



Developing an e-Module about Sound Waves with a STEM Approach to Improve Students' Critical Thinking Skills

* **Aslamiyah Rambe, Syahrudin Aritonang, Malika Ritonga, Nur Hasanah**
Physics Education Study Program, Faculty of Teacher Training and Education,
Muhammadiyah University of South Tapanuli, L. Sutan Moh. Arif No. 32, Padangsidempuan,
22733 Indonesia.

*Corresponding Author e-mail: aslamiyah@um-tapsel.ac.id

Received: August 2025; Revised: November 2025; Published: January 2026

Abstract

The integration of information and communication technology (ICT) into education has encouraged the development of innovative learning resources, particularly electronic modules (e-modules), to support interactive and independent learning. Physics, despite its fundamental role in fostering analytical and critical thinking, is often perceived as abstract and difficult, with conventional instruction limiting student engagement and higher-order thinking. To address these challenges, this study developed a STEM-based e-module on sound waves aimed at enhancing students' critical thinking skills. This study employed a 4D development model—define, design, develop, and disseminate—with 34 11th-grade students from SMAN 6 Padangsidempuan as participants. Instruments included expert validation (content, media, and language), teacher and student questionnaires, and a pretest-posttest assessment of critical thinking. This electronic module achieved a validity score of 96.66% (very valid), a practicality rating of 96.36% from teachers and 85.95% from students (very practical), and effectiveness was demonstrated by a significant increase in students' posttest scores ($M = 85.59$) compared to pretest scores ($M = 36.76$), exceeding the minimum competency. The results of the paired t-test showed $t = 17.89$ and $df = 33$, $p < 0.001$, with a very large effect size (Cohen's $d = 3.26$). The results of the study show that the use of STEM-based e-modules is effective in improving students' critical thinking skills. Results dissemination shows involvement of active students and ability adaptation across the board. These findings confirm that this STEM-based electronic module is valid, practical, and effective, and provides an innovative solution to support critical thinking, problem-solving, and technological literacy in 21st-century physics education.

Keywords: critical thinking; e-module; ICT; STEM; physics

How to Cite: Rambe, A., Aritonang, S., Ritonga, M., & Hasanah, N. (2026). Developing an e-Module about Sound Waves with a STEM Approach to Improve Students' Critical Thinking Skills. *Prisma Sains : Jurnal Pengkajian Ilmu Dan Pembelajaran Matematika Dan IPA IKIP Mataram*, 14(1), 94–108. <https://doi.org/10.33394/j-ps.v14i1.17375>



<https://doi.org/10.33394/j-ps.v14i1.17375>

Copyright© 2026, Rambe et al.

This is an open-access article under the [CC-BY](https://creativecommons.org/licenses/by/4.0/) License.



INTRODUCTION

The rapid advancement of information and communication technology (ICT) has brought significant transformations in various fields, including physics education and learning. The integration of ICT in the classroom is not merely a tool to support learning, but also a driver of innovation in the development of interactive and effective learning resources (Haleem et al., 2022; Mena-Guacas et al., 2025; Mhlongo et al., 2023; Soriano-Sánchez, 2025; Timotheou et al., 2023). Among these innovations, electronic modules (e-modules) have emerged as a promising digital learning resource, designed to facilitate self-paced and interactive learning. Previous studies have shown that e-modules play an important role in improving students' conceptual understanding and learning outcomes, especially in subjects that require in-depth conceptual reasoning (Abdulrahman et al., 2020; Barua & Lockee, 2024; Errabo & Ongoco,

2024; Kerimbayev et al., 2023; Lampropoulos & Kinshuk, 2024; Monib et al., 2025; Wardani et al., 2025; Yaseen et al., 2025), such as physics.

Physics, as a fundamental branch of science, studies natural phenomena through the interactions of matter and energy across space and time. Physics is essential in equipping students with critical and analytical thinking skills, key competencies for the 21st century (Bao & Koenig, 2019; Mena-Guacas et al., 2025; Mulyono, 2018). However, physics is often perceived as abstract and difficult, largely due to its mathematical nature and the dominance of conventional teaching methods that emphasize rote learning and problem practice. This instructional approach tends to result in passive learning, where students simply absorb information without actively engaging in concept construction (Bozzi et al., 2021; Dahl & Mørch, 2025; Nilimaa, 2023; Redish & Burciaga, 2004; Schuster et al., 2018). As a result, students' critical thinking skills are still underdeveloped, especially in topics such as sound waves, which are often considered difficult to understand due to their abstract nature and low achievement scores (Hidayati et al., 2024; Pardo, 2017; Reddy & Panacharoensawad, 2017).

To address these challenges, innovative learning approaches are needed that actively engage students in constructing their own knowledge. The STEM (Science, Technology, Engineering, and Mathematics) approach offers a promising framework by emphasizing inquiry, experimentation, and analysis, thereby fostering higher-order thinking skills (Ammar et al., 2024; Anchunda & Kaewurai, 2025; Arifin et al., 2025; Bhardwaj et al., 2025; Bhuttah et al., 2024; Halawa et al., 2024; Kwangmuang et al., 2021; Morris, 2025; Pardo, 2017; Schuster et al., 2018; Siller & Ahmad, 2024). STEM-based learning has been widely recognized as effective in fostering communication, collaboration, creativity, and especially critical thinking—skills collectively referred to as the 4Cs, which are essential for 21st-century education (Akon-Yamga et al., 2024; Nuriyah et al., 2020). Furthermore, critical thinking has been identified as a higher-order thinking skill that contributes not only to academic achievement but also to moral, social, and cognitive development (Barta et al., 2022; Golden, 2023; Kumandaş-Öztürk & Ulu-Kalın, 2025; Loyens et al., 2023; Pollarolo et al., 2023; Rivas et al., 2022; Simonovic et al., 2023).

The integration of STEM into digital learning materials such as e-modules offers an opportunity to overcome limitations of time, resources, and classroom infrastructure. To date, various studies have demonstrated the effectiveness of STEM-based e-modules in systematically guiding students through problem-solving processes, providing interactive simulations, and providing instant feedback, thus supporting independent and effective learning (Tartiyoso, 2025; Yani et al., 2024).

However, most of this research still focuses on the development of conventional e-modules based on computer simulations without direct integration with digital sensor-based experimental activities. This means that there is not much research examining the integration of STEM-based e-modules with the Phyphox application, as a real-world smartphone-based experimental medium. This approach has the potential to overcome the constraints of limited laboratory facilities while encouraging more participatory and contextual physics learning. This *research gap* is the primary basis for conducting this study.

