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Development and Validation of the Microbes E-Module as a Project-Based Digital Learning Resource to Support Sustainable Quality Education in Undergraduate Microbiology

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Abstract: This study aimed to evaluate the validity of the Microbes E-Module as a digital learning resource for undergraduate microbiology education. The study employed a Research and Development (R&D) approach using the ADDIE model. The validation process was conducted during the Development phase and involved nine expert validators. The validated aspects included content, media, Project-Based Learning (PjBL), educational game components, and language. Data were collected using a validation questionnaire and analyzed descriptively using validity percentages. The results showed validity percentages of 99% for content, 94% for media, 96% for Project-Based Learning (PjBL), 95% for educational game components, and 98% for language. The overall validity percentage of the Microbes E-Module was 96%, indicating that it met the criteria of very valid. These findings provide evidence that the Microbes E-Module has achieved a very high level of validity based on expert evaluation across all validated aspects. Further studies are recommended to investigate the module's practicality and effectiveness during the Implementation and Evaluation phases of the ADDIE model.

Keywords: Digital Learning Resource; E-Module; Gamification; Microbiology Education; Project-Based Learning; Validity

Introduction

The rapid advancement of digital technology has fundamentally transformed educational practices worldwide, particularly in higher education, where digital learning has become an essential component of teaching and learning. Digital transformation has shifted learning environments from conventional teacher-centered instruction toward more flexible, accessible, and student-centered approaches that enable learners to access educational resources regardless of time and place (Chan, 2023; Chugh et al., 2023). This transformation is closely aligned with Sustainable Development Goal 4 (SDG 4: Quality Education), which emphasizes equitable access to quality education through innovative teaching approaches and technology-enhanced learning resources. Consequently, higher education institutions are increasingly encouraged to develop digital instructional materials that facilitate meaningful learning experiences while addressing the diverse learning needs of students (Trevisan et al., 2023). Digital learning resources have become one of the most widely adopted educational innovations because they integrate multimedia elements, including text, graphics, animations, videos, simulations, and interactive activities, which can enhance students' engagement and understanding of complex concepts. Previous studies have shown that interactive digital learning resources promote learning autonomy, improve conceptual understanding, and support more flexible learning experiences in higher education (Nasution & Ariyanti, 2025; Yeşilyurt & Vezne, 2023).

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Microbiology is one of the fundamental courses in biology education because it introduces students to microorganisms and their roles in health, agriculture, industry, biotechnology, and environmental sustainability. Despite its importance, microbiology remains one of the most challenging subjects for undergraduate students because many microbiological concepts involve microscopic structures and biological processes that cannot be directly observed. Topics related to viruses, bacteria, and fungi require students to visualize invisible organisms, understand complex biological interactions, and connect abstract scientific concepts with real-world phenomena. Conventional learning materials that rely mainly on textual explanations and static illustrations often provide insufficient support for developing comprehensive conceptual understanding. Consequently, students frequently experience misconceptions and difficulties in understanding fundamental microbiological concepts, particularly those related to microbial structure, metabolism, genetics, and evolution, highlighting the need for instructional approaches that promote conceptual understanding and meaningful visualization (Briggs et al., 2017; Fidiastuti et al., 2024). These challenges indicate the need for more interactive digital learning resources capable of presenting microbiological concepts through meaningful visualization and student-centered learning activities.

One promising approach for addressing these instructional challenges is the development of electronic modules (e-modules). E-modules integrate instructional content, multimedia resources, self-directed learning activities, and formative assessments within a single digital learning environment. Compared with conventional printed modules, e-modules provide students with greater flexibility to learn independently through interactive learning materials that combine text, graphics, animations, instructional videos, hyperlinks, and digital assessments. Such integration enables students to engage with learning content more actively while supporting different learning styles and promoting deeper conceptual understanding. Previous studies have consistently demonstrated that e-modules improve students' conceptual understanding, science literacy, learning motivation, and learning independence by providing richer and more interactive learning experiences than traditional instructional materials (Alamin et al., 2024; Rahmiati et al., 2023; Reid et al., 2024). Furthermore, because e-modules can be accessed through computers, tablets, and mobile devices, they facilitate flexible learning by allowing students to study anytime and anywhere, thereby supporting the implementation of digital and student-centered learning in higher education.

