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Development of a Physics E-Module on Sound Wave Materials Using an Inquiry Approach Based on Scientific Processes

Dhia Kharimah[1*]
[1*]Universitas Islam Negeri Sunan Gunung Djati Bandung, Indonesia
Email: [1*]dhiakharimah1@mail.com

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Abstract
This research aims to develop and evaluate the effectiveness of inquiry-based e-modules in teaching the physics of sound waves at SMA Negeri 26 Bandung. The research employs a quantitative R&D approach following the 4D model by Thiagarajan: define, design, develop, and disseminate. Data were collected through concept comprehension tests, questionnaires, and direct observations. Findings show a significant improvement in students' understanding of physics concepts post-implementation of the e-module, with average scores rising from 45.32 to 78.56. Student feedback was positive, with 85% stating the e-module aided their comprehension and 90% finding the learning process more engaging. The study concludes that inquiry-based e-modules are effective in enhancing the quality of physics education and student engagement.

CORRESPONDING AUTHOR(S): dhiakharimah1@mail.com

INTRODUCTION

The rapid development of information technology in the 21st century has fundamentally changed the paradigm of education, with a shift from a teacher-centred approach to a more dynamic and student-focused learning environment (Subtianah, 2023). In the context of physics education, this digital transformation presents both challenges and opportunities.

Physics as a discipline requires a deep conceptual understanding and the application of mathematical principles, although in practice students often find it difficult to relate abstract concepts to real phenomena (Andrianto, 2024). The gap between theoretical understanding and practical application is becoming more apparent in the digital age, where students need more engaging and interactive learning experiences.

The educational context in Indonesia shows rapid development in technology integration, although challenges related to access equity and content quality are still encountered (Miasari et al., 2024). As one of the leading educational centres, the city of Bandung has actively promoted various digital learning initiatives. The Bandung City Education Office has provided technological infrastructure in the form of laptops, tablets, and internet packages for students, accompanied by the development of the Sikaya application to facilitate the teaching and learning process (InfoPublik, 2024; Disdik Kota Bandung, 2024). These various efforts represent strategic steps in building a technology-supported learning ecosystem, although the development of pedagogical digital content remains a crucial aspect.

The identification of specific challenges in physics learning at SMA Negeri 26 Bandung was conducted through a series of preliminary observations. Analysis of learning evaluation data showed that only 35% of Grade XI natural science programme students achieved the minimum passing criteria for sound wave material, with an average class score of 58. A survey conducted in the school environment revealed that 80% of students considered physics to be a difficult and uninteresting subject (SMAN 26 Bandung, 2024). Further pedagogical observations confirmed low student participation and suboptimal mastery of science process skills during physics lessons (Dra. Sri Nurhayati, 2024). These findings underscore the urgency of developing innovative learning solutions that can simultaneously address conceptual understanding and learning motivation issues.

The development of e-modules is represented as a strategic response to these challenges. E-modules provide a structured, independent, and interactive learning experience that allows for flexible and autonomous study (Hutahaean et al., 2021; Cheng et al., 2021). However, the process of digitising content alone is not sufficient. The pedagogical approach integrated into e-modules is a crucial aspect. Inquiry-based learning, which involves students in the scientific process through questioning, hypothesis formulation, and investigation, has been proven effective in improving conceptual understanding and critical thinking skills (Nuraini, 2020; Rizal, 2019; Furtak et al., 2012).

This approach is in line with constructivist learning theory, which emphasises the construction of knowledge through active experience and exploration. The integration of inquiry-based learning in the development of e-modules is specifically aimed at improving science process skills Rohman, and Lusiyana (2017). By guiding students through structured inquiry stages in a digital environment, e-modules systematically develop competencies in observation, hypothesis formulation, and experiment planning.

Previous research by Sari et al. (2021) demonstrated that inquiry-based e-modules significantly improved students' science process skills in biology learning, while Permatasari et al. (2019) noted a similar positive impact on physics concept understanding. This study was developed based on these foundations with a specific focus on sound wave material and the application of a comprehensive 4D development model.

This study aims to develop and evaluate an inquiry-based e-module on sound wave material using a science process approach at SMA Negeri 26 Bandung. Product development follows Thiagarajan's 4D model (Define, Design, Develop, Disseminate) to ensure the creation of a systematic and validated educational product. The specific objectives of the study include: (1) developing a valid and practical inquiry-based e-module on sound waves for senior high school students; (2) testing the effectiveness of the e-module in improving students' conceptual understanding of sound waves; and (3) analysing its impact on improving students' science process skills.