Therefore, this study aims to develop a STEM-based e-module on sound waves to improve students' critical thinking skills. The specific objectives are to test the validity, practicality, and effectiveness of the developed e-module in improving students' critical thinking skills in physics.

METHOD

Research Approach and Design

This research is a Research and Development (R&D) development study using the Define, Design, Develop, and Disseminate (4D) development model (Thiagarajan et al., 1974). In the define stage, an analysis of the curriculum, materials, and students was carried out. In

the design stage, an e-module of sound waves was developed with a STEM approach to improve students' critical thinking skills. In the develop stage, the product of the design in the form of an e-module of sound waves with a STEM approach to improve students' critical thinking skills was tested for validity, practicality, and effectiveness. The research subjects in this F stage were students of class XI-1 of SMAN 6 Padangsidempuan City, North Sumatra Province. totaling 34 people. Sampling was carried out by means of *purposive sampling* .

The instruments used in this study were validation instruments conducted by media experts, material experts, and linguists to measure the feasibility of the developed e-module product, as well as student and teacher response questionnaires to determine the level of practicality of the e-module after use. Then, pre-test and post-test questions were prepared, as well as student effectiveness questionnaires to measure the effectiveness of the e-module. Data analysis techniques used to ensure product validity were quantitative and qualitative data analysis. The validity of the e-module on sound wave material with a STEM approach to improve students' critical thinking was obtained through validation results from material experts, media experts, and linguists. The practicality of the e-module on sound wave material with a STEM approach to improve students' critical thinking was obtained through student and teacher response questionnaires and to measure effectiveness using descriptive statistical analysis for validity and practicality as well as parametric analysis (paired sample t test) to measure students' critical thinking skills achievement using the e-module. Then, an N-gain test was conducted to determine the effectiveness of the e-module on sound wave material with a STEM approach to improve students' critical thinking that was developed. Data analysis to measure the level of effectiveness can be done using SPSS 22 and a Likert scale.

E-module Validity Test

Validity testing was carried out by comparing the average validity scores of all material, media, and language experts using the criteria: (Syukri et al., 2024) as presented in Table 1.

Table 1. Validity Categories

Score	Interval (%)	Category
1	$0 < x \leq 20$	Totally invalid
2	$20 < x \leq 40$	Invalid
3	$40 < x \leq 60$	Less valid
4	$60 < x \leq 80$	Legitimate
5	$80 < x \leq 100$	Very valid

The e-module on sound wave material with a STEM approach to improve students' critical thinking skills is said to be valid from material, media, and language experts if the average validity value based on the valid criteria obtained is at least valid.

e-module Practical Test

The practicality of the e-module on sound waves using the STEM approach to improve students' critical thinking skills in this study was assessed based on student and teacher questionnaire responses to the use of the e-module. Practicality criteria are presented in Table 2 (Asfiya et al., 2024) .

Table 2. Practicality Categories

Interval (%)	Category
$80 < x \leq 100$	Very practical
$60 < x \leq 80$	Practical
$40 < x \leq 60$	Less practical
$20 < x \leq 40$	Not practical
$x \leq 20$	Very impractical

The electronic module on sound wave material with a STEM approach to improve students' critical thinking skills is said to be practical based on student and teacher response questionnaires with an average score based on the minimum practical assessment criteria.

Testing the Effectiveness of e-modules

The effectiveness of the e-module on sound waves with a STEM approach in improving students' critical thinking skills can be seen from the achievement of the Minimum Completion Criteria (KKM) for students' critical thinking skills, namely 75. The critical thinking test questions consist of ten questions, as in Figure 1, question indicators in Table 3.

SOAL PRETEST MATERI GELOMBANG BUNYI
(KETERAMPILAN BERPIKIR KRITIS)

1. Sebuah sumber bunyi bergerak mendekati pendengar. Pendengar merasakan frekuensi bunyi lebih tinggi daripada frekuensi aslinya. Fenomena ini disebut ...
 A. Interferensi bunyi
 B. Efek Doppler
 C. Pemantulan bunyi
 D. Resonansi

2. Dalam suatu eksperimen, kecepatan bunyi di udara diukur dengan memantulkan bunyi dari dinding sejauh 170 m. Waktu yang dicatat untuk perjalanan pulang-pergi bunyi adalah 1 detik. Berapakah kecepatan bunyi di udara?
 A. 170 m/s
 B. 255 m/s
 C. 340 m/s
 D. 510 m/s

3. Seorang siswa membunyikan garpu tala di dekat permukaan air. Ia melihat gelombang pada permukaan air bergetar bersamaan dengan getaran garpu tala. Hal ini menunjukkan bahwa bunyi ...

Figure 1. Pre-Test Questions

Table 3. Question Indicators

Question	Critical Thinking Skills Indicators	Thinking Level (Bloom)
1.	Identifying the Doppler effect phenomenon	Analysis
2.	Able to apply mathematical concepts & numerical analysis	Application/Analysis
3.	Understanding sound requires a medium	Understanding/Analysis
4.	Recognizing interference & wave patterns	Analysis
5.	Applying physics formulas to solve problems	Application
6.	Relating the speed of sound vs light	Analysis
7.	Designing appropriate experimental methods	Synthesis
8.	Applying the formula distance = speed × time	Application
9.	Explaining the relationship between sound waves and directional perception	Analysis
10.	Identify the Doppler effect & explain the physical phenomena	Analysis

Then, a comparison of the average score with the difference in scores before using the e-module (pretest) and after using the e-module (posttest) was conducted using the n-gain test. The n-gain criterion can be determined using Formula 1 (Ramdhani et al., 2020) . The normalized gain value criteria can be seen in Table 3.

$$N \text{ Gain} = \frac{\text{Posttest score} - \text{Pretest score}}{\text{Ideal score} - \text{Pretest score}} \quad (1)$$

Table 4. N-Gain Conversion

Number.	N Benefits	Category
1.	$N \text{ gain} \geq 0.7$	Tall
2.	$0.3 \leq N \text{ Gain} < 0.7$	Currently
3.	$N \text{ Gain} < 0.3$	Low

RESULTS AND DISCUSSION

Determine the Phase

The initial phase of this research focused on analyzing the curriculum, materials, and learners to ensure alignment with the Independent Curriculum objectives in phase F. The analysis showed that the expected learning outcomes and objectives could be effectively achieved through the chosen topic, namely sound waves. The sound wave material includes subtopics such as wave characteristics, types of sound, speed of sound, and the Doppler effect, all of which require conceptual understanding and the ability to connect theory to real-life phenomena. Integrating these subtopics with the STEM approach is considered essential to stimulate students' critical thinking skills.