Beyond digital learning resources, contemporary science education emphasizes the importance of student-centered instructional approaches that actively engage learners in constructing knowledge. One of the most widely recommended approaches is Project-Based Learning (PjBL), which encourages students to investigate authentic scientific problems, design solutions, collaborate with peers, and communicate scientific findings through project activities. Project-Based Learning has consistently been shown to enhance higher-order thinking, critical thinking, collaboration, communication, creativity, and problem-solving skills that are essential for twenty-first-century education (Loyens et al., 2023; Zhang & Ma, 2023). In microbiology education, project-based and inquiry-based learning approaches enable students to connect microbiological concepts with authentic scientific issues, actively engage in laboratory investigations, and develop transferable skills such as teamwork, scientific communication, and evidence-based problem solving, thereby promoting deeper conceptual understanding and meaningful learning experiences (McKee et al., 2023).

Another instructional strategy that has received increasing attention is the incorporation of educational game components into digital learning environments. Educational game components, such as points, badges, levels, rewards, challenges, and immediate feedback, are intentionally designed to support instructional objectives while maintaining students' engagement throughout the learning process. Gamification integrates game mechanics into learning activities to create enjoyable, meaningful, and interactive learning experiences that encourage students to participate actively in the learning process. Previous studies have reported that the implementation of gamification can enhance students' motivation, creativity, engagement, and learning outcomes by providing immediate feedback, increasing participation, and fostering a more stimulating learning environment (Rahmatiah et al., 2023; Zidan et al., 2024). Therefore, integrating educational game components into e-modules has the potential to create more engaging and interactive microbiology learning experiences while facilitating students' conceptual understanding and sustaining their motivation throughout the learning process.

Although previous studies have demonstrated positive educational outcomes associated with e-modules, Project-Based Learning (PjBL), and educational game components, these instructional approaches have generally been investigated independently. Research on e-modules has primarily focused on multimedia integration and learning achievement, whereas studies on Project-Based Learning have emphasized inquiry skills, scientific

literacy, and problem-solving. Likewise, studies involving educational game components have mainly investigated students' motivation and engagement. Limited attention has been devoted to developing a single digital learning resource that systematically integrates multimedia-supported e-modules, Project-Based Learning activities, and educational game components specifically for undergraduate microbiology education. Furthermore, relatively few studies have reported comprehensive expert validation covering content, media, language, and instructional design before classroom implementation, despite expert validation being an essential stage in ensuring the quality and feasibility of educational products (Husnadi et al., 2024; Maulia et al., 2024). This gap indicates the need for developing and validating an integrated digital learning resource before evaluating its practicality and effectiveness in authentic learning environments.

The novelty of this study lies in the development and expert validation of the Microbes E-Module, which integrates multimedia-based learning materials, Project-Based Learning activities, and educational game components within a single digital learning resource designed for undergraduate microbiology education. Unlike previous studies that generally investigated these instructional approaches separately, this study provides comprehensive expert validation covering content, e-module media, Project-Based Learning components, educational game components, and language before classroom implementation. This study is important because expert validation represents an essential stage in educational product development to ensure that digital learning resources meet appropriate academic, pedagogical, and technical standards before proceeding to practicality and effectiveness evaluation (Dwiningsih et al., 2024; Hamidi et al., 2024). Therefore, the findings provide empirical evidence regarding the validity of the developed e-module and establish a foundation for future studies examining its practicality and effectiveness during the subsequent phases of the ADDIE development model.

Accordingly, this study aimed to evaluate the validity of the Microbes E-Module as a digital learning resource for undergraduate microbiology education. The validation process focused on five aspects, namely content, e-module media, Project-Based Learning components, educational game components, and language, through expert judgment. The findings are expected to provide empirical evidence regarding the validity of the developed e-module and serve as a foundation for subsequent studies investigating its practicality and effectiveness during the later phases of the ADDIE development model.

