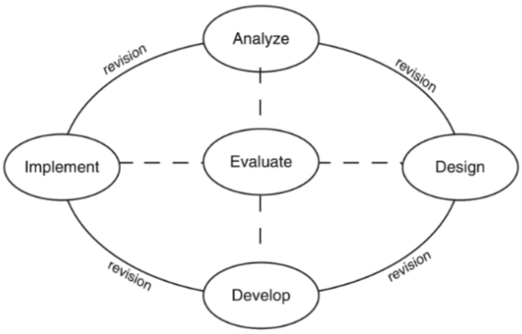

Figure 1. ADDIE Development Model

The analysis of the needs of teaching materials is applied in the analysis stage by considering the characteristics of students and learning outcomes. The design stage is focused on the initial draft of the e-module. The development stage is carried out by conducting a feasibility test on the draft e-module that has been designed. The assessment instrument uses a validation sheet adapted from the guidelines of Pusat Kurikulum dan Perbukuan for determining the feasibility of the draft e-module presented in Table 1.

Table 1. E-Module Feasibility Requirements

Range of Score	Meaning
> 85	Feasible = **Excellent**
55 ≤ skor ≥ 85	Feasible = **Good**
< 55	Not Eligible

Source: (Pusat Kurikulum dan Perbukuan, 2014)

The implementation stage is carried out by testing the e-module that has been validated in a limited group, namely teachers, as users of the e-module as science learning material innovations, and 19 seventh-grade students in secondary school, as target learners. The evaluation stage includes evaluating each stage of development to ensure the suitability of the process with the set objectives and assessing the readability and effectiveness of the use of the e-module. Measurement guidelines and interpretation guidelines for the results of the readability and effectiveness test (using the N-gain formula) using the following formulas and Table 2 and Table 3, respectively.

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Readability Test Formula:

$$\% \text{ response} = \frac{\textit{total answer score "yes"}}{\textit{total max score}} \times 100\%$$

Table 2. Proportion Responses Interpretation

Proportion (%)	Meaning
0-20	Impractical
21-40	Less Practical
41-60	Quite Practical
61-80	Practical
81-100	Very Practical

N-gain Formula:

$$\text{Normalized gain} = \frac{\text{posttest score} - \text{pretest score}}{\textit{max score} - \textit{pretest score}}$$

Table 3. N-gain Score Interpretation of Effectiveness

Score	Meaning
$0{,}70 \leq$ normalized gain	High
$0{,}30 \leq$ normalized gain $< 0{,}70$	Average
normalized gain $< 0{,}30$	Low

Results and Discussion

This research implements the development of STEM-based e-module that are integrated with Virtual SEM in the context of science learning in secondary school as an innovative instructional resource through the use of virtual microscopic data. The advantage of this research lies in a different approach compared to previous research, because the e-module developed not only presents conceptual simulations but also presents a more comprehensive scientific workflow, including the stages of data collection (virtually), measurement, analysis, and communication of science results. Students will be able to have a more authentic learning experience, resembling the practice of scientists in studying real phenomena (Ambusaidi et al., 2017; Hamed & Aljanazrah, 2020). The e-module can be integrated into the science curriculum through thematic learning units that emphasize inquiry, experimentation, and design. Within the framework of STEM education, it aligns with curriculum objectives such as developing scientific literacy, nurturing critical and creative thinking, and applying interdisciplinary knowledge (Marzuki et al., 2024; Nugraha et al., 2024; Santos, 2017).

Stage 1: Analyze

The analyze stage is carried out by identifying learning needs related to the teaching materials to be developed. This process includes the study of learning objectives, as well as considering the characteristics of students. Needs analysis ensures the suitability and accuracy of e-module that are relevant, directed, and able to answer problems in science learning (Hendri et al., 2021). The needed data were obtained through interviews with teachers and by filling out questionnaires that represented conditions in the field.