Furthermore, analysis of student characteristics at SMA Negeri 6 Padangsidempuan show limited motivation , low critical thinking skills, and inadequate facilities. These findings highlight the urgent need for innovative learning tools that not only support conceptual mastery but also motivate students to actively engage in the learning process. Previous research has shown that low motivation and lack of infrastructure often contribute to passive learning behavior (Castillo et al., 2025; Fütterer et al., 2022; Kooloos et al., 2020; Major et al., 2021; Manlapig, 2024; Rezai et al., 2025) , which in turn negatively impacts higher-order thinking skills (Mangul & Pratiwi, 2025; Sinaga et al., 2025) .

Design Stage

In the design phase, an e-module on sound waves was developed with a STEM-based structure to meet curriculum requirements. This design included a systematic presentation of concepts, enriched with illustrations, videos, and simple STEM-based experimental activities. Furthermore, assessment items were integrated to measure the development of students' critical thinking skills. To facilitate practical engagement, digital applications such as Frequency Generator and Phyphox were embedded within the module to support experiments and data collection. The e-module's ability to enhance students' critical thinking skills can be seen in Figure 2.

This design ensures that the e-module is not only informative but also interactive, encouraging learners to connect scientific concepts with technology and engineering practices. The inclusion of hands-on experiments is consistent with the core principle of STEM, namely learning by doing (Chen & Liu, 2025; Huang et al., 2022; Kranz et al., 2023; Margot & Kettler, 2019; Yannier et al., 2020; Yilmaz et al., 2024) , which has been reported to significantly improve conceptual understanding and critical thinking in physics learning (Nuriyah et al., 2020; Rambe et al., 2023).

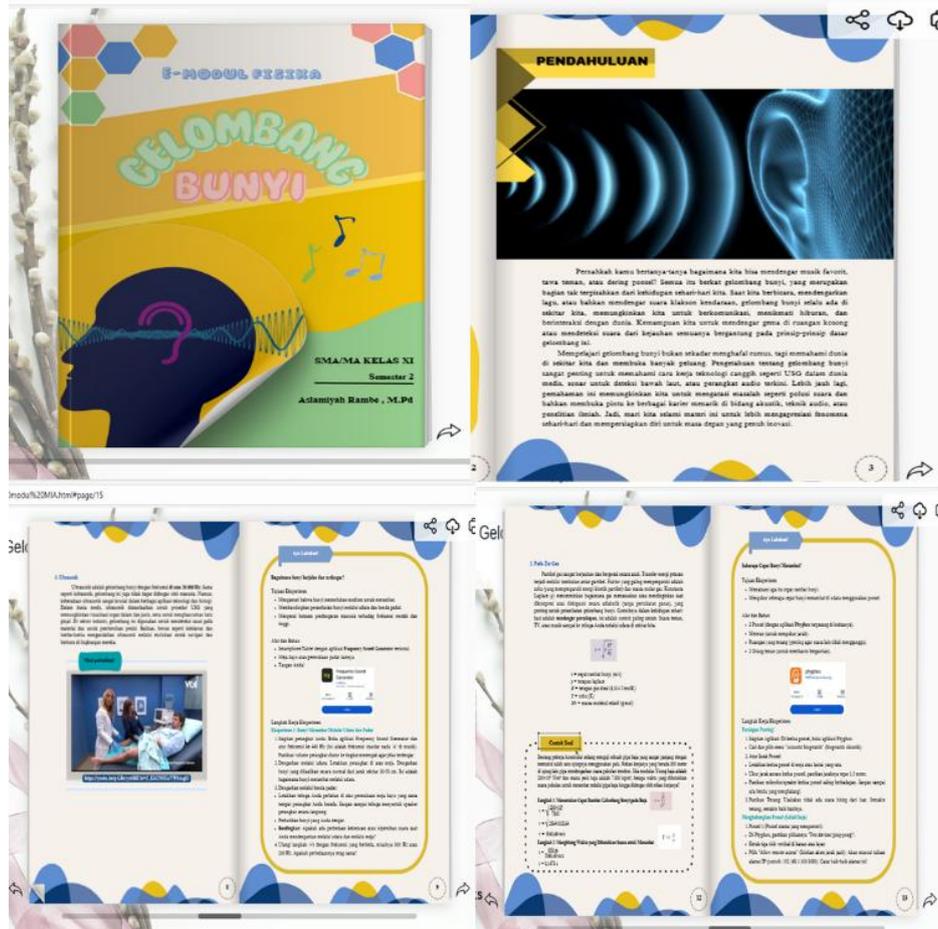


Figure 2. E-module with STEM approach (<file:///D:/BIMA/e%20modul.html>)

Stage Development

Stage development consists of The e-module was evaluated based on three main evaluations: validity, practicality, and effectiveness. Validity testing was conducted through expert review by media, content, and language specialists. The e-module obtained an average score of 96.66%, categorizing it as "highly valid" (see Table 4). Revisions suggested by the language experts—such as correcting spelling and refining the cover page—were implemented to improve clarity and presentation. High validity scores indicate that the e-module meets quality standards in content accuracy, language use, and media design (Abdullah et al., 2024; Fatmawati & Murtinugraha, 2024; Lestari & Nugraheni, 2022) . Similar results have been reported in other STEM-based module development studies, where expert validation plays a crucial role in ensuring instructional quality (Jannah et al., 2025; Rahma et al., 2021) .

Table 5. Results of E-Module Validation by Experts

NO	Validator	Percentage of Assessment (%)	Category
1	EH	100	Very Valid
2	FH	90	Very Valid
3	HA	100	Very Valid
	Average	96.66	Very Valid

The practicality test was conducted using teacher and student response questionnaires. The results showed that the e-module was very practical, with an average score of 96.36 % from teachers (see Table 6) and 85.95% of students (see Table 7). Practicality is reflected in students' positive perceptions of usefulness, interactivity, and relevance to the physics

curriculum (Arizona et al., 2025; Guerrero-Zambrano et al., 2025; Pansri et al., 2025; Rizki et al., 2025) . This finding aligns with previous research emphasizing that practicality is a strong determinant of successful classroom implementation (Diansah & Asyhari, 2020).