Method

The validity of the Microbes E-Module was evaluated using a structured expert validation questionnaire. The instrument consisted of 41 items grouped into five validation aspects: content (5 items), media (13 items), Project-Based Learning (PjBL) components (8 items), educational game components (9 items), and language (6 items). Each item was assessed using a five-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree). Accordingly, the maximum possible score for each validator was 205. The validation process involved nine experts with expertise in microbiology, instructional media, Project-Based Learning, educational game components, and language. Data analysis techniques use descriptive analysis to assess the validity score and the level of validity. The validity of the Microbes E-Module was analyzed using descriptive percentage analysis.

$$\text{Validity Percentage} = \frac{\text{Obtain Score}}{\textit{Minimum Score}} \text{x} 100 \quad (1)$$

The validity percentage was calculated separately for each validation aspect and then averaged to obtain the overall validity percentage of the Microbes E-Module**.**

Table 1. Criteria for Validity Categories (Arikunto, 2013)

Percentage score (%)	Validity Category
81–100	Very Valid
61–80	Valid
41–60	Fairly Valid
21–40	Less Valid
0–20	Invalid

Results and Discussion

Expert Validation of the Microbes E-Module

The validity of the Microbes E-Module was evaluated by nine expert validators consisting of content experts, media experts, educational technology experts, and language experts. The validation process aimed to determine the feasibility of the developed e-module as a digital learning resource in microbiology. The validation results from each expert are presented in Table 2.

Table 2. Expert Validation Results of the Microbes E-Module

Expert	Expert Score	Maximum Score	Validity Value (%)
1	200	205	98.00
2	201	205	98.00
3	202	205	99.00
4	189	205	92.00
5	200	205	98.00
6	203	205	99.00

Expert	Expert Score	Maximum Score	Validity Value (%)
7	200	205	98.00
8	184	205	90.00
9	200	205	98.00
Average Validity Value			96.00

The results indicate that the average validity value of the Microbes E-Module was 96%. Based on the validity criteria, this score falls within the a very high level of validity based on expert evaluation across the assessed aspects All validators provided validity scores above 90 demonstrating a high level of agreement regarding the quality and appropriateness of the developed product. Further analysis was conducted for each validation aspect. The results are presented in Table 3.

Table 3. Validation Results by Aspect

Validation Aspect	Validity (%)	Category
Content	99.00	Very Valid
E-Module Media	94.00	Very Valid
Project-Based Learning (PjBL) Components	96.00	Very Valid
Educational Game Components	95.00	Very Valid
Language	98.00	Very Valid
Average Validity	96.00	Very Valid

The results showed that all validation aspects achieved validity scores above 90.00%. The highest validity score was obtained in the content aspect 99.00%, followed by language 98.00%, PjBL components 96.00%, educational game components 95%, and e-module media94.00%. The overall validity score of 96% indicates that the Microbes E-Module meets the criteria of a highly validity.

The content aspect of the Microbes E-Module obtained a validity percentage of 99.00%, indicating that the instructional content was evaluated as very valid by the expert validators. This finding demonstrates that the developed e-module adequately represents the intended learning outcomes, microbiology concepts, and Project-Based Learning (PjBL) activities required for undergraduate biology education. The high validity score also indicates that the content is conceptually accurate, systematically organized, and relevant to the curriculum. However, the present findings should be interpreted as evidence of content validity based on expert judgment rather than evidence of instructional effectiveness because the present study was limited to the Development phase of the ADDIE model and did not involve classroom implementation.

The high content validity may be attributed to the systematic instructional design process adopted during the development of the Microbes E-Module. The module was developed through comprehensive curriculum analysis, identification of students' learning needs, formulation of learning outcomes, organization of microbiology concepts, and integration of Project-Based Learning activities. Such a systematic development process is consistent with recent instructional design principles emphasizing that digital learning resources should demonstrate coherence among learning objectives, instructional content, learning activities, and assessment to support meaningful learning experiences in higher education (Galvis & Carvajal, 2022; Maffei et al., 2022). These instructional design principles ensure that educational materials are pedagogically aligned before implementation, which may explain the high level of expert agreement regarding the content validity of the developed e-module.