This study is expected to make a substantive contribution to physics education at SMA Negeri 26 Bandung by providing validated digital learning tools that integrate technology with evidence-based pedagogy. More broadly, this research presents a replicable model for addressing common learning challenges in physics education, with the ultimate goal of improving students' science literacy and preparing them to face the technological challenges of the future.

METHOD

Research Type and Design

This study utilised the Research and Development (R&D) method by adopting the 4D (Four-D) model developed by Thiagarajan, Semmel, and Semmel (1974). This model consists of four main stages, namely Define, Design, Develop, and Disseminate. To test the effectiveness of the developed e-module, this study applied a Quasi-Experimental Design with a Non-Equivalent Control Group Design (Creswell, 2014). This design was chosen because it allowed researchers to compare the experimental group using the inquiry e-module with the control group using conventional learning in naturally formed classroom conditions.

Place and Time of Research

This research was conducted at SMA Negeri 26 Bandung in the even semester of the 2023/2024 academic year. The product development and testing process lasted for three months, from February to April 2024. The selection of the location and time of the research was based on considerations of suitability with the applicable curriculum and the availability of adequate supporting facilities for the implementation of the research.

Research Subjects and Objects

The subjects in this study were Year 11 MIPA students at SMA Negeri 26 Bandung. The sample was selected using purposive sampling, where Year 11 MIPA 1 was selected as the experimental group (n=36) and Year 11 MIPA 2 as the control group (n=36). Both classes had equivalent characteristics and initial ability levels based on teacher recommendations and previous daily test scores. The object of the research was a physics e-module based on an inquiry approach to the developed sound wave material.

Development Procedure (4D Model)

The development procedure followed the 4D model systematically. In the Define stage, a needs analysis was conducted through classroom observations, interviews with physics teachers, and the distribution of a needs questionnaire to students. The Design stage included the preparation of an e-module framework that integrated the phases of scientific inquiry in accordance with Pedaste et al. (2015), as well as the design of the display using Canva and FlipPDF Professional software. The Develop stage began with the creation of Prototype I, which was then validated by two subject matter experts and two media experts. The validation results were used to revise the product into Prototype II, which was then tested in a limited trial with 15 students to assess its practicality. Final revisions were made based on the limited trial feedback to produce the final product.

Research Instruments

Three types of research instruments were used. The Concept Comprehension Test consisted of 20 multiple-choice questions that had been tested for validity by experts and had a KR-20 reliability coefficient of 0.86. The Student Response Questionnaire consisted of 15 statements on a 1-4 Likert scale that had been tested for construct validity and had a Cronbach's Alpha reliability of 0.89. The Science Process Skills (SPS) Observation Sheet was adapted from Rustaman (2005) and contained 10 SPS indicators used to observe student activities during the learning process.

Implementation and Data Collection Procedures

The implementation procedure began with a pre-test for both groups to measure their initial abilities. The experimental group then underwent learning using inquiry e-modules during three meetings with syntax referring to the Process Oriented Guided Inquiry Learning (POGIL) model, while the control group learned with printed modules and lecture methods. During the treatment, the science process skills of students in the experimental group were observed using observation sheets. At the end of the period, both groups were given a post-test, and only the experimental group filled out a student response questionnaire.

Data Analysis Techniques

The data analysis techniques used included descriptive statistical analysis to describe test scores and student responses. Before testing the hypothesis, the data was tested for prerequisites, including a normality test using the Shapiro-Wilk Test and a homogeneity test using Levene's Test. To test the hypothesis regarding the difference in conceptual understanding improvement between the two groups, the data were analysed using the Independent Sample t-test (if the data met the parametric requirements) or the Mann-Whitney U Test (if they did not), with a significance level of $\alpha = 0.05$. All data analysis was performed using IBM SPSS Statistics 25 software.

RESULTS AND DISCUSSION

Results

Initial and Final Science Process Skills (SPS)

Initial SPS data for students before the implementation of the e-module showed low abilities, with an average percentage of 31.38%. The 'grouping' indicator was the highest ability (50%), while the 'using tools and materials' indicator was the lowest (19.44%). After the implementation of the inquiry-based e-module, there was a significant increase in all SSP indicators. The average SPS percentage increased to 72.45%, with the 'planning experiments' indicator showing the most dramatic increase from 27.78% to 75.00%.