Table 6. Practicality Test Results (Teacher Response Questionnaire)

NO	Teacher Response Questionnaire	Validator value (%)		Average	Category
		EH	Emergency Room		
1	Electronic module	96.36	96.36	96.36	Very Practical
	Average			96.36	Very Practical

Table 7. Practicality Test Results (Student Response Questionnaire)

Student	N	Minimum	Maximum	Means	Standard Deviation
P1	34	2	4	3.12	.591
P2	34	3	4	3.59	.500
P3	34	3	4	3.44	.504
P4	34	3	4	3.56	.504
P5	34	2	4	3.56	.561
Page 6	34	3	4	3.44	.504
P7	34	2	4	3.24	.496
Page 8	34	3	4	3.47	.507
P9	34	3	4	3.41	.500
P10	34	2	4	3.56	.613
Average_practicality	34	2.70	4.00	3.4382	.33030
Practicality value	85.95 (very practical)				

Effectiveness testing involves comparing critical thinking skills. student through pre-test And post-test . Before Pre-test And post test done test validity , reliability , power differentiator And degrees difficulties on ten grains question . As for results the can seen on Table 8.

Table 8. Results Test validity Question Think Critical

Question	r	Category
Question 1	0.633	Valid
Question 2	0.624	Valid
Question 3	0.677	Valid
Question 4	0.781	Valid
Question 5	0.832	Valid
Question 6	0.736	Valid
Question 7	0.668	Valid
Question 8	0.685	Valid
Question 9	0.742	Valid
Question 10	0.761	Valid

The test instrument was tested for reliability using Cronbach's Alpha , and a value of 0.893 was obtained for 10 questions. This value indicates that the instrument has high internal consistency and can be used to measure student abilities (Table 9).

Table 9. Reliability of Critical Thinking Test.

Instrument	N Items	Cronbach's Alpha
Critical Thinking Test	10	0.893

The critical thinking test used consisted of 10 items with a total of N = 34 respondents . Descriptive statistics for each item showed an average value of 0.35–0.59 , a median of 0–1 , and a standard deviation of 0.485–0.508 , with a minimum score of 0 and a maximum of 1. Reliability analysis using Cronbach's Alpha produced a value of 0.893 , indicating high internal consistency, and varying levels of item difficulty. Thus, this instrument can be considered reliable and its measurement transparency is more adequate than before.

Table 10. Level of Question Difficulty

	Q 1	Q 2	Q 3	Q 4	Q 5	Q 6	Q 7	Q_8	Q 9	Q 10
N Valid	34	34	34	34	34	34	34	34	34	34
Missing	0	0	0	0	0	0	0	0	0	0
Mean	,56	,53	,59	,44	,44	,38	,38	,50	,53	,35
Median	1.00	1.00	1.00	0.00	0.00	0.00	0.00	,50	1.00	0.00
Standard Deviation	,504	,507	,500	,504	,504	,493	,493	,508	,507	,485
Minimum	0	0	0	0	0	0	0	0	0	0
Maximum	1	1	1	1	1	1	1	1	1	1

The average pre-test score was 36.76 (see Table 11, in general significant lower than the average post-test score of 85.59 (see Table 12). The results of the paired t-test show $t = 17.89$ and $df = 33$, $p < 0.001$, with a very large effect size (Cohen's $d = 3.26$) Improvement substantial This showed that the use of STEM-based e-modules effectively improved students' critical thinking skills, exceeding the minimum competency criteria (MCC = 75). Furthermore, the effectiveness questionnaire showed an average score of 98.11%, confirming the module's high impact. The significant difference between pre-test and post-test scores reinforces previous findings that STEM-based digital resources can substantially improve higher-order thinking skills (Maziyah & Hidayati, 2022).

Table 11. Effectiveness Test Results (Pretest Value)

Number	Value Interval	Number of Students	Total Value
1.	10	1	10
2.	20	5	100
3.	30	11	330
4.	40	5	200
5.	50	11	550
6.	60	1	60
Total Overall Score			1250
Average			36.76

Table 12. Effectiveness Test Results (Post-Test Score)

NO	Value Interval	Number of Students	Total Value
1.	40	1	40
2.	50	0	0
3.	60	0	0
4.	70	3	210
5.	80	9	720
6.	90	16	1440
7	100	5	500
Total Overall Score			2910
Average			85.59

Distribution Stage

During the dissemination phase, the e-module was implemented by other teachers in different classrooms, demonstrating its adaptability and transferability. Teachers reported that students became more active during the lessons, engaging in discussions, conducting experiments, and critically reflecting on their findings. The application of STEM principles through the e-module format supported independent learning while encouraging collaboration and problem-solving.

These results are consistent with the principles of instructional design, which emphasize the presentation of material that is systematic, clear, and interesting to enhance understanding (Jannah et al., 2025). In addition that, integration Phyphox as tool experiment Mobile-based applications provide a cost-effective and accessible solution for physics learning (Imtinan & Kuswanto, 2023; Jeli & Chandra, 2025), which supports previous studies highlighting the potential of smartphone applications to enhance science education (Junita et al., 2024; Raharja et al., 2024).

These findings indicate that the developed STEM-based e-module on sound waves is valid, practical, and effective in enhancing students' critical thinking skills. This module not only addresses the challenges identified during the needs analysis but also aligns with broader 21st-century educational goals, which emphasize the development of critical thinking, problem-solving, and technological literacy.

CONCLUSION

This study developed and validated a STEM-based e-module on sound waves to improve students' critical thinking skills. The research was conducted through four stages: definition, design, development, and dissemination. A needs analysis showed that students at SMA Negeri 6 Padangsidempuan show low motivation and limited critical thinking skills, which indicates the need for innovative digital learning resources. This e-module design integrates the concept of sound waves with interactive illustrations, videos, simple STEM experiments, and digital applications (Frequency Generator and Phyphox), so that draft abstract becomes more concrete and applicable.