Another factor contributing to the high content validity is the integration of authentic microbiology contexts into the learning materials through Project-Based Learning activities. Instead of presenting microbiological concepts only through descriptive explanations, the module encourages students to investigate authentic scientific problems related to viruses, bacteria, and fungi while completing structured project activities. This instructional approach is supported by recent studies on digital learning, which emphasize that meaningful learning occurs when students actively construct knowledge through authentic inquiry and interaction with well-designed digital learning environments (Galvis & Carvajal, 2022; Pribadi et al., 2022). Consequently, the contextual organization of learning activities contributed to the experts' positive evaluation of the instructional content, although its influence on students' conceptual understanding remains to be investigated during classroom implementation.

The findings of the present study are consistent with previous research on digital learning resource development. Saputra et al. (2024) reported that an augmented reality-assisted e-module achieved a very high level of content validity because the instructional materials were systematically aligned with curriculum objectives and scientific literacy indicators. Likewise, Sapira et al. (2024) found that integrating Project-Based Learning contributed to high expert validation by providing authentic learning experiences and improving curriculum alignment. Similar findings were reported by Nasution & Ariyanti (2025), who concluded that a Project-Based Learning e-module demonstrated high content validity because the learning materials were scientifically accurate, systematically organized, and aligned with intended learning outcomes. Collectively, these studies support the present findings by demonstrating that systematic curriculum alignment

and contextual learning activities are essential factors in establishing the validity of digital instructional materials.

Evidence from international studies also supports these findings. Pike et al. (2022) emphasized that high-quality digital microbiology learning resources should provide scientifically accurate content, meaningful visual representations, and structured learning activities to facilitate students' understanding of complex microbiological concepts. Similarly, Galvis & Carvajal (2022) concluded that successful digital learning resources in higher education are characterized by systematic instructional design, learner-centred activities, and alignment between learning objectives and instructional strategies. These findings reinforce the present study by demonstrating that the characteristics identified by the expert validators are consistent with internationally recognized principles for developing digital instructional resources.

Overall, the findings indicate that the content component of the Microbes E-Module achieved a very high level of validity according to expert judgment. The systematic alignment among curriculum objectives, microbiology concepts, Project-Based Learning activities, and multimedia-supported instructional materials contributed to the experts' positive evaluation of the developed module. Nevertheless, these findings should not be interpreted as evidence that the module improves students' learning achievement or conceptual understanding because such outcomes require empirical investigation involving learners during the Implementation and Evaluation phases of the ADDIE model. Instead, the present study provides evidence that the developed instructional content satisfies expert validation criteria and establishes a sound basis for future studies evaluating the practicality and effectiveness of the Microbes E-Module in undergraduate microbiology education.

The media aspect of the Microbes E-Module obtained a validity percentage of 94.00%, indicating that the media component was classified as very valid by the expert validators. This finding demonstrates that the visual interface, navigation system, typography, multimedia presentation, colour composition, and overall layout of the e-module met the quality criteria expected for digital learning resources in undergraduate microbiology education. The high media validity suggests that the developed media were considered appropriate for supporting the presentation of microbiological concepts through an attractive and well-organized learning environment. However, these findings should be interpreted as evidence of media validity based on expert judgment, rather than evidence of usability or instructional effectiveness, because the present study was limited to expert validation during the Development phase of the ADDIE model.

The high media validity may be attributed to the systematic media design process implemented throughout the development of the Microbes E-Module. The interface was designed to provide consistent navigation, readable typography, balanced visual elements, relevant illustrations, and multimedia resources that facilitate students' interaction with learning materials. Recent studies have emphasized that the quality of digital learning media depends not only on aesthetic appearance but also on the integration of multimedia elements that support learners' cognitive processing and instructional interaction (Lin & Yu, 2023). Similarly, digital learning resources that present information through well-organized visual layouts and intuitive navigation provide more accessible learning experiences and improve the instructional quality of educational products before classroom implementation.

The findings of the present study are consistent with previous research on digital media development in science education. Abdilah and Wulandari (2024) reported that an e-module developed for science learning achieved a high level of media validity because the interface design, visual presentation, and multimedia organization successfully met expert expectations regarding instructional media quality. Likewise, Aji et al. (2025) found that an e-module demonstrated excellent media validity owing to its systematic integration of multimedia elements, user-friendly navigation, and visually consistent interface. These studies indicate that effective media design requires careful alignment between instructional objectives and multimedia presentation to produce high-quality digital learning resources.