Stage 2: Design

The design stage focuses on the preparation of the initial design of the e-module. At this stage, a conceptual framework is formulated that includes the selection and preparation of materials relevant, according to the results obtained from the previous stage, so the resulting product has a systematic, interactive structure and supports the achievement of 21st-century competencies. In addition, this stage also involves planning the structure of the

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material presentation, graphic display, and integration of STEM and Virtual SEM approaches into the e-module. The prototype design of the e-module is presented in Figure 2 below.

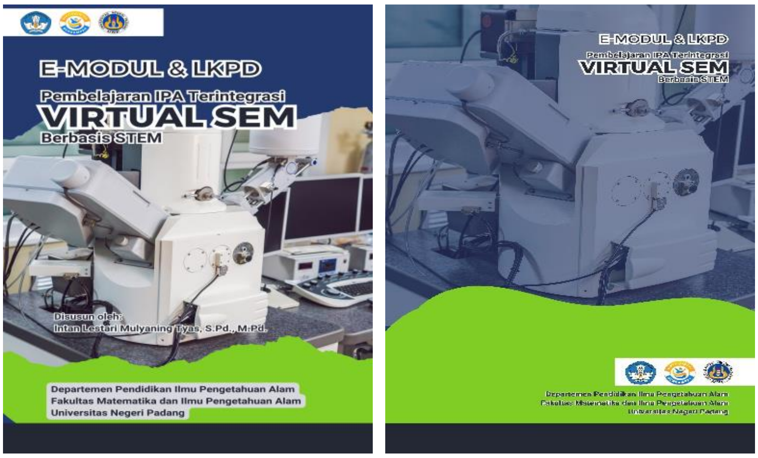

Figure 2. E-Module Cover Prototype

Stage 3: Develop

The development stage is carried out through a validation process for the e-module prototype that has been prepared at the design stage. The process involves experts according to their expertise, such as material, language, and presentation aspects. The main purpose of the validation process is to ensure that the e-module is in accordance with the standards. In addition, the validation also aims to assess the feasibility level of the e-module so that the e-module can be used practically and effectively. The results of validation are presented in Table 4.

Table 4. E-Module Validation Results

Aspects	Score			Average	Category
	Validator 1	Validator 2	Validator 3		
Material	82	84	82	82.67	Feasible
Language	88	88	88	88	Feasible
Presentation	86	87	87	87.3	Feasible

The validation results showed that the e-module obtained the "Feasible" category in all aspects of the assessment, including material, language, and presentation, with average scores of 82.67, 88, and 87.3, respectively. These findings confirm that the product has met the established quality criteria, so it can proceed to the next stage. Thus, the e-module has a strong empirical basis to be implemented in limited field trials.

Stages 4 and 5: Implement and Evaluate

The implementation stage is carried out by testing e-module that are valid and feasible. The trial involved teachers as direct users and students as target learners to measure the effectiveness and practicality of the e-module as a science teaching material innovation. At this stage, the assessment is focused on the aspects of ease of accessibility, clarity of presentation in the material, attractiveness of the display, and the potential of e-module in supporting the achievement of learning objectives. The results are an important basis for obtaining empirical input before implementation on a wider scale and are used as a basis for further improvement. The evaluation stage is carried out to ensure the suitability of the series of development processes that have been carried out. The data from this stage is used as a principle in conducting the final revision. The results can be seen in Table 5 and Table 6 below.

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Table 5. Practicality Responses Interpretation

Percentage (%)	Meaning	Number of Responders
0-20	Impractical	0
21-40	Less Practical	0
41-60	Quite Practical	2
61-80	Practical	9
81-100	Very Practical	10

Table 5 presents the practicality test through the readability aspect of the e-module developed. Based on the data, the response range was in the categories of "Quite Practical," "Practical," and "Very Practical," with a distribution of 2, 9, and 10 respondents, respectively. It means that the e-module was easy to use and interactive for secondary school students. These findings show that the majority of responders (10 people) rated the e-module in the category of "Very Practical." The dominance of positive responses indicates that the STEM-based e-module integrated with Virtual SEM is considered to have a high level of readability and ease of use and to be in accordance with learning needs. Furthermore, good acceptance from respondents is expected to make a real contribution to the understanding of science concepts for students, as well as support the effectiveness of learning through the use of innovation-based technology. Table 6 presents data on the results of the effectiveness test of the use of e-module.