The expert validation results yielded an average score of 96.66%, categorizing the e-module as "highly valid." The practicality test showed positive responses from teachers (96.36%) and students (85.95%), indicating that the e-module was user-friendly, relevant, and highly applicable in the classroom environment. The effectiveness test further demonstrated a significant increase in students' critical thinking skills, with the post-test score ($M = 85.59$) significantly higher than the pre-test score ($M = 36.76$), exceeding the minimum competency criteria. These findings confirm that the developed STEM-based e-module is valid, practical, and effective in developing higher-order thinking skills in physics learning.

Integration integrated STEM principles Phyphox to in e-module format provides effective learning innovation to overcome challenges in teaching abstract physics concepts, especially sound waves. This module not only encourages critical thinking but also supports independent learning, problem-solving, and technological literacy, which align with the competencies required in 21st-century education.

Although the Phypho x application has been proven to provide many conveniences in learning physics, especially STEM-based experimental activities, its use has several limitations. First, the accuracy of measurements depends on the specifications of the mobile phone sensor, so variations between devices can affect the results. Second, this application requires a basic understanding of experimental activities, so teacher guidance is still needed to ensure the experimental process and data collection are valid. Third, Phypho x cannot be used for all types of physics experiments. Considering these limitations, the results of the study still show that Phypho x is effective as a physics learning tool, but its use must be accompanied by technical and pedagogical considerations.

RECOMMENDATION

The findings of this study indicate that STEM-based e-modules on sound waves can be effectively implemented in broader educational contexts. It is recommended that teachers integrate similar digital modules into classroom practice to enhance students' critical thinking and problem-solving skills. Curriculum developers should consider integrating STEM-based digital resources into the Independent Curriculum (Kurikulum Merdeka) to align with 21st-century competencies, while professional development programs are needed to equip teachers with the skills to design and implement such innovations sustainably. Future research is encouraged to explore the long-term impact of STEM-based e-modules on various learning outcomes and test their scalability across different physics topics and educational levels. Furthermore, technological enhancements, such as the integration of augmented reality (AR) or virtual laboratories, can be developed to further enrich student engagement and provide a more immersive and interactive learning experience.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to SMA Negeri 6 Padangsidempuan for their access, support, and participation during the implementation of this research. Special thanks are also extended to the students and teachers who actively contributed to the trial and evaluation of the developed e-module. The authors also thank Muhammadiyah University of South Tapanuli for their academic guidance, facilities, and institutional support that made this research possible.

FUNDING INFORMATION

No external financial support, grants, or institutional funding were received for the conduct of this study, the analysis of the data, or the preparation of the manuscript.

AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Aslamiyah Rambe	✓	✓		✓	✓	✓	✓	✓	✓			✓	✓	✓
Syahrudin Aritonang		✓	✓		✓	✓	✓	✓		✓	✓			✓
Malika Ritonga		✓	✓		✓	✓	✓	✓		✓	✓			✓
Nur Hasanah		✓	✓		✓	✓	✓	✓		✓	✓			✓

CONFLICT OF INTEREST STATEMENT

The authors state that they have no conflict of interest related to the research, authorship, or publication of this article.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

This research was conducted with the approval of the Principal of SMAN 6 Padangsidempuan with letter number: 400.3.8. /681/SMAN6.PSP/VIII/2025

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

Abdullah, A., Herdini, H., & Putri, TS (2024). Validity and Practicality of Phenomenon-Based Learning E-Modules Using Articulate Storyline on Colligative Properties of Solutions. *Journal of Science Education Research* , 10 (2), 764–775. <https://doi.org/10.29303/jppipa.v10i2.5837>

Abdulrahman, MD, Faruk, N., Oloyede, AA, Surajudeen-Bakinde, NT, Olawoyin, LA, Mejabi, O. V, Imam-Fulani, YO, Fahm, AO, & Azeez, AL (2020). Multimedia tools in the teaching and learning process: A systematic review. *Heliyon* , 6 (11), e05312. <https://doi.org/https://doi.org/10.1016/j.heliyon.2020.e05312>

- Akon-Yamga, G., Funkor, G., Tsey, K., Kingsford-Adaboh, R., Quaye, W., & Ntewusu, D.A. (2024). Students' and teachers' perspectives on the challenges of teaching and learning STEM subjects in Ghana. *Frontiers in Education* , 9 (April), 1–16. <https://doi.org/10.3389/feduc.2024.1288413>
- Ammar, M., Al-Thani, N.J., & Ahmad, Z. (2024). The role of pedagogical approaches in fostering innovation among K-12 students in STEM education. *Social Sciences & Humanities Open* , 9 , 100839. <https://doi.org/https://doi.org/10.1016/j.ssaho.2024.100839>
- Anchunda, H.Y., & Kaewurai, W. (2025). Development of inquiry-based and problem-based learning models to improve teamwork and collaborative problem-solving competencies of prospective teachers. *Social Sciences & Humanities Open* , 11 , 101480. <https://doi.org/https://doi.org/10.1016/j.ssaho.2025.101480>
- Arifin, Z., Sukarmin, Saputro, S., & Kamari, A. (2025). The effect of inquiry-based learning on students' critical thinking skills in science education: A systematic review and meta-analysis. *Eurasia Journal of Mathematics, Science and Technology Education* , 21 (3). <https://doi.org/10.29333/ejmste/15988>
- Arizona, K., Sucilestari, R., Nirmala, BMA, & Meiliyadi, LAD (2025). Project-Based Science-Physics E-Book to Train Students' Creativity. *Journal of Science Education Research* , 11 (6), 718–725. <https://doi.org/10.29303/jppipa.v11i6.11112>
- Asfiya, N., Razi, P., Hidayati, & Sari, SY (2024). Development of e-Modules for Independent Learning of Physics Material Based on Independent Curriculum. *International Journal of Information Technology and Education* , 14 (5), 761–769. <https://doi.org/10.18178/ijiet.2024.14.5.2100>
- Bao, L., & Koenig, K. (2019). Physics education research for 21st-century learning. *Disciplinary and Interdisciplinary Science Education Research* , 1 (1), 2. <https://doi.org/10.1186/s43031-019-0007-8>
- Barta, A., Fodor, L.A., Tamas, B., & Szamoskozi, I. (2022). Developing students' critical thinking skills and dispositions through the concept mapping learning method – A meta-analysis. *Educational Research Review* , 37 , 100481. <https://doi.org/https://doi.org/10.1016/j.edurev.2022.100481>
- Barua, L., & Lockee, B.B. (2024). A review of strategies for incorporating flexibility into higher education course design. *Discover Education* , 3 (1), 127. <https://doi.org/10.1007/s44217-024-00213-8>
- Bhardwaj, V., Zhang, S., Tan, Y.Q., & Pandey, V. (2025). Redefining learning: Student-centered strategies for academic and personal growth. *Frontiers in Education* , 10 (February), pp. 1–15. <https://doi.org/10.3389/feduc.2025.1518602>
- Bhuttah, T.M., Xusheng, Q., Abid, M.N., & Sharma, S. (2024). Enhancing critical thinking and student learning outcomes through innovative pedagogical approaches in higher education: The mediating role of inclusive leadership. *Scientific Reports* , 14 (1), 24362. <https://doi.org/10.1038/s41598-024-75379-0>
- Bozzi, M., Raffaghelli, J.E., & Zani, M. (2021). Peer Learning as a Key Component of Integrated Teaching Methods: Addressing the Complexities of Teaching Physics in Large Classes. *Educational Sciences* , 11 (2). <https://doi.org/10.3390/educsci11020067>
- Castillo, J.F.V., Santiago, L.B., & García, S.M. (2025). Optimizing Physics Learning Through Immersive Virtual Reality: A Study of the Efficacy of Serious Games. *Applied Sciences* , 15 (6). <https://doi.org/10.3390/app15063405>
- Chen, J.-C., & Liu, C.-Y. (2025). Developing Interdisciplinary Practical Learning Activities with the 6E Model to Enhance Students' STEM Knowledge, Learning Motivation, and Creativity. *Journal of Computer-Assisted Learning* , 41 (3), e70031. <https://doi.org/https://doi.org/10.1111/jcal.70031>
- Dahl, J.E., & Mørch, A. (2025). A theoretical and empirical analysis of the tension between