Comparable findings have also been reported in biology education. Laswi & Bungawati (2024) found that media achieved high expert validity because the interface design and multimedia features successfully facilitated visualization of biological concepts while maintaining ease of use for learners. Similarly, Vardar-Ulu et al. (2024) demonstrated that biology education provide meaningful visualization through interactive media that enhance the instructional quality of digital learning environments. Although these studies examined different biology topics, they consistently highlight the importance of visual representation, multimedia integration, and user-friendly interfaces in the development of digital instructional media.

Overall, the findings indicate that the media component of the Microbes E-Module achieved a very high level of validity according to expert judgment. The systematic integration of visual design principles, multimedia resources, intuitive navigation, and

instructional consistency contributed to the positive evaluation provided by the expert validators. Nevertheless, these findings should not be interpreted as evidence that the developed media improve students' motivation, engagement, or learning outcomes because these variables were beyond the scope of the present study. Instead, the findings demonstrate that the media component satisfies the expert validation criteria required during the Development phase of the ADDIE model and provides a strong basis for future studies examining the practicality and effectiveness of the Microbes E-Module in undergraduate microbiology education.

The Project-Based Learning (PjBL) component of the Microbes E-Module obtained a validity percentage of 96.00%, indicating that this component was classified as very valid according to the expert validators. This finding demonstrates that the project activities incorporated into the e-module were considered pedagogically appropriate and aligned with the intended learning outcomes of undergraduate microbiology education. The expert validators agreed that the project orientation, learning activities, project implementation procedures, and assessment guidance reflected the essential characteristics of Project-Based Learning. However, these findings should be interpreted as evidence of the validity of the PjBL design rather than evidence of its effectiveness in improving students' learning outcomes, since the present study was limited to expert validation during the Development phase of the ADDIE model.

The high validity of the PjBL component may be attributed to the systematic integration of authentic project activities throughout the e-module. Students are guided to identify microbiological problems, develop project plans, conduct investigations, and communicate project outcomes using structured learning stages. Recent studies have emphasized that Project-Based Learning should provide authentic, inquiry-oriented activities that promote active knowledge construction and collaboration while maintaining alignment with course learning outcomes (Lanubile et al., 2023). Furthermore, systematic reviews indicate that integrating Project-Based Learning into e-modules enables learning resources to support independent learning and authentic scientific inquiry through well-organized project stages (Nuralita et al., 2025).

The findings of the present study are consistent with previous research on the development of project-based instructional materials. Tampubolon and Sipahutar (2024) reported that project-based modules achieved high expert validity because the learning activities were systematically organized to develop critical thinking and problem-solving skills. Likewise, Sapira et al. (2024) found that integrating a student-centred learning model with digital instructional media resulted in highly valid learning resources owing to the close alignment between instructional activities and curriculum objectives. These findings reinforce the present study by demonstrating that carefully designed project activities contribute substantially to expert judgments regarding the pedagogical appropriateness of digital learning resources.

Comparable findings have also been reported in recent studies on digital instructional development. Aji et al. (2025) emphasized that integrating technology-enhanced learning activities within digital modules can improve the instructional quality of educational products when learning tasks are aligned with intended competencies. Similarly, Nuralita et al. (2025) concluded that Project-Based Learning e-modules have become an important trend in science education because they integrate digital technology, authentic learning experiences, and student-centred instructional strategies within a single learning resource. These findings support the present study by indicating that the project activities embedded in the Microbes E-Module are consistent with current developments in digital science education.

Overall, the findings indicate that the Project-Based Learning component of the Microbes E-Module achieved a very high level of validity according to expert judgment. The systematic integration of authentic projects, inquiry-oriented activities, collaborative learning processes, and structured project guidance contributed to the experts' positive evaluation. Nevertheless, these findings should not be interpreted as evidence that the Project-Based Learning activities improve students' critical thinking, collaboration, or learning achievement because these outcomes were not evaluated in the present study. Instead, the results provide evidence that the PjBL component satisfies expert validation criteria and establishes a sound basis for future studies examining its practicality and effectiveness during classroom implementation.

