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Development of STEM (Science, Technology, Engineering, and Mathematics) Based E-Modules to Improve Student Collaboration Skills

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Abstract: This study aims to develop a STEM-based physics e-module as innovative teaching material to improve students' collaboration skills. The research used a Research and Development (R&D) method with a 4D model consisting of Define, Design, Develop, and Disseminate stages. The research subjects included three expert validators, ten physics teachers as practitioners, and thirty students from class X.B of SMA Muhammadiyah 1 Unismuh Makassar. Data were collected using validation sheets, practitioner questionnaires, and collaboration skill tests based on the Situational Judgment Test (SJT), which measured four indicators: cooperation, communication, problem solving, and responsibility. The results showed that the STEM-based e-module met the criteria of validity, practicality, and effectiveness. The validation results obtained an average Aiken's V index of 0.93 (valid category). Practitioner assessments showed an average practicality score of 96.6% (very practical), while the effectiveness test using N-Gain analysis reached 0.84 or 84% (high category). These findings indicate that the developed STEM-based e-module is valid, practical, and effective for improving students' collaboration skills in physics learning.

Keywords: Collaboration skills; E-module; STEM

Introduction

The rapid development of science and technology in the 21st century has brought major changes to various aspects of human life, including education. The world is now shifting from the industrial era to the knowledge era, which demands high-level thinking skills, flexibility, and rapid adaptation to global changes (Sole & Anggraeni, 2018). In this context, education is no longer solely oriented toward the mastery of conceptual knowledge, but also toward the formation of 21st-century skills, such as critical thinking, creativity, communication, and collaboration. These skills are essential for students to be able to deal with the complexity of real-world problems in a collaborative and innovative manner.

Collaboration is one of the essential competencies that must be developed early, as the modern workplace requires individuals to work effectively in teams across disciplines and cultures. According to Lelasari et al. (2017), collaboration is the ability to interact dialogically in exchanging ideas, opinions, and thoughts to achieve common goals. Richards (2009) emphasize that collaboration is mutually beneficial and oriented toward collective problem-solving, while Greenstein (2011) adds that collaboration skills include the ability to participate actively, work productively, be responsible, and appreciate the contributions of others. Based on these definitions, collaboration skills can be described as

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the ability to work effectively with others through communication, shared problem-solving, and accountability for individual roles in achieving group goals. However, field observations show that students' collaboration skills in Indonesia, particularly in physics learning, remain low. Observations at SMA Muhammadiyah 1 Unismuh Makassar revealed that most students still tend to work individually, lack group communication, and are unable to share responsibilities evenly.

Physics, as a fundamental science, plays a strategic role in developing scientific reasoning and supporting technological innovation. Physics learning should not only emphasize conceptual understanding but also encourage collaborative practices through experiments, discussions, and problem-solving activities (Abbas & Hidayat, 2018). One of the most relevant approaches to achieving this is the Science, Technology, Engineering, and Mathematics (STEM) approach. STEM integrates four disciplines in a real-world context, providing students with opportunities to explore scientific and technological phenomena meaningfully. Afriana et al. (2016) state that STEM-based learning can increase students' interest and problem-solving skills by positioning them as active participants in contextual and project-based learning. Rahmiza et al. (2015) further explains that STEM education fosters higher-order thinking through authentic and challenging experiences that stimulate curiosity and creativity.

Integrating STEM into physics education is considered effective in strengthening students' collaboration skills. Tseng et al. (2013) highlight that STEM-based project activities encourage students to interact actively, support one another, and construct solutions collaboratively. Through these inquiry-oriented experiences, students develop teamwork, social responsibility, and scientific communication skills. However, despite its potential, the implementation of STEM-based learning in Indonesian schools remains limited due to the scarcity of integrated and technology-oriented teaching materials (Herak & Lamanepa, 2019; Pratiwi & Ramli, 2019). A recent systematic review by Lafifa et al. (2023) further confirmed that the STEM approach significantly improves students' 21st-century skills particularly collaboration, creativity, communication, and critical thinking yet its classroom integration in Indonesia is still relatively limited.

One promising innovation to address this challenge is the development of STEM-based e-modules. E-modules are digital teaching materials designed systematically and interactively, accessible through various devices such as computers, tablets, or smartphones (Majid, 2020). They integrate multiple media—text, images, videos, and simulations—to make learning more engaging and flexible (Herawati & Muhtadi, 2018). Moreover, STEM-based e-modules foster collaborative learning through project tasks and group discussions that promote communication, teamwork, and responsibility (Ngabekti et al., 2019; Tipani et al., 2019). Through the integration of science, technology, engineering, and mathematics, students not only understand physical concepts but also relate them to real-life contexts through hands-on experimentation and design projects (Pangesti et al., 2017).

Based on the results of a survey by the Indonesian Internet Service Providers Association (APJI, 2023) released in early 2024, internet penetration in Indonesia reached 79.5% of the total population, equivalent to approximately 221 million internet users, showing strong readiness for digital-based learning implementation. SMA Muhammadiyah 1 Unismuh Makassar already has adequate infrastructure such as computer laboratories, Wi-Fi in every classroom, and widespread ownership of digital devices among students. This condition presents an opportunity to implement digital-based STEM learning effectively, particularly through interactive e-modules that promote collaboration and problem-solving.