- learning objects and constructivism. *Education and Information Technology* .
<https://doi.org/10.1007/s10639-025-13636-z>
- Errabo, DD, & Ongoco, AA (2024). The effect of an interactive mobile learning module on student engagement and understanding in genetics. *Journal of Research in Innovative Teaching and Learning* , 17 (2), 327–351. <https://doi.org/10.1108/JRIT-01-2024-0023>
- Fatmawati, DA, & Murtinugraha, RE (2024). E-Module Development: Learning Innovation to Improve Students' Understanding of Building Materials Science. *Journal of Engineering Education and Pedagogy* , 2 (1), 16–23. <https://doi.org/10.56855/jeep.v2i1.1034>
- Fütterer, T., Scheiter, K., Cheng, X., & Stürmer, K. (2022). Quality trumps frequency? Investigating students' learning efforts when introducing technology in the classroom. *Contemporary Educational Psychology* , 69 , 102042. <https://doi.org/https://doi.org/10.1016/j.cedpsych.2022.102042>
- Golden, B. (2023). Supporting the development of critical thinking in higher education through the use of structured planning tools. *Irish Educational Studies* , 42 (4), 949–969. <https://doi.org/10.1080/03323315.2023.2258497>
- Guerrero-Zambrano, M., Sanchez-Alvarado, L., Valarezo-Chamba, B., & Lamilla-Rubio, E. (2025). Transforming Physics Teacher Training Through ChatGPT: A Study of Its Usability and Impact. In *Educational Sciences* (Vol. 15, Issue 7). <https://doi.org/10.3390/educsci15070887>
- Halawa, S., Lin, T.-C., & Hsu, Y.-S. (2024). Exploring instructional design in K-12 STEM education: a systematic literature review. *International Journal of STEM Education* , 11 (1), 43. <https://doi.org/10.1186/s40594-024-00503-5>
- Haleem, A., Javaid, M., Qadri, M.A., & Suman, R. (2022). Understanding the role of digital technology in education: A review. *Sustainable Operations and Computers* , 3 , 275–285. <https://doi.org/https://doi.org/10.1016/j.susoc.2022.05.004>
- Hidayati, A., Munasir, M., & Sudiby, E. (2024). Development of a Problem-Based Learning Model (PBM) of Physics Teaching Aids to Improve High School Students' Critical Thinking Skills. *IJORER: International Journal of Current Educational Research* , 5 (1), 77–89. <https://doi.org/10.46245/ijorer.v5i1.496>
- Huang, B., Siu-Yung Jong, M., Tu, Y.-F., Hwang, G.-J., Chai, C.S., & Yi-Chao Jiang, M. (2022). Trends and exemplary practices of STEM teacher professional development programs in K-12 contexts: A systematic review of empirical studies. *Computers & Education* , 189 , 104577. <https://doi.org/https://doi.org/10.1016/j.compedu.2022.104577>
- Intinan, N., & Kuswanto, H. (2023). The Use of Phyphox Applications in Physics Experiments: A Literature Review. *JIPF (Journal of Physics Education)* , 8 (2), 183. <https://doi.org/10.26737/jipf.v8i2.4167>
- Jannah, M., Faelasup, F., Sangatta, S., & Timur, K. (2025). *Conceptual Analysis of Learning Material Design: Principles, Characteristics, and Steps* . 04 (02), 657–666.
- Jeli, & Chandra, AN (2025). Development of a Simple Pyphox-Based Uniform Linear Motion Lab Tool. *Impulse: Journal of Physics Education Research and Innovation* , 4 (2), 107–117. <https://doi.org/10.14421/impulse.2024.42-04>
- Junita, O., Sanlan, S., & Khusnani, A. (2024). Development of a Physics Experiment Guidebook Using Smartphones Assisted by the Phyphox Application. *Journal of Physics Education and Technology* , 10 (1), 29–35. <https://doi.org/10.29303/jpft.v10i1.6679>
- Kerimbayev, N., Umirzakova, Z., Shadiev, R., & Jotsov, V. (2023). Student-centered approach using modern technologies in distance learning: a systematic review of the literature. *Intelligent Learning Environments* , 10 (1), 61. <https://doi.org/10.1186/s40561-023-00280-8>
- Kooloos, JGM, Bergman, EM, Scheffers, MAGP, Schepens-Franke, AN, & Vorstenbosch, MATM (2020). The Effect of Passive and Active Educational Methods Applied in Repetitive Activities on Anatomical Knowledge Retention. *Anatomical Science*