The Educational Game Components of the Microbes E-Module achieved a validity percentage of 95.00%, indicating that this aspect was evaluated as very valid by the expert validators. This finding demonstrates that the educational game elements incorporated into the e-module including interactive quizzes, immediate feedback, achievement indicators, and formative evaluation were considered appropriate for supporting microbiology learning. Rather than functioning merely as entertainment features, the educational games were designed to reinforce conceptual understanding while maintaining alignment with the intended learning outcomes. Therefore, the high validity score reflects

expert agreement regarding the appropriateness of integrating educational games into the instructional design of the e-module. Nevertheless, these findings should be interpreted only as evidence of expert validation rather than proof that the game components improve students' motivation or learning achievement.

The positive evaluation of the educational game components can be explained by their instructional function in supporting active learning and formative assessment. Immediate feedback, progressive challenges, and interactive learning tasks encourage students to review microbiological concepts while monitoring their own learning progress. Recent studies have emphasized that educational games should be designed to strengthen instructional objectives rather than merely increasing enjoyment during learning activities (Usman et al., 2024; Zidan et al., 2024). Accordingly, the educational games embedded within the Microbes E-Module were intentionally aligned with microbiology concepts so that each activity contributes to conceptual reinforcement and continuous learning evaluation.

The present findings are consistent with previous studies on gamified digital learning resources. Hanifah & Ninggolan (2023) reported that a gamification-based e-module obtained high expert validation because the game elements supported student interaction, independent learning, and instructional engagement. Likewise, Zidan et al. (2024) concluded that integrating gamification into science learning promotes more meaningful learning experiences when game mechanics are directly associated with instructional objectives rather than functioning solely as motivational rewards. These findings support the present study by demonstrating that educational games contribute to the instructional quality of digital learning resources when they are systematically integrated into the learning process.

Comparable findings have also been reported in international microbiology education. Estoppey et al. (2024) demonstrated that gamification successfully facilitated students' understanding of microbial interactions and soil microbiology by encouraging active participation and collaborative learning. Similarly, Rivard (2024) reported that board game-based microbiology learning increased student engagement by enabling learners to explore microbiological concepts through interactive gameplay and immediate decision-making. Although these studies evaluated different forms of educational games, they consistently highlight that well-designed game elements can enrich microbiology instruction by creating interactive learning experiences while maintaining scientific accuracy.

Overall, the findings indicate that the educational game component of the Microbes E-Module achieved a very high level of validity according to expert judgment. The integration of meaningful game mechanics, formative feedback, and concept-oriented learning activities contributed to the experts' positive evaluation. However, these findings should not be interpreted as evidence that the educational game components improve students' motivation, engagement, or learning outcomes because these variables were beyond the scope of the present study. Instead, the findings indicate that the educational game component satisfies expert validation criteria and provides a sound basis for future implementation studies evaluating its practicality and instructional effectiveness.

The language aspect of the Microbes E-Module obtained a validity percentage of 98.00%, indicating that the language component was classified as very valid by the expert validators. This finding demonstrates that the language used throughout the e-module was considered clear, consistent, grammatically appropriate, and suitable for undergraduate microbiology students. The validators also agreed that the scientific terminology, learning instructions, and explanations facilitated comprehension without reducing scientific accuracy. Nevertheless, the present findings should be interpreted as evidence of language validity based on expert evaluation rather than evidence of students' reading comprehension or communication skills.

The high language validity may be explained by the use of concise instructional language, consistent scientific terminology, and logically structured explanations throughout the e-module. Clear instructional language is essential in microbiology because many concepts involve complex scientific processes and unfamiliar terminology. Recent studies have shown that the quality of instructional language influences learners' ability to understand digital learning materials and independently follow learning activities (Alamin et al., 2024; Syahfitri & Safitri, 2024). Consequently, the clarity and consistency of language contribute significantly to the instructional quality of digital learning resources.

The findings of the present study are consistent with previous research on digital instructional materials. Laswi & Bungawati (2024) reported that biology learning media should employ language that is scientifically accurate while remaining understandable for learners, enabling students to navigate instructional content independently. Likewise, Syahfitri & Safitri (2024) found that digital interactive modules received positive expert evaluations because the instructional language effectively communicated complex biological concepts and supported students' learning motivation.