Table 6. Effectiveness of Using the E-Module

Responder	*Pre-test*	*Post-test*	*N-gain*	Meaning
YF	50	85	0.7	High
YY	45	95	0.91	High
DR	40	90	0.83	High
ZH	55	90	0.78	High
ME	70	100	1	High
RP	60	85	0.63	Average
DS	55	70	0.33	Average
EH	45	100	1	High
SF	45	85	0.73	High
AF	55	90	0.78	High
RY	75	85	0.4	Average
KM	65	90	0.71	High
VB	50	85	0.7	High
RW	60	95	0.88	High
DY	35	100	1	High
BA	40	100	1	High
RF	45	80	0.64	Average
LU	30	75	0.64	Average
VA	35	70	0.54	Average
DE	40	85	0.75	High
Average			0.75	High

The average calculation of the N-Gain value was obtained from the implementation of pre-test and post-test of 0.75. The value is in the "High" category, which indicates that it is effective in improving knowledge. These findings indicate that STEM-based virtual SEM-integrated e-module are able to make a positive contribution as teaching materials for science learning. The effectiveness test showed that the use of e-module was able to provide a significant improvement in cognitive learning outcomes. This confirms that the product of this research is not only theoretically and practically feasible but also effective in improving the quality of learning (W. O. Pratiwi et al., 2024; Susetyo et al., 2025; Yani et al., 2024).

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The results of the study reinforce that STEM-based e-module are effective in improving learning outcomes (Irdawati et al., 2023; Kholistiyawatin et al., 2023). This research makes a new contribution by integrating Virtual SEM as a primary data source, allowing students to practice scientific image analysis skills. This is different from previous research that relied only on macroscopic simulations or simple illustrations. As a digital learning resource, the e-module can be positioned as an alternative instructional innovation that promotes contextual understanding and meaningful learning experiences (I. A. Pratiwi et al., 2025).

The information obtained through the developed e-module allows its use to be more relevant and focused on the context needed by students (Thobroni et al., 2022). With the presentation of material that is structured, systematic, and according to the level of ability, students can more easily access knowledge that really supports learning needs. This accommodates the application of information effectively and on target, and can be directly implemented in appropriate situations or problems. E-module can be applied to learning, and well-designed enrichment programs can be in the form of providing more in-depth material related to the topics that have been studied, thereby expanding their horizons and enriching students' knowledge. The enrichment program has great potential to be applied to science learning topics related to the use of microscopes.

In classroom practice, this innovation allows teachers to shift from traditional text-based instruction toward more interactive, inquiry-driven STEM approaches. Teachers can incorporate the e-module into lesson plans as a supplementary tool for exploration and problem-solving based on the worksheet that is contained in e-module by integrating STEM with Virtual SEM. For example, in the Classification of Living Things topic, the e-module is designed to present contextual problems that encourage students to initiate an exploration of their prior knowledge. Working collaboratively in groups, students are guided to examine biological characteristics that are unique to certain classifications of living organisms, such as the presence of hair in mammals. This initial stage aims to stimulate critical thinking as students attempt to construct explanations and propose solutions to the problems presented (Nilyani et al., 2023; Senarpi, 2023).

In the aspects of Technology and Mathematics, students are provided with opportunities to observe microscopic structures virtually by using Virtual SEM, which are otherwise inaccessible in a typical school laboratory setting, particularly in science learning with the biology topic, and fosters authentic engagement with scientific phenomena, such as analyzing microscopic images of hair samples provided in Virtual SEM. This promotes a deeper conceptual understanding (Asrizal, 2025). Through this activity, they are required to measure the diameter of hair, compare results across samples, determine the actual size, and relate the observed structures to their biological functions. Students are also encouraged to identify noteworthy findings and articulate insights from their observations. These activities not only foster analytical and quantitative skills but also provide an authentic scientific inquiry experience that bridges theory with practice. From the perspective of Engineering, the e-module challenges students to engage in collaborative discussions aimed at generating design ideas for tools or products inspired by the structure and function of animal hair. This stage provides an opportunity for students to integrate creativity with scientific understanding, thereby enhancing their capacity for innovation (Hanif et al., 2019; Sirajudin et al., 2021). Finally, the learning process concludes with a reflection stage, where students consolidate what they have learned, articulate their understanding of the topic, and evaluate the relevance of the knowledge gained. This reflective practice is intended to deepen comprehension and ensure that students recognize the broader significance of applying