- Education* , 13 (4), 458–466. <https://doi.org/10.1002/ase.1924>
- Kranz, J., Baur, A., & Möller, A. (2023). Learners' challenges in understanding and conducting experiments: a systematic review of the literature. *Studies in Science Education* , 59 (2), 321–367. <https://doi.org/10.1080/03057267.2022.2138151>
- Kumandaş-Öztürk, H., & Ulu-Kalın, Ö. (2025). The Impact of Critical Thinking, Creative Thinking, Metacognitive Thinking, and Empathy Skills on High and Low Academic Achievement of Prospective Teachers. *Journal of Intelligence* , 13 (4). <https://doi.org/10.3390/jintelligence13040050>
- Kwangmuang, P., Jarutkamolpong, S., Sangboonraung, W., & Daungtod, S. (2021). Development of learning innovations to improve higher-order thinking skills for junior high school students in Thailand. *Heliyon* , 7 (6), e07309. <https://doi.org/https://doi.org/10.1016/j.heliyon.2021.e07309>
- Lampropoulos, G., & Kinshuk. (2024). Virtual reality and gamification in education: a systematic review. *Educational Technology Research and Development* , 72 (3), 1691–1785. <https://doi.org/10.1007/s11423-024-10351-3>
- Lestari, S., & Nugraheni, AS (2022). The Effect of Google Classroom in Improving Students' Learning Motivation and Critical Thinking Skills. *AL-ISHLAH: Journal of Education* , 14 (1), 61–70. <https://doi.org/10.35445/alishlah.v14i1.973>
- Loyens, S.M.M., van Meerten, J.E., Schaap, L., & Wijnia, L. (2023). Situating Higher-Order, Critical, and Critical-Analytical Thinking in Problem- and Project-Based Learning Environments: A Systematic Review. *Educational Psychology Review* , 35 (2), 39. <https://doi.org/10.1007/s10648-023-09757-x>
- Major, L., Francis, G.A., & Tsapali, M. (2021). The effectiveness of technology-based personalized learning in low- and middle-income countries: A meta-analysis. *British Journal of Educational Technology* , 52 (5), 1935–1964. <https://doi.org/https://doi.org/10.1111/bjet.13116>
- Manggul, FCM, & Pratiwi, HY (2025). *Integration of Wayang Kulit Ethnoscience in Guided Inquiry E-Module to Strengthen Critical Thinking in Learning Light and Optical Tools* . 8 (1), 220–233.
- Manlapig, E. (2024). Enhancing Students' Physics Learning Motivation Through Interactive Physics Education Technology (PhET) Simulations. *Schrödinger: Journal of Physics Education* , 5 (3), 88–97. <https://doi.org/10.37251/sjpe.v5i3.1025>
- Margot, KC, & Kettler, T. (2019). Teachers' perceptions of integration and STEM education: a systematic literature review. *International Journal of STEM Education* , 6 (1), 2. <https://doi.org/10.1186/s40594-018-0151-2>
- Maziyah, KN, & Hidayati, FH (2022). Development of an e-module with a STEM approach to facilitate students' critical thinking skills in trigonometry material. *Jurnal Tadris Matematika* , 5 (2), 241–256.
- Mena-Guacas, A.F., López-Catalán, L., Bernal-Bravo, C., & Ballesteros-Regaña, C. (2025). Transforming education through new technologies: a critical review of scientific impact on learning. *Educational Sciences* , 15 (3). <https://doi.org/10.3390/educsci15030368>
- Mhlongo, S., Mbatha, K., Ramatsetse, B., & Dlamini, R. (2023). Challenges, opportunities, and prospects for the adoption and use of intelligent digital technologies in learning environments: An iterative review. *Heliyon* , 9 (6), e16348. <https://doi.org/https://doi.org/10.1016/j.heliyon.2023.e16348>
- Monib, W.K., Qazi, A., & Apong, R.A. (2025). Microlearning beyond boundaries: A systematic review and a new framework for improving learning outcomes. *Heliyon* , 11 (2), e41413. <https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e41413>
- Morris, D.L. (2025). Rethinking Science Education Practice: Shifting from Investigation-Centered to Comprehensive, Inquiry-Based Learning. *Education Sciences* , 15 (1).

- <https://doi.org/10.3390/educsci15010073>
- Mulyono, Y. (2018). Critical Thinking Skills of Physics Education Students Yatin Mulyono. *Science, Engineering, Education, and Development Studies* , 2 (1), 65–76.
- Nilimaa, J. (2023). A New Testing Approach for Real-World Creativity and Problem-Solving Skills in Mathematics. *Trends in Higher Education* , 2 (3), 477–495. <https://doi.org/10.3390/higheredu2030028>
- Nuriyah, D., Sutarto, & Prihatin, J. (2020). Development of a STEM-CP-based environmental change textbook to improve problem-solving skills in high school biology learning. *Journal of Physics: Conference Series* , 1563 (1). <https://doi.org/10.1088/1742-6596/1563/1/012054>
- Pansri, B., Thongchotchat, V., Kurashige, K., Watanabe, S., & Sato, K. (2025). Self-Directed Learning in Action: Empowering the Physics Curriculum with ICT and Practical Approaches. *Technology, Knowledge, and Learning* . <https://doi.org/10.1007/s10758-025-09854-6>
- Pardo, D.C.G. (2017). Self-Reported Physics Difficulty as a Predictor of Student Achievement. *International Journal of Scientific & Engineering Research* , 8 (3), 1134–1138. <https://doi.org/10.14299/ijser.2017.03.005>
- Pollarolo, E., Størksen, I., Skarstein, T.H., & Kucirkova, N. (2023). Children's critical thinking skills: Norwegian early childhood educators' perceptions. *European Journal of Early Childhood Education Research* , 31 (2), 259–271. <https://doi.org/10.1080/1350293X.2022.2081349>
- Raharja, EP, Irianti, M., Lestari, RD, & Kabes, Y. (2024). Development of a smartphone sensor-based physics experiment module in the field of mechanics for high school students. *Journal of Physics Education Research and Studies* , 11 (1), 1–10. <https://doi.org/10.12928/jrpkpf.v11i1.634>
- Rahma, VN, Rustana, CE, & Umiatin. (2021). Development of Electronic Physics Learning Module with Phet Simulation (Physical Education and Technology) on Elasticity and Hooke's Law Material in Grade XI Senior High School. *Journal of Physics: Conference Series* , 2019 (1), 12047. <https://doi.org/10.1088/1742-6596/2019/1/012047>
- Rambe, A., Darwis, M., A., Abidan, A.A., & Sahor Bangun Ritonga, M. (2023). Development of Physics Learning Device Modules Based on Inquiry Models with Concept Map Techniques to Improve Student Learning Outcomes. *KnE Social Sciences* , 2023 , 125–133. <https://doi.org/10.18502/kss.v8i4.12891>
- Ramdhani, EP, Khoirunnisa, F., & Siregar, NAN (2020). Integrated multi-representation electronic effectiveness module on chemical bonding material. *Journal of Research and Technology* , 6 (1), 162–167.
- Reddy, MVB, & Panacharoensawad, B. (2017). Students' Problem-Solving Difficulties and Their Implications in Physics: An Empirical Study of Influencing Factors. *Journal of Education and Practice* , 8 (14), 59–62. www.iiste.org
- Redish, E.F., & Burciaga, J.R. (2004). Teaching Physics with Physics Suite. *American Journal of Physics* , 72 (3), 414. <https://doi.org/10.1119/1.1691552>
- Rezai, A., Ahmadi, R., Ashkani, P., & Hosseini, G.H. (2025). Applying an active learning approach to increase motivation, reduce anxiety, and shape positive attitudes: A case study of EFL learners. *Acta Psychologica* , 253 , 104704. <https://doi.org/https://doi.org/10.1016/j.actpsy.2025.104704>
- Rivas, S.F., Saiz, C., & Ossa, C. (2022). Metacognitive Strategies and the Development of Critical Thinking in Higher Education. *Frontiers in Psychology* , 13 , 913219. <https://doi.org/10.3389/fpsyg.2022.913219>
- Rizki, IA, Mirsa, FR, Islamiyah, AN, Saputri, AD, Ramadani, R., & Habibulloh, M. (2025). Virtual physics simulation enhanced with ethnoscience and augmented reality with inquiry learning: Its impact on students' creativity and motivation. *Thinking Skills and*