Similar findings have also been reported internationally. Pike et al. (2022) emphasized that effective online science learning depends not only on instructional content but also on clear communication that enables students to interpret learning activities accurately. Likewise, Vardar-Ulu et al. (2024) reported that understandable instructions and well-organized explanations improved students' interaction with digital biology learning resources, particularly when learning abstract molecular concepts. These findings reinforce the present study by demonstrating that language quality is an essential component of instructional design in digital science education.

Overall, the language component of the Microbes E-Module achieved a very high level of validity according to expert judgment. The use of clear scientific language, consistent terminology, and understandable learning instructions contributed to the positive evaluation provided by the validators. However, the findings should not be interpreted as evidence that the language component improves students' comprehension or communication skills because these outcomes require empirical investigation involving learners during the implementation stage. Instead, the present study confirms that the language component satisfies expert validation criteria and is appropriate for subsequent classroom implementation.

The overall validation of the Microbes E-Module resulted in an average validity percentage of 96.00%, indicating that the developed product was categorized as very valid according to the expert validators. This result demonstrates that all evaluated components, including content, e-module media, Project-Based Learning (PjBL) components, educational game components, and language, collectively satisfied the quality standards required for digital learning resources in microbiology education. The consistently high scores across all validation aspects indicate that the development process successfully integrated pedagogical, technological, and content-related considerations into a coherent instructional product. Nevertheless, the overall validity should be interpreted as evidence of expert agreement regarding the appropriateness of the developed e-module rather than evidence of its instructional effectiveness because classroom implementation has not yet been conducted.

The high overall validity reflects the systematic application of the ADDIE development model throughout the product development process. The comprehensive needs analysis conducted during the Analysis phase enabled the identification of curriculum requirements, students' learning characteristics, and instructional challenges in microbiology courses. These findings subsequently guided the design and development of learning materials that integrated Project-Based Learning activities, educational game components, multimedia resources, and structured learning guidance into a single digital learning resource. Such a systematic development process is consistent with previous studies emphasizing that educational products developed through structured instructional models tend to achieve high levels of expert validity because each development stage contributes to improving product quality before implementation (Hamidi et al., 2024; Shiyamsyah et al., 2024).

The present findings are also consistent with previous studies reporting high validity of digital learning resources developed for science education. Hamidi et al. (2024) found that a PBL-based e-module achieved very feasible criteria after expert evaluation because the instructional content, language, presentation, and learning activities were systematically designed to support science process skills. Shiyamsyah et al. (2024) likewise reported that Project-Based Learning teaching modules demonstrated high validity and practicality owing to the integration of authentic learning activities and competency-oriented instructional design. These findings reinforce the present study by indicating that systematic instructional planning is an essential factor contributing to expert judgments regarding educational product quality.

Evidence from international studies further supports these findings. Gruber et al. (2023) reported that coherent Project-Based Learning systems contribute to the development of high-quality instructional resources because learning activities, assessment, and project implementation are systematically connected. Likewise, Shachar et al. (2023) emphasized that project-based instructional approaches supported by digital learning resources provide meaningful learning experiences when instructional design, scientific inquiry, and assessment are integrated into a coherent learning environment. Although these studies evaluated implementation outcomes rather than product validation, they consistently highlight the importance of rigorous instructional design before educational products are introduced into classroom practice.

Overall, the findings indicate that the Microbes E-Module has achieved a very high level of validity according to expert judgment. The consistent validation results across all assessed components demonstrate that the developed e-module satisfies the essential requirements of a digital learning resource for undergraduate microbiology education. However, these findings should not be interpreted as evidence that the e-module improves students' learning achievement, motivation, or science process skills because these variables were not investigated in the present study.

Instead, the validated product provides a strong foundation for subsequent studies examining its practicality and effectiveness during classroom implementation.

The findings of this study provide several important implications for the development of digital learning resources in higher education, particularly in microbiology education. First, the high validity achieved across all evaluated components indicates that integrating Project-Based Learning, educational game components, multimedia resources, and structured instructional content within a single e-module is feasible from the perspective of expert evaluation. This finding supports the growing emphasis on designing digital learning resources that not only present scientific information but also facilitate active, student-centred learning experiences.