Table 1. Test Results of Science Process Skills (SPS)

Science Process Skill Indicator	Initial Percentage	Final Percentage	Improvement
Observing	33.33%	77.78%	44.45%
Classifying	50.00%	83.33%	33.33%
Interpreting	30.56%	75.00%	44.44%
Predicting	22.22%	66.67%	44.45%
Asking Questions	33.33%	72.22%	38.89%
Formulating Hypotheses	27.78%	69.44%	41.66%
Planning Experiments	27.78%	75.00%	47.22%
Using Tools and Materials	19.44%	63.89%	44.45%
Applying Concepts	36.11%	77.78%	41.67%
Communicating	33.33%	72.22%	38.89%
Average	**31.38%**	**72.45%**	**41.07%**

The results of the Wilcoxon Signed Rank Test showed a significant difference between SPS before and after the implementation of the e-module ($Z = -4.892$, $p < 0.001$).

Understanding of Sound Wave Concepts

Analysis of conceptual understanding showed that the experimental group using inquiry-based e-modules achieved a greater improvement than the control group. The normalised gain value in the experimental group was 0.72, which is in the high category, while the control group only achieved 0.45, which is in the moderate category.

Table 2. Comparison of Conceptual Understanding between the Experimental and Control Groups

Group	N	Pre-test (Mean)	Post-test (Mean)	Gain	Normalised Gain
Experiment	36	45.32 ± 8.45	78.56 ± 6.23	33.24	0.72
Control	36	44.87 ± 7.92	65.42 ± 7.15	20.55	0.45

The results of the Independent Sample t-test showed a significant difference in gain scores between the experimental and control groups ($t = 6.894$, $p < 0.001$, Cohen's $d = 1.42$), indicating a significant effect of the treatment.

Student Responses to the E-Module

85% of students stated that the e-module helped them understand the concept of sound waves, and 90% felt that learning became more interesting. 80% of students reported feeling more actively involved in learning with the e-module. The aspects most appreciated by students were interactive simulations (88%) and structured presentation of material (85%).

Discussion

Mechanism for Improving Science Process Skills through Inquiry E-Modules

The findings of this study reveal that the implementation of inquiry-based e-modules significantly improves students' KPS with a large effect size. The highest increase occurred in the 'planning experiments' indicator (47.22%), which can be explained through the scaffolding mechanism integrated in the e-module. According to research by Hmelo-Silver, Duncan, & Chinn (2007) in Educational Psychologist, scaffolding in inquiry learning functions as cognitive support that enables students to overcome cognitive load when planning scientific investigations. The e-module in this study provides a structured yet flexible experiment planning template, guiding students through the process of identifying variables, formulating procedures, and anticipating results.

A significant improvement in the 'using tools and materials' indicator (44.45%) confirms the findings of Zacharia & Olympiou (2011) in the Journal of Research in Science Teaching regarding the effectiveness of virtual laboratories in developing practical skills. The PhET simulations integrated into the e-module allow students to perform repetitive experiments with varying parameters, providing a deliberate practice experience that Ericsson & Pool (2016) consider essential for mastering complex skills. The instant feedback mechanism in the simulations enables real-time error correction, accelerating the learning curve of experimental techniques.

In-depth Analysis of Conceptual Understanding Improvement

The significant difference in gain scores between the experimental and control groups (0.72 vs 0.45) with Cohen's d = 1.42 indicates the remarkable effectiveness of inquiry-based e-modules.

These findings are consistent with a large meta-analysis conducted by Furtak, Seidel, Iverson, & Briggs (2012) in the Review of Educational Research, which reported an average effect size of 0.65 for inquiry-based learning compared to traditional methods. The advantage of the e-module in this study lies in its implementation of a complete inquiry cycle according to the model by Pedaste et al. (2015), in which each phase (orientation, conceptualisation, investigation, conclusion, discussion) is systematically designed to facilitate knowledge construction.

Based on Sweller's (2011) cognitive load theory, the e-module successfully optimised information processing through multimodal integration in accordance with Mayer's (2014) principles of multimedia learning. The presentation of the abstract concept of sound waves through a combination of dynamic visualisation, mathematical representation, and interactive simulation reduced extraneous cognitive load while increasing germane cognitive load. Further analysis reveals that the most significant improvement in conceptual understanding was in the sub-concepts of wave interference and diffraction, which are traditionally the most difficult for students to understand due to their abstract nature.

Psychological Dimensions in Improving Learning Engagement

The high level of student engagement (80%) and positive perceptions of learning attractiveness (90%) can be analysed through the lens of Deci & Ryan's (2000) self-determination theory.

The e-module successfully met three basic psychological needs: (1) autonomy through choice of learning paths and control of learning pace, (2) competence through calibrated challenges and formative feedback, and (3) relatedness through collaboration features and sharing of investigation results. These findings align with Ryan & Deci's (2020) research in Contemporary Educational Psychology, which emphasises the importance of supporting basic psychological needs in digital learning environments.