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STEM principles to real-world contexts. In this way, the e-module is carried out in accordance with the curriculum and the instructional design outlined

Through this e-module, teachers can present interesting, interactive, and innovative learning activities for students. Simulation/visualization of electron microscope images (topography, morphology, particle size) with pseudo-control of parameters (magnification, focus, contrast, working distance) can facilitate scientific data literacy at the micro-nano scale without logistical obstacles/instrument costs. This will be able to provide opportunities for students to understand concepts more deeply, as well as improve science literacy skills. The use of e-module as a source of independent, multimedia, interactive learning also facilitates the creation of a learning process that is interactive, adaptive, and in line with the demands of the 21st century (Haryanti et al., 2025; Tarigan et al., 2021; Tartiyoso, 2025). Therefore, technology-based learning can no longer be seen as just an alternative but has become an essential need to prepare students to face challenges in an increasingly digitalized era.

Conclusion

The STEM-based e-module integrated with Virtual SEM was developed by employing the ADDIE instructional design model, resulting in a product that meets the criteria of validity, practicality, and effectiveness for science learning activities. The validation process produced strong outcomes across several dimensions: the material component achieved a score of 82.67, the language aspect received a score of 88, and the presentation dimension was rated at 87.3. These results indicate that the e-module demonstrates a high degree of accuracy in content, clarity of language, and appropriateness of instructional presentation. In terms of practicality, teacher evaluations yielded a score of 80%, which was categorized as "practical." This suggests that the e-module can be readily implemented in classroom contexts with minimal obstacles. From the student perspective, the practicality test produced even stronger results, with the majority of responses categorized as "very practical". This demonstrates that learners find the e-module accessible, engaging, and user-friendly in supporting their learning experiences.

The effectiveness of the e-module was further confirmed through the calculation of N-gain scores following its classroom implementation. The analysis revealed an average N-gain score of 0.75, which is categorized as "high". This outcome signifies that the use of the e-module contributed substantially to improving students' conceptual understanding and scientific literacy, thereby validating its effectiveness as a STEM-based digital learning innovation. Overall, these findings affirm that the developed e-module is not only theoretically sound but also pedagogically practical and empirically effective, making it a viable resource for advancing science learning in secondary school in line with the demands of 21st-century competencies, especially in terms of science literacy, critical thinking skills, and the use of digital technology.

Recommendation

Based on the findings of this study, teachers are encouraged to enrich modern learning strategies and improve the quality of science education in the digital era, such as adopting STEM-based e-module integrated with Virtual SEM as a part of their instructional plan. The use of this innovation should not be limited to enrichment but embedded within daily classroom activities to foster inquiry, experimentation, and critical discussion. Teachers may gain confidence in designing, modifying, and implementing a digital module in accordance with curriculum objectives. Teachers are also advised to utilize the e-module for differentiated learning. By assigning tasks of varying complexity within the module, they can

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accommodate diverse student abilities while still promoting higher-order thinking. Furthermore, integration with project-based or problem-based learning strategies will maximize its potential in strengthening students' scientific literacy, problem-solving, and collaborative skills. For future researchers, this research serves as a basis for the continued refinement and advancement of implementing other topics as well as a wider scale of implementation, and also can enrich developed learning material with augmented reality (AR) or gamification elements to further enhance engagement, interactivity, and learning motivation of students. The measurement of long-term effects can also be investigated to determine how sustained use of the e-module influences students' scientific literacy toward the STEM approach.

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