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Development of microlearning media science concepts in senior high school: Emphasis on technology literacy

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ABSTRACT

Science learning in secondary schools often struggles to explain abstract concepts such as biological mechanisms and cellular processes, which are difficult for students to visualise using conventional teaching methods. This condition contributes to low conceptual understanding and limited technological literacy among students. To address this issue, this study developed science microlearning media designed in short, interactive, and focused learning units. This study aimed to identify the characteristics of science learning in secondary schools, determine the validity of the developed microlearning media, and examine their effectiveness in improving students' conceptual understanding and technological literacy. The study employed a research-and-development method that included needs analysis, product development, expert validation, and feasibility testing. The validation results showed that the developed media achieved a very high validity score, with a content score of 4.52. Feasibility assessments also demonstrated high acceptance with average scores of 4.47 and 4.51, respectively. These findings indicate that the developed microlearning media are feasible and have strong potential to support science learning, particularly in facilitating students' understanding of abstract concepts. Future studies are recommended to conduct broader experimental investigations and integrate advanced technologies to enhance the scalability and effectiveness of microlearning media.

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INTRODUCTION

Science learning in secondary schools demands an understanding of abstract and complex concepts, often not directly observable, such as atomic structure and molecular phenomena beyond everyday experience (Aleknavičiūtė et al., 2023). Conceptual understanding is a major challenge because students often bring inappropriate prior knowledge or misconceptions that need to be restructurd through deeper learning processes (Aleknavičiūtė et al., 2023; Soeharto et al., 2019). Research in the science education literature indicates that addressing complex concepts with lectures and traditional statistical media alone is often ineffective in fostering profound conceptual change and addressing students' misconceptions (Addido et al., 2022). These findings align with those of a systematic review, which shows that identifying misconceptions is a crucial step in fostering conceptual change and meaningful science learning, as misconceptions tend to persist without appropriate intervention and hinder accurate scientific understanding (Guerra-Reyes et al., 2024). The characteristics of today's high school students indicate that they belong to a generation that is very familiar with digital technology in their daily lives, but their technological literacy has not yet developed optimally in the context of formal learning, especially in science learning (Laius & Orgusaar, 2025; Mat et al., 2024). Technological literacy not only includes the technical ability to operate digital devices but also includes critical thinking skills in understanding, comprehending, processing, and utilising digital information to build accurate and meaningful scientific knowledge. Recent research confirms that students' digital literacy competencies are an important factor, including science process skills such as data collection, interpretation of results, and the ability to draw critical conclusions about scientific phenomena (Astalini et al., 2023).

However, despite the increasing prevalence of technology in science classrooms, the pedagogical integration of digital media is often hampered by limited teacher preparedness, limited learning infrastructure, and curricula that do not fully support optimal technology use (Apriyanto, 2025; Laius & Orgusaar, 2025). The lack of a systematic approach to technology integration means students' opportunities to use technology as a tool for critical and exploratory thinking have not been fully realised (Son & Ha, 2024). Higher technological literacy enables students to evaluate digital information sources, use interactive simulations to build mental models of science, and connect science concepts with real-world phenomena more effectively. Furthermore, educational literature indicates that science learning that does not consistently incorporate pedagogical digital media, such as simulations, virtual laboratories, interactive platforms, and data science software, may underutilise students' potential for technological literacy development (Apriyanto, 2025). This, in turn, has an impact on students' low ability to think critically and creatively in a scientific context, even though these two skills are important components of 21st-century technological literacy.

Technological literacy has become a central component of contemporary education, encompassing competencies beyond basic technical skills. This includes the ability to access, evaluate, interpret, and apply digital information effectively and ethically (van Laar et al., 2019). International frameworks such as DigCompEdu and UNESCO's Global Framework for Digital Literacy emphasise that technological literacy is essential for lifelong learning and active participation in a knowledge-based society (Ghomi & Redecker, 2019; Law et al., 2018). In science education, technological literacy is crucial because scientific knowledge is increasingly represented and communicated through digital media (Okra, 2023). Students are expected to interpret data visualisations, simulations, and digital models and evaluate the credibility of online scientific information. Research shows that although secondary school students frequently use digital devices, their technological literacy often remains at a functional level, focusing on information access rather than critical analysis and application (Antonietti et al., 2025; Oktasari et al., 2025).

Empirical studies have shown that integrating technological literacy into subject-specific instruction leads to improved learning outcomes and higher-order thinking skills (Sung et al., 2016). In science education, technological literacy supports inquiry-based learning, data analysis, and problem-solving, which are core components of scientific practice. Microlearning media offer structured opportunities to embed technological literacy skills into science learning activities by requiring students to interact with digital representations, evaluate information sources, and reflect on their learning process.