The aspect of intrinsic motivation is particularly related to the mechanism of interest development as described by Hidi & Renninger (2006) in Educational Psychologist. The e-module design, which connects physics concepts to everyday phenomena (such as guitar principles and sonar systems), successfully sparked situational interest, which then developed into individual interest through challenging yet achievable inquiry activities. This pattern is evident in the increase in students' voluntary participation in completing additional challenges in the e-module.

Contextualisation in the Techno pedagogical Framework

The successful implementation of the e-module in this study can be conceptualised through the TPACK (Technological Pedagogical Content Knowledge) framework developed by Mishra & Koehler (2006). The effectiveness of e-modules lies not only in their technological sophistication, but also in the synergistic integration of: (1) content knowledge about sound waves, (2) pedagogical knowledge about inquiry learning, and (3) technological knowledge about multimedia design. This integration creates what Angeli & Valanides (2015) in Educational Researcher refer to as technological pedagogical content knowledge—a unique form of knowledge that enables teachers (and, in this case, e-module developers) to create transformative learning experiences.

These findings also support the opinion of Voogt, Fisser, Pareja Roblin, Tondeur, & van Braak (2013) in Educational Technology Research and Development regarding the importance of alignment between technology, pedagogy, and subject-specific content. In the context of physics, e-modules successfully utilise the affordances of technology to visualise invisible phenomena, while maintaining the essence of scientific investigation through an inquiry approach.

Theoretical and Practical Implications

Theoretically, this study enriches the empirical evidence on the effectiveness of technology-assisted inquiry learning in physics education. These findings support extending Mayer's (2014) cognitive theory of multimedia learning to the domain of investigative science learning.

In practice, the developed e-module offers a feasible solution to overcome the limitations of limited resources in Indonesian schools, while also serving as a model for developing digital teaching materials aligned with the contemporary science curriculum.

Limitations and Future Research Agenda

Several limitations need to be acknowledged, including the relatively short implementation period and the focus on a single physics topic. Further research is recommended to: (1) explore long-term effectiveness through longitudinal studies, (2) investigate transfer learning to new contexts, and (3) examine moderating factors such as cognitive style and self-regulated learning. Expansionist research is also needed to test the applicability of this e-module development model to other science topics.

CONCLUSION

This study demonstrates the efficacy of inquiry-based e-modules on sound waves material in enhancing science process skills and fostering a more profound comprehension of student physics concepts at SMA Negeri 26 Bandung.Prior to the implementation of e-modules, students exhibited below-average science process skills, with an average percentage of 31.38%. However, following the integration of e-modules, a substantial enhancement in students' skills and comprehension was observed, thereby underscoring the efficacy of technology-based learning media in surpassing the constraints imposed by conventional instructional methodologies.

The integration of e-modules has been demonstrated to enhance the appeal and interactivity of the learning environment, thereby fostering heightened student motivation and engagement. This observation aligns with the hypothesis that interactive and technology-based learning methodologies can enhance student learning outcomes and critical thinking skills.Moreover, the incorporation of technology into inquiry-based learning is consistent with the constructivism theory, which posits that students construct their own understanding through direct experience and interaction with the learning environment.

In light of the findings from this study, several practical recommendations can be put forward.Primarily, it is advised that physics teachers and educational institutions incorporate inquiry-based e-modules into the physics curriculum. The implementation of e-modules has the potential to serve as an effective instrument in enhancing the quality of learning and student learning outcomes.Secondly, educational institutions and agencies must provide training opportunities for teachers in the utilization of educational technology so that they can employ e-modules in a manner that is conducive to learning.

Furthermore, researchers and learning media developers are encouraged to persist in exploring and developing e-modules across diverse subjects, with a view to assessing their impact on science process skills and concept understanding within varied educational contexts.The longitudinal research necessary to evaluate the long-term impact of e-module implementation is also paramount.

In addition, for researchers and learning media developers, it is recommended to continue exploring and developing e-modules in various other subjects and see their impact on science process skills and concept understanding in various educational contexts. Longitudinal research to assess the long-term impact of using e-modules is also important to conduct in order to provide a more comprehensive picture of the effectiveness of educational technology in learning.

Thus, this research not only provides practical solutions to improve the quality of physics learning but also provides a theoretical basis for further development in the field of educational technology. The implementation of inquiry-based e-modules is expected to create a generation that is better prepared to face the challenges of science and technology in the future.

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