Second, the validated e-module may serve as an alternative instructional resource for lecturers who seek to implement more interactive microbiology learning. Recent studies have emphasized that Project-Based Learning integrated with digital instructional materials encourages students to participate actively in scientific inquiry while strengthening science process skills and problem-solving abilities (Hamidi et al., 2024; Puspita et al., 2024). Likewise, digital learning resources incorporating interactive learning activities have been reported to support students' independent learning and increase flexibility in higher education environments (Shiyamsyah et al., 2024).

Third, the present study contributes to the field of educational product development by providing empirical evidence that comprehensive expert validation can be used as an important quality assurance process before classroom implementation. Although the present findings do not demonstrate instructional effectiveness, the validated e-module provides a reliable foundation for future implementation studies. Consequently, higher education institutions may consider adopting similar development procedures when designing digital learning resources intended to support active and technology-enhanced learning.

Several limitations should be considered when interpreting the findings of the present study. First, the study focused exclusively on the Development phase of the ADDIE model and therefore only evaluated the validity of the Microbes E-Module through expert judgment. The present study did not examine product practicality, students' responses, or instructional effectiveness during classroom implementation. Consequently, the findings cannot be generalized to indicate improvements in students' learning outcomes, motivation, science process skills, or conceptual understanding.

Second, the expert validation involved a limited number of validators with expertise in content, instructional media, Project-Based Learning, educational game components, and language. Although the validators represented relevant fields of expertise, broader validation involving experts from different institutions may provide more comprehensive evidence regarding the quality of the developed product.

Future studies should continue the subsequent phases of the ADDIE model by examining the practicality of the Microbes E-Module in authentic classroom settings and evaluating its effectiveness through quasi-experimental or experimental research designs. Furthermore, future research should investigate the influence of the validated e-module on students' conceptual understanding, learning motivation, science process skills, collaborative learning, and problem-solving abilities. Comparative studies involving different higher education institutions are also recommended to examine the generalizability of the findings. Such investigations will provide more comprehensive evidence regarding the educational value of the Microbes E-Module and strengthen its contribution to digital microbiology education.

Conclusion

The validation results showed that the Microbes E-Module achieved a content validity score of 99%, media validity score of 94%, Project-Based Learning (PjBL) component validity score of 96%, educational game component validity score of 95%, and language validity score of 98%. All evaluated aspects were categorized as very valid, indicating that the developed e-module meets the expert validation criteria for content, media, Project-Based Learning components, educational game components, and language. The overall validation result showed that the Microbes E-Module obtained an average validity score of 96%, which falls within the very valid category. These findings indicate that the developed e-module demonstrates a high level of validity based on expert judgment. However, the findings should be interpreted only as evidence of product validity because this study was limited to the expert validation stage of the ADDIE development model and did not evaluate the practicality or effectiveness of the e-module. Based on these findings, the Microbes E-Module can be considered a validated digital learning resource for microbiology education that has met the expert validation criteria in terms of content, media, Project-Based Learning components, educational game components, and language. Further studies are required to obtain more comprehensive evidence regarding its practicality and effectiveness through

implementation in authentic learning environments. Based on the findings of this study, several recommendations are proposed. First, future studies should continue the subsequent phases of the ADDIE model by evaluating the practicality of the Microbes E-Module through classroom implementation involving lecturers and students. Second, future research should investigate the effectiveness of the validated e-module using appropriate experimental or quasi-experimental designs to examine its effects on students' learning outcomes, science process skills, scientific literacy, critical thinking skills, learning motivation, self-directed learning, and collaborative learning. Finally, further validation involving broader educational contexts and different higher education institutions is recommended to strengthen the generalizability of the findings and provide more comprehensive evidence regarding the use of the Microbes E-Module in microbiology education.

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Author Contributions
V.F. was responsible for conceptualization, methodology, investigation, data collection, data analysis, development of the Microbes E-Module, and manuscript writing. M.T.B.B contributed to supervision, methodology validation, and manuscript review. A.B.T. contributed to supervision, scientific review, and manuscript editing. All authors have read and agreed to the published version of the manuscript.

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