The integration of microlearning and technological literacy is a strategic approach to addressing conceptual and skill-based learning objectives in science education. Microlearning environments inherently rely on digital platforms, making them well-suited for embedding components of technological literacy. Research shows that microlearning modules designed with interactive elements and reflective tasks can simultaneously support conceptual understanding and the development of technological literacy (Sung et al., 2016). From a constructivist perspective, learning occurs through active engagement and interaction with content and tools (Escobar-Castillejos et al., 2024). Microlearning media that encourage exploration, experimentation, and reflection align with constructivist principles and support meaningful learning. Furthermore, microlearning facilitates self-directed learning by allowing students to control the pace, sequence, and repetition of learning activities, which are key aspects of technology-mediated learning environments. Despite its potential, experts caution that microlearning must be carefully designed to avoid knowledge fragmentation (Boulton & Cobb, 2017). Effective integration requires a coherent sequence of micro-units and explicit connections between concepts. When these conditions are met, microlearning can increase conceptual depth while encouraging critical and reflective use of technology.

Although existing research highlights the potential benefits of microlearning and technological literacy in education (Antonietti et al., 2025; Oktasari et al., 2025), several gaps remain. First, most empirical research on microlearning has focused on higher education and professional training contexts, with limited attention to secondary school science education. Second, studies often examine the effectiveness of microlearning in terms of engagement or achievement without explicitly addressing technological literacy outcomes. Furthermore, there is a lack of comprehensive research integrating microlearning design principles with established technological literacy frameworks in science education. Many studies use microlearning as a delivery strategy without systematically embedding technological literacy goals into the instructional design. This gap underscores the need for research examining how microlearning media can be intentionally designed to support conceptual understanding and the development of technological literacy in secondary school science classrooms. Addressing this gap is crucial for advancing pedagogical innovation and informing evidence-based instructional design.

Given these conditions, developing micro-learning media for science concepts in secondary schools is both relevant and strategic. This development is not only aimed at improving students' conceptual understanding of science materials, but also at equipping them with functional, critical, and contextual technological literacy. Through structured, interactive, and technology-based learning experiences, micro-learning media can bridge the demands of the 21st-century curriculum with classroom practices, while strengthening students' readiness to face the challenges of learning and life in the digital era. There are 3 problems in this study, namely: a) What are the characteristics of secondary school science learning in the development of micro-learning media based on technological literacy (RM 1)? b) What is the level of validity of the micro-learning media developed for learning science concepts (RM 2)? and c) What is the effectiveness of micro-learning media in improving secondary school students' conceptual understanding of science and technological literacy (RM 3)? This study aims to contribute to this body of knowledge by developing and evaluating microlearning media for secondary school science education that explicitly integrates technological literacy components.

METHOD

This study uses a Research and Development (R&D) approach to develop, validate, and test the effectiveness of technological literacy-based micro-learning media for science learning in secondary schools. The R&D approach was chosen because the research focuses not only on testing relationships among variables but also on producing pedagogical artefacts in the form of learning media that are feasible, valid, and effective for use in real-life learning contexts (Marlina et al., 2025; Son & Ha, 2024). The development model used is a simplified adaptation of the Borg & Gall model, tailored to the research needs, with three main stages as shown in Figure 1.