- Creativity* , 57 , 101846. <https://doi.org/https://doi.org/10.1016/j.tsc.2025.101846>
- Schuster, D., Cobern, W.W., Adams, B.A.J., Undreiu, A., & Pleasants, B. (2018). Learning Core Disciplinary Ideas: A Comparison of the Efficacy of Two Different Modes of Science Learning. *Research in Science Education* , 48 (2), 389–435. <https://doi.org/10.1007/s11165-016-9573-3>
- Siller, HS, & Ahmad, S. (2024). Analyzing the impact of a collaborative learning approach on sixth-grade students' mathematics achievement and attitudes. *Eurasia Journal of Mathematics, Science and Technology Education* , 20 (2). <https://doi.org/10.29333/ejmste/14153>
- Simonovic, B., Vione, K., Stupple, E., & Doherty, A. (2023). It's not what you think, it's how you think: A critical thinking intervention improves argumentation, analytical thinking, and metacognitive sensitivity. *Thinking Skills and Creativity* , 49 , 101362. <https://doi.org/https://doi.org/10.1016/j.tsc.2023.101362>
- Sinaga, CE, Silaban, YE, Naibaho, KS, & Simamora, RO (2025). *Analysis of Problems in Physics Learning, Evaluation, and Assessment and Solutions to Overcome Them: A Literature Review* . 10 (3), 167–186.
- Soriano-Sánchez, JG (2025). The Impact of ICT on Elementary School Students' Science Learning in Support of Diversity: A Meta-Analysis. *Educational Sciences* , 15 (6). <https://doi.org/10.3390/educsci15060690>
- Syukri, M., Herliana, F., Aksa, Y., Mulyati, D., Ngadimin, N., Artika, W., & Iswadi, I. (2024). Flipbook E-Module Based on STEM Approach on Renewable Energy Topic as Physics Learning Media. *Journal of Physics: Conference Series* , 2866 (1). <https://doi.org/10.1088/1742-6596/2866/1/012116>
- Tartiyoso, S. (2025). Development of STEM-Based E-Modules to Improve Science Literacy and Science Process Skills in Chemistry Learning. *Journal of Science Education Research* , 11 (4), 1124–1132. <https://doi.org/10.29303/jppipa.v11i4.10844>
- Thiagarajan, S., Semmel, D.S., & Semmel, M.I. (1974). *Instructional development for the training of teachers of children with special needs: A sourcebook* . Indiana University.
- Timotheou, S., Miliou, O., Dimitriadis, Y., Sobrino, S.V., Giannoutsou, N., Cachia, R., Monés, A.M., & Ioannou, A. (2023). The impact of digital technologies on education and factors influencing schools' digital capacity and transformation: A literature review. *Education and Information Technology* , 28 (6), 6695–6726. <https://doi.org/10.1007/s10639-022-11431-8>
- Wardani, HK, Pramartaningthias, EK, Rohman, T., & Alimin, A. (2025). Development of Interactive E-Modules to Cultivate EFL Students' Critical Thinking in Essay Writing. *Jurnal Kependidikan: Jurnal Hasil Penelitian dan Kajian Kependidikan dalam Lapangan Pendidikan* , 11 (1), 190. <https://doi.org/10.33394/jk.v11i1.13577>
- Yani, NLS, Rusdarti, & Oktarina, N. (2024). STEM-Based E-Modules to Improve Students' Critical Thinking Skills in Economics Learning. *Journal of Thinking Skills and Creativity* , 7 (1), 115–121. <https://doi.org/10.23887/tscj.v7i1.73518>
- Yannier, N., Hudson, S.E., & Koedinger, K.R. (2020). Active Learning Beyond Hands-On: A Mixed Reality AI System to Support STEM Education. *International Journal of Artificial Intelligence in Education* , 30 (1), 74–96. <https://doi.org/10.1007/s40593-020-00194-3>
- Yaseen, H., Mohammad, A.S., Ashal, N., Abusaimh, H., Ali, A., & Sharabati, A.-A.A. (2025). Impact of Adaptive Learning Technology, Personalized Feedback, and Interactive AI Tools on Student Engagement: The Moderating Role of Digital Literacy. *Sustainability* , 17 (3). <https://doi.org/10.3390/su17031133>
- Yilmaz, M.M., Bekirler, A., & Sigirtmac, A.D. (2024). Stimulating a Passion for Science from an Early Age: The Impact of Hands-On Activities on Children's Motivation. *ECNU Review of Education* , 7 (4), 1033–1053. <https://doi.org/10.1177/20965311241265413>