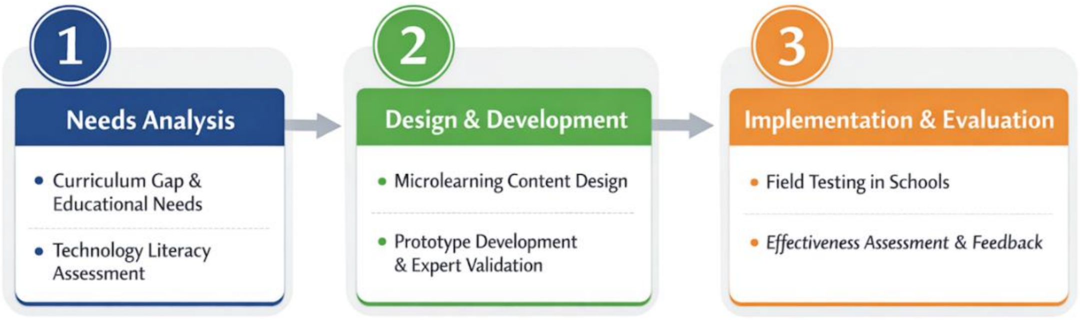

Figure 1. Research Stages

The research was conducted over 8 months (March – October 2025). The needs analysis stage was conducted in March 2025, the design and development stage from April to August 2025, and the implementation and evaluation stage from September to October 2025. This method was designed to answer three main research problems. Research problem 1 (RP1) focuses on identifying the characteristics and needs of secondary school science learning to develop technological literacy-based micro-learning media. The main results of this stage are learning media design specifications, including learning objectives, microlearning content characteristics, digital media forms, and the technological literacy elements to be developed. Research problem 2 (RP2) aims to assess the level of validity and feasibility of the developed micro-learning media. The method used to address this problem formulation is expert validation, involving science, learning media, and educational technology experts. The validation process focuses on content suitability with science concepts, pedagogical quality, clarity of microlearning presentations, and integration of technological literacy into the media. Research problem 3 (RP3) aims to test the effectiveness of micro-learning media in improving students' conceptual understanding of science and technological literacy. To achieve this, a quasi-experimental pretest–posttest design was used in the experimental and comparison groups. The experimental group used the developed micro-learning media, while the comparison group used conventional learning or media commonly used in schools. A summary of the relationship between the problem formulation, the method, and the expected results is shown in Table 1.

Table 1. Description of Research Subject

No.	Research Problem	Research Stage	Time	Research Subject	Number of Participants
1.	RP1	Need analysis	March 2025	Science Teacher Student	3 60
2.	RP2	Development and Expert Validation	April – August 2025	Science Teacher Lecturer	3 3
3.	RP3	Quasy Experiment	September – October 2025	Student	204

This study involved several groups of participants tailored to the Research and Development (R&D) stages, namely needs analysis, product validation, and effectiveness testing. This study was conducted in Sintang Regency, approximately 150 km from the centre of Pontianak, the capital of West Kalimantan, Indonesia. In the needs analysis stage, participants were 60 high school students in Sintang Regency, selected through purposive sampling. The criteria for student selection were having attended lessons using microlearning media within the last 6 months. The teachers involved consisted of 6 science teachers from three public junior high schools in Sintang Regency. Teacher selection was carried out using random sampling. Students were selected from grades VIII and IX with the following criteria: (1) having attended science lessons regularly, (2) having basic access to digital devices, and (3) having never used microlearning media systematically. The science teachers involved had at least two years of teaching experience and were actively teaching science subjects. In the product validation stage, participants included 10 experts: 5 science teachers, 2 lecturers from the Mathematics and Natural Sciences Department of the Faculty of Teacher Training and Education, Tanjungpura University, Pontianak, and 3 lecturers in educational technology.

The experts were selected based on academic qualifications of at least a master's degree, professional experience in their field, and involvement in the development or research of technology-based learning media. In the effectiveness test stage, participants were 204 high school students from the same 3 senior high schools, divided into an experimental group (102 students) and a comparison group (102 students). Group selection was conducted using the intact-group technique to maintain the naturalness of the learning experience. The participant criteria at this stage included: (1) curriculum equivalence, (2) relatively similar initial ability levels based on pretest results, and (3) willingness to follow the entire learning series. Research instruments were developed to support each stage of research and development (R&D), namely needs analysis, product validation, and testing the effectiveness of microlearning media. Table 2 displays the type and purpose of each instrument.

Table 2. Instrument

No.	Instrument	Indicator	Research Stage	References
1	Needs Analysis Questionnaire	Identifying the needs, preferences, and characteristics of participants as a basis for developing learning media	Needs Analysis	Bayar & Ağgül (2023)
2	Technology Literacy Scale	Measuring participants' ability to understand, use, and utilise digital technology	Development Expert Validation	Farahiba (2022)
3	Expert Validation Sheet	Assess the content validity, suitability and appropriateness of learning media through expert assessment.	Expert Validation	Saputri et al., (2023)
4	Conceptual Understanding Test	Measuring the level of mastery of science concepts of participants after the application of learning media	Effectiveness Assessment	Sinha & Rinki (2025)
5	Observation Sheet	Observing behaviour, participation, and effectiveness of media implementation directly in the classroom or laboratory	Effectiveness Assessment	Rathi et al., (2022)

The needs analysis questionnaire includes both closed- and open-ended questions that assess demographics, prior experiences, and participants' expectations regarding the learning materials and methods. The data collected is quantitative (Likert scale) and qualitative (open-ended). Quantitative data analysis calculates frequencies, percentages, averages, and priority needs scores. Validity and reliability tests (e.g., Cronbach's Alpha) can also be used to test the instrument's validity and reliability. Qualitative data analysis, i.e., open-ended responses, is analysed by coding to group themes into participants' needs and preferences. The technology literacy scale uses a Likert scale to assess technical skills, understanding of digital applications, and participants' attitudes and confidence in utilising technology. The data types are quantitative and Likert scale. Quantitative data are analysed by calculating total and average scores for participants' technology literacy, and descriptive statistics (mean, SD) are used to determine literacy levels. Next, reliability testing (Cronbach's alpha) is conducted to ensure instrument consistency, or comparative analysis is conducted to compare different participant groups.The Expert Validation Sheet covers criteria such as readability, material relevance, suitability to learning objectives, and visual design. The data obtained were quantitative (validity scale) and qualitative (expert comments). Quantitative data were analysed by calculating the Content Validity Index (CVI) for each media aspect. Qualitative data were analysed to examine expert suggestions and criticisms for media improvement.

The Conceptual Understanding Test was designed based on expected competency indicators. This test is descriptive in nature to evaluate students' conceptual understanding, application of principles, and analytical skills. The data was quantitative (test scores). Data analysis was descriptive (mean, completion percentage, score distribution). Normality and differences were then tested before and after the intervention (pre-test and post-test) using a paired t-test or wilcoxon test, if the distribution was not normal. Observation sheets were used to directly observe participant behaviour, participation, and responses during the implementation of the learning media. This instrument recorded aspects such as participant engagement, interactions, emerging difficulties, and the actual application of concepts. The data were both qualitative and quantitative (behaviour frequency). Quantitative data were analysed by calculating the frequency and scores of participant engagement, interaction, and participation. Qualitative data in the form of field notes were analysed using thematic analysis to identify behavioural patterns, obstacles, and student responses. The effectiveness of the developed microlearning media was analysed using the normalised gain (N-gain) score to assess the improvement in students' technological literacy following the learning intervention. The N-gain was calculated using the following Formula 1.

$$g = \frac{\text{Post-test Score} - \text{Pre-test Score}}{\text{Maximum Score} - \text{Pre-test Score}} \quad (1)$$

Where g represents the normalised gain score, the post-test score represents students' achievement after the intervention, the pre-test score represents students' initial achievement before the intervention, and the maximum score refers to the highest possible score that could be obtained. The use of N-gain allows the measurement of learning improvement relative to students' initial performance levels (Smallwood et al., 2026). The categorisation of N-gain scores followed the criteria, namely: (1) great improvement if $g > 0.70$, (2) moderate improvement if $0.30 \leq g \leq 0.70$, and (3) low improvement if $g < 0.30$ (Ghomi & Redecker, 2019). Based on these criteria, the obtained N-gain scores for all dimensions of technological literacy were categorised as moderate improvement, indicating that the developed microlearning media meaningfully enhanced students' technological literacy skills. Before testing the effectiveness of the developed microlearning media, prerequisite statistical analyses were conducted to ensure that the data met the assumptions required for parametric testing. A normality test was performed using the Shapiro–Wilk test to determine whether the pre-test and post-test data were normally distributed. In addition, a homogeneity test was conducted using Levene's Test to examine the equality of variances between groups. The results indicated that the data were normally distributed and homogeneous, allowing further parametric analysis. To measure the effectiveness of the developed microlearning media in improving students' conceptual understanding and technological literacy, a paired-samples t-test was used to compare pre-test and post-test scores.

This analysis was conducted to determine whether there was a statistically significant difference in students' scores before and after the implementation of the microlearning media. The level of significance used in this study was $p < 0.05$. In addition, the improvement in students' learning outcomes was analysed using the normalised gain (N-gain) score, which quantified the magnitude of learning improvement after the intervention. The N-gain categories followed the criteria proposed by Richard R. Hake, namely high ($g > 0.70$), moderate ($0.30 \leq g \leq 0.70$), and low ($g < 0.30$) (Son & Ha, 2024). These analyses provided both statistical significance and practical interpretation regarding the effectiveness of the developed microlearning media.

RESULTS AND DISCUSSION

Results

Characteristics of Students and Teachers in the Development of Science Microlearning (RP1)

Understanding the characteristics of students and teachers is an essential initial step in developing effective microlearning media for science education. Identifying learners' needs, learning habits, technological readiness, and the instructional challenges teachers face is important to ensure that the developed media aligns with classroom learning conditions and supports meaningful learning experiences. Therefore, a needs analysis was conducted to explore the characteristics of students and teachers as the foundation for developing science microlearning media (Figure 2).

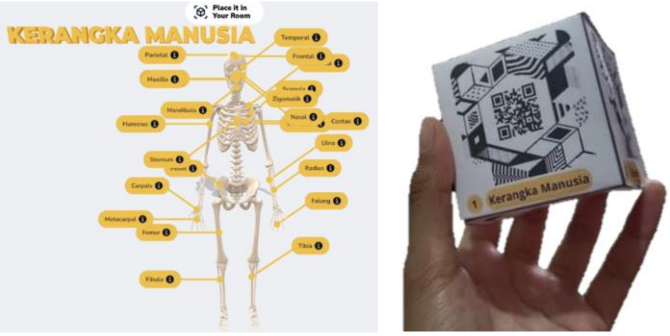

Figure 2. Science Microlearning (Human Movement System)

A needs analysis was conducted through a survey of high school students and interviews with science teachers to identify student characteristics and instructional needs. Quantitative data indicated that students were familiar with digital technology, but their technological literacy in the context of science learning was still limited. Table 3 presents the characteristics of students and teachers in the development of science microlearning.

Table 3. Characteristics of Students and Teachers

No.	**Aspect**	**Indicator**	**Teacher**		**Student**	
			Total	**Percentage (%)**	**Concept**	**Difficulty Level**
1	Media Ownership	Learning Media	58	96.4	Microscopic Phenomenon	High
2	Media Preference	Short Video (< 5 minutes)	49	82.1	Molecular Interaction	High
3	Media Preference	Interactive Visualitation/ Simulation	47	78.6	Mechanism	High
4	Instructional Preference	Conventional Method	12	19.3	Cellular Process	High
5	Technology Literacy	Able to critically evaluate digital science content	17	27.8	Physiological System	Medium
6	Technology Literacy	Information access	43	72.2	Interactions of Living Things	Medium

Media ownership, media preferences, instructional preferences, and technology literacy describe students' learning habits, access to digital learning resources, and readiness to use technology-based learning media. These findings were used to determine the appropriate format and features of the developed microlearning media. For example, the high percentage of students preferring short videos and interactive visualisations indicated a need for concise, visually engaging learning content.

Validity Level of Microlearning Media

The validity and feasibility of the developed microlearning media were evaluated through expert assessment and user feedback. The validation involved three expert categories: content, instructional design, and media/technology. Table 4 shows the results of expert validation of the microlearning media.

Table 4. Expert Validation Result

No.	**Aspect**	**Mean Score**	**Validity Level**
1	Content accuracy and relevance	4.52	Very Valid
2	Instructional design and pedagogy	4.41	Very Valid
3	Visual design and interactivity	4.47	Very Valid
4	Integration of technology literacy	4.38	Very Valid
Overall Validity		**4.45**	**Very Valid**

The research results show that microlearning media achieved a very high level of validity across all assessed dimensions. Experts emphasised the clarity of conceptual segmentation, coherence between learning objectives and activities, and the appropriate integration of digital interactions to support the development of technological literacy.

Effectiveness of Microlearning Media

The effectiveness of microlearning media was tested using a quasi-experimental pre-test and post-test design. Two outcome variables were measured: conceptual understanding of science and technological literacy. Table 5 shows student and teacher responses to each aspect.

Table 5. Feasibility Responses

No.	Aspect	Students Mean Score	Teachers Mean Score	Feasibility Level
1	Ease of Use	4.46	4.50	Very Feasible
2	Content Clarity	4.42	4.47	Very Feasible
3	Visual Attractiveness	4.51	4.55	Very Feasible
4	Learning Engagement	4.48	4.52	Very Feasible
Overall Feasibility		**4.47**	**4.51**	**Very Feasible**

Students who learned using micro-learning media showed a significant increase in conceptual understanding compared to those taught using conventional methods. Table 6 displays the average results of the technological literacy measurements.

Table 6. Pre-Test and Post-Test Results on Technological Literacy

No.	Dimention	Pre-Test Mean	Post-test Mean	N-Gain	Cronbach's Alpha
1	Accessing Digital Information	63.4	85.2	0.60	0.88
2	Interpreting Scientific Visuals	58.6	81.9	0.56	0.85
3	Evaluating Digital Science Content	54.1	78.3	0.53	0.83
Overall Technology Literacy		**58.7**	**81.8**	**0.56**	**0.85**

The results of the study showed consistent improvements across all dimensions of technological literacy, indicating that interactions with microlearning media effectively supported students' ability to interpret and critically engage with digital scientific content. The dimension "evaluating digital science content" had the lowest N-gain score (0.53) among the technological literacy dimensions, although it was still categorised as a moderate improvement. This finding may indicate that evaluative literacy skills are more cognitively complex and require higher-order thinking processes than skills related to accessing information or interpreting scientific visuals. Evaluating digital science content involves critically assessing the accuracy, credibility, relevance, and scientific validity of information obtained from digital sources (Ghomi & Redecker, 2019). Such competencies require not only technological familiarity but also critical thinking, scientific reasoning, and information evaluation skills that generally develop over a longer learning process.

Another possible explanation is that students are more accustomed to using digital technology to access information than to analyse the quality of the information they encounter critically (Guo et al., 2014). Although the developed microlearning media provided interactive, technology-based learning experiences, the learning activities may have focused more on understanding and visualising science concepts than on explicit training in evaluating digital scientific information. As a result, improvements in evaluative literacy skills were lower than in other dimensions.

Discussion

Characteristics of Students and Teachers in the Development of Science Microlearning (RP1)

Survey results showed that 96.4% of teacher respondents stated that their students owned smartphones. This high level of device ownership indicates that barriers to technology access are no longer a major issue in implementing digital learning in secondary schools. This finding aligns with various studies showing that mobile device penetration among Indonesian adolescents has reached very high levels, even surpassing personal computer ownership (Zuccarini & Malgieri, 2024). In the context of microlearning, smartphone ownership is a crucial prerequisite, as it relies heavily on fast, flexible, and mobile access. Microlearning is designed to be accessed briefly, repeatedly, and contextually, making it highly compatible with the personal, on-demand nature of smartphone use (Senadheera et al., 2024). Therefore, this finding provides empirical justification for developing science microlearning with an adequate infrastructure foundation at the student level.

However, device ownership does not automatically correlate with pedagogical readiness. Several studies confirm that the success of digital learning is determined more by the quality of instructional design and user technological literacy than simply the availability of devices (Backfisch et al., 2021; Ghomi & Redecker, 2019). Therefore, while device ownership demonstrates a highly supportive environment, other aspects, such as technological literacy and learning preferences, require more critical analysis. The preference for short videos is a characteristic of the digital generation, accustomed to concise, concise, and to-the-point content. Shorter video duration significantly increases retention rates and learning engagement (Guo et al., 2014). In the science context, short videos allow for segmented presentations of complex concepts, thereby reducing learners' cognitive load.

Meanwhile, the high preference for interactive visuals and simulations reflects learners' need for concrete representations of abstract science concepts. Science, particularly topics such as microscopic phenomena, molecular interactions, and biological mechanisms, demands a high level of abstract thinking skills. Visualisations and simulations play a crucial role as cognitive bridges between theoretical concepts and students' conceptual understanding (Mayer & Fiorella, 2022). These findings support multimedia learning theory, which holds that integrating text, images, animations, and simulations can enhance conceptual understanding when designed according to cognitive principles (Mayer & Fiorella, 2022). In microlearning, interactive visualisations are a key element because they can convey the essence of concepts quickly and meaningfully without burdening students' working memory.

Only 19.3% of teachers stated that students still prefer conventional lectures. This figure shows the declining relevance of one-way learning methods in modern science learning. Conventional lectures tend to position students as passive recipients of information, making them less effective at building in-depth conceptual understanding, especially in processual, systemic science material. Various studies have shown that effective science learning requires active student engagement through exploration, visualisation, and reflection (Bayar & Ağgül, 2023). Microlearning, with its modular and interactive format, offers an alternative that better suits these needs. This finding reinforces the urgency of transforming science pedagogy from teacher-centred to learner-centred learning. Despite high device ownership and a preference for digital media, data show that only 27.8% of teacher respondents reported that students can critically evaluate digital science content. Conversely, 72.2% of students are still limited in their ability to access information without adequate evaluative skills.

The data in Table 2 show that concepts such as microscopic phenomena, molecular interactions, biological mechanisms, and cellular processes are categorised as high in difficulty. Meanwhile, physiological systems and dynamic system interactions are moderately difficult to model. This characteristic reflects the hierarchical and abstract nature of science. Many scientific concepts cannot be directly observed, so they require symbolic, visual, or model representations to understand. This conceptual difficulty is often a major source of misconceptions among students (Zuccarini & Malgieri, 2024). In this context, microlearning offers a relevant approach by allowing gradual, segmented presentation of concepts. Rather than presenting complex material in a single long session, microlearning breaks it into smaller units that focus on a single core concept. This approach aligns with cognitive load theory, which emphasises the importance of managing information complexity to prevent it from exceeding students' working memory capacity (Ayres & Paas, 2012).

Validity Level of Microlearning Media (RP2)

Validation results show that the content accuracy and relevance aspect obtained an average score of 4.52, which is categorised as very valid. This score indicates that the material presented in the microlearning media aligns with current, accurate scientific concepts and is relevant to the applicable curriculum. Content validity is a fundamental aspect in the development of science learning media, given that science is hierarchical and cumulative. Small errors in the presentation of concepts can impact ongoing misconceptions in students. Therefore, the involvement of content experts is crucial to ensure the suitability of concepts, the accuracy of scientific terms, and the interrelationships between subconcepts (Chi & Wylie, 2014). The very high validity score in this aspect indicates that the concept segmentation in microlearning has been appropriately carried out, breaking complex material into small units that focus on a single main idea. This approach aligns with the characteristics of microlearning, which emphasise the presentation of information in a concise, specific, and contextual manner, thereby facilitating the understanding of abstract science concepts such as microscopic phenomena, biological mechanisms, and system interactions (Senadheera et al., 2024).

The instructional design and pedagogy aspect received an average score of 4.41, indicating very high validity. This finding indicates that the microlearning media were designed based on effective instructional design principles and aligned with modern learning theory. This finding aligns with constructivist learning theory, which emphasises that learners actively construct knowledge through interactions with materials and the learning environment. In microlearning, focused instructional design enables learners to learn independently, incrementally, and iteratively as needed. Furthermore, microlearning is considered effective at managing learners' cognitive load. Segmenting material into small units helps reduce the complexity of information that must be processed simultaneously, thus supporting deeper conceptual understanding. This aligns with cognitive load theory, which states that learning is more effective when information is presented within learners' working memory capacity (Marlina & Hamdani, 2023).

The visual design and interactivity received an average score of 4.47, indicating very high validity. This assessment indicates that the microlearning media have good visual quality and an appropriate level of interactivity to support science learning. The interactivity provided, such as self-navigation, immediate feedback, and simple activities, was also deemed effective in increasing learning engagement. The microlearning was not complex but was designed to strengthen focus on learning objectives. This aligns with the view that meaningful interactivity is more important than excessive interactivity in digital learning (Backfisch et al., 2021). The integration of the technology literacy aspect received an average score of 4.38, categorised as very valid. These results indicate that microlearning media serve not only as a means of delivering science material but also as a vehicle for developing students' technological literacy. This integration of technology literacy is crucial, as previous needs analysis results indicated that most students are still at the basic digital literacy stage, limited to accessing information without adequate evaluative skills. Well-validated microlearning media have the potential to become a tool for improving critical technological literacy, particularly in the context of science. This aligns with the digital competency framework, which emphasises that technological literacy in education must encompass the ability to understand, use, and evaluate digital information responsibly (Ghomi & Redecker, 2019).

The overall validity of 4.45, categorised as very valid, indicates that the developed microlearning media meet the eligibility standards for content, pedagogy, visuals, and technology. Consistently high validity across all aspects indicates that this media is suitable for use in the effectiveness testing and implementation stages of learning. These results confirm that the microlearning media development process has been carried out systematically and in line with users' real needs. Expert validation plays a crucial role in refining the product before it is tested with students, thereby minimising the potential for conceptual, pedagogical, and technical errors.

Effectiveness of Microlearning Media (RP3)

The feasibility responses from students and teachers (Table 4) indicate that the microlearning media is categorised as very feasible across all assessed aspects, with an overall average score of 4.47 (students) and 4.51 (teachers). This finding indicates a very high level of user acceptance of the developed media. The ease of use aspect received high scores from students (4.46) and teachers (4.50). This indicates that the microlearning media interface is intuitive and easy to navigate, thus not creating technical barriers during the learning process. Ease of use is a crucial factor in technology-based learning, as excessive technical complexity can increase extrinsic cognitive load and disrupt the learning process (Marlina et al., 2025). Easy-to-use microlearning media allows students to focus on understanding science concepts, rather than on how to operate the technology. The content clarity aspect also received very high scores from students (4.42) and teachers (4.47). Content clarity reflects the media's success in presenting science concepts in a concise, structured, and easy-to-understand manner. In the context of microlearning, content clarity is key, as the material is presented in short units that require concise, focused delivery of ideas. Previous research has shown that clarity in the presentation of microlearning material directly contributes to improved conceptual understanding, particularly in abstract science material.

The visual attractiveness aspect received the highest score compared to other aspects, from both students (4.51) and teachers (4.55). This indicates that the visual design of microlearning media is not only aesthetic but also supports learning functions. Effective visualisations, such as animations, dynamic diagrams, and simple simulations, help students construct mental representations of scientific phenomena that cannot be directly observed. This finding aligns with multimedia learning theory, which holds that integrating relevant visuals with text can improve comprehension and retention (Mayer & Fiorella, 2022). The learning engagement aspect also scored very high, with students scoring 4.48 and teachers scoring 4.52. This high level of engagement indicates that microlearning media can capture students' attention and encourage active participation in learning. Well-designed microlearning allows students to learn independently, control their pace, and repeat material as needed, ultimately increasing motivation and learning engagement (Kikas et al., 2024; Marlina et al., 2023).

The results showed that students who learned using microlearning media experienced a significant increase in conceptual understanding compared to students who learned using conventional methods. This finding can be explained by the key characteristics of microlearning, which emphasise material segmentation, a focus on a single core concept, and a gradual presentation of information. In science learning, conceptual understanding is often hindered by the complexity of the material and initial misconceptions. Microlearning media helps overcome these challenges by breaking complex concepts into smaller, easier-to-process units. This approach aligns with cognitive load theory, which states that learning is more effective when information is presented in a format that does not exceed students' working memory capacity. The results of the technological literacy measurement (Table 5) showed consistent improvement across all measured dimensions, with an overall N-gain of 0.56 (medium-high category). This improvement reflects that interaction with microlearning media not only improved understanding of science content but also significantly developed students' technological literacy.

The dimension of accessing digital information increased from a pretest score of 63.4 to a posttest score of 85.2, yielding an N-gain of 0.60. These results indicate that students became more skilled at navigating and utilising digital information sources presented in learning media. This ability is the foundation of technological literacy and a prerequisite for advanced digital skills (Marlina et al., 2023). The interpreting scientific visuals dimension also experienced a significant increase with an N-gain of 0.56. This indicates that microlearning using digital visualisation and simulation is effective in developing students' ability to understand technology-based scientific representations. The ability to interpret scientific visuals is a crucial competency in modern science learning, given that many scientific concepts and data are presented in the form of graphs, models, and digital simulations (Cheng & Xie, 2018; Marlina et al., 2024a). The evaluating digital science content dimension showed an increase with an N-gain of 0.53. Although slightly lower than the other dimensions, this increase still indicates that microlearning media can encourage students to think more critically about digital scientific information. Technological literacy encompasses not only the ability to use technology but also the ability to evaluate the credibility and relevance of information critically (Akram et al., 2021; Marlina et al., 2024b). The relatively balanced improvement across all dimensions indicates that technological literacy is developed holistically through microlearning media. This strengthens the argument that technological literacy should be integrated contextually into subject learning, rather than taught as a separate skill.

CONCLUSION

This study shows that developing microlearning media for science learning in secondary schools is a relevant, valid, and effective approach to addressing science learning challenges and strengthening students' technological literacy. The results of the needs analysis revealed that although students are familiar with digital devices, their technological literacy in the context of science learning remains limited to information access and has not developed critically. In addition, abstract and microscopic science concepts are still perceived as difficult to understand through conventional learning approaches, requiring support from more contextual and interactive digital learning media. Expert validation shows that the developed microlearning media have a very high level of validity across all aspects, including content accuracy and relevance, instructional design, visual quality and interactivity, and integration of technological literacy. These findings indicate that the developed media have met the pedagogical and technological standards required for use in science learning in secondary schools. Effectiveness testing shows that using microlearning media significantly improves students' conceptual understanding of science and technological literacy compared to conventional learning. Consistent improvements across all dimensions of technological literacy confirm that pedagogically designed technology integration in science learning can equip students with functional and critical digital skills. Thus, microlearning media not only serve as a means of delivering material but also as a vehicle for developing 21st-century competencies. Overall, this study makes an empirical contribution to the development of technology-based learning media in science education and emphasises the importance of structured, meaningful microlearning designs. The findings of this study suggest the need for further research to expand the development and evaluation of microlearning media across broader science topics, different educational levels, and more diverse learning contexts. Future studies are also recommended to investigate the long-term impact of microlearning media on conceptual understanding, higher-order thinking skills, and technological literacy using more robust research designs such as longitudinal and experimental studies. In addition, further product development may integrate emerging technologies such as artificial intelligence, adaptive learning systems, augmented reality, and gamification to enhance the media's interactivity, personalisation, and scalability for wider educational applications.

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