Based on these considerations, this study aims to develop and validate a STEM-based e-module for physics learning focused on renewable energy topics to improve students' collaboration skills. The selection of energy-related material in this study is also supported by previous research showing that energy contexts are particularly effective for implementing STEM-based learning. Büyükdede & Tanel (2019) found that STEM activities designed around work–energy topics significantly improved students' academic achievement and engagement by connecting theoretical physics concepts to real-world applications. Building on this evidence, the present study integrates the topic of renewable energy into a digital STEM-based e-module to strengthen collaboration skills. The novelty of this study lies in the integration of collaborative skill assessment through the Situational Judgment Test (SJT) within a STEM-based e-module an aspect that remains rarely explored in previous research in Indonesia. This study is expected to contribute theoretically to the field of STEM education and practically to provide teachers with innovative, technology-supported teaching materials that promote collaboration as one of the core competencies of 21st-century learning.

Method

Research Types and Designs

This research is a research and development study that aims to produce a product in the form of a Science, Technology, Engineering, and Mathematics (STEM)-based e-module and to test its validity, practicality, and effectiveness in improving students' collaboration skills. The development model used is the 4-D Model, which consists of four main stages: Define, Design, Develop, and Disseminate. This approach was chosen because it can systematically produce learning products that are tested for quality both theoretically and empirically.

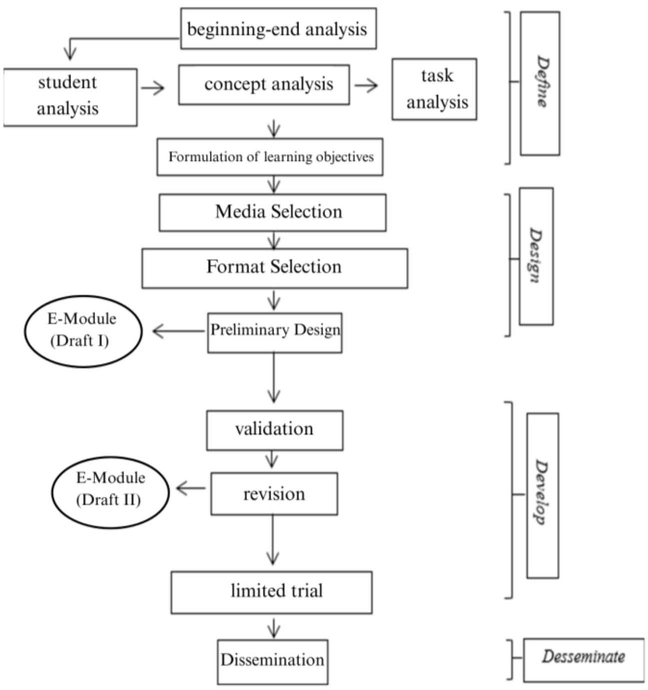

Figure 1. 4D model development procedure

Define Stage

The define stage aims to determine learning needs and collect relevant information for the development of STEM-based e-modules. At this stage, a series of analyses are carried out, including preliminary analysis, student analysis, concept analysis, task analysis, and learning objective analysis.

The initial analysis was conducted to identify problems in the physics learning process at SMA Muhammadiyah 1 Unismuh Makassar. Based on the results of observations and interviews with physics teachers, it was found that learning resources were still limited to one textbook and simple printed modules that focused on individual activities. Learning had not optimally developed students' collaboration skills, even though this skill is one of the important competencies of the 21st century. In addition, the results of observations showed that the school had supporting facilities such as computer laboratories and Wi-Fi networks in each classroom, so that in terms of infrastructure, it was ready for the implementation of digital-based teaching materials. Based on these conditions, the development of STEM-based e-modules was seen as a relevant solution to create more interactive, collaborative, and contextual learning.

Furthermore, an analysis of the students was conducted to determine the characteristics of 10th grade students, who are on average 15–16 years old and are in the formal operational stage according to Piaget's theory. At this stage, students are capable of abstract thinking and logical reasoning, but observations show that these abilities have not been optimally developed. Collaboration skills are still relatively low, characterized by a tendency for students to work individually, uneven group communication, and a lack of shared responsibility. However, almost all students have digital devices such as smartphones or laptops, which represent a great potential for supporting learning using STEM-based e-modules.

Concept analysis aims to determine teaching materials that are relevant to the development of collaboration skills. Based on the results of the curriculum review, the material selected is Renewable Energy because it is closely related to everyday life and allows for the application of the STEM approach. This material provides opportunities for students to relate science, technology, engineering, and mathematics concepts in real contexts, such as the use of solar, wind, and water energy. The e-modules developed are aimed at fostering critical thinking skills while improving collaborative skills through exploration, experimentation, and group projects.

Task analysis is conducted to design learning activities in accordance with the Learning Outcomes (CP) and Learning Objectives (TP) of the Merdeka Curriculum. Each task is designed to encourage students to think and work collaboratively. For example, activities include identifying forms of energy around us, the "Mapping Energy in Our Homes" project, simulating the law of conservation of energy, and creating simple prototypes such as solar-powered fans. These activities are designed to strengthen students' abilities to work together, communicate, solve problems, and take responsibility for group results.

Finally, learning objectives are analyzed to formulate the goals to be achieved through STEM-based e-modules. Learning objectives focus not only on cognitive aspects but also on developing students' collaborative skills. Thus, STEM-based renewable energy learning is expected to not only improve conceptual understanding but also foster attitudes of cooperation, effective communication, responsibility, and problem-solving skills within groups.

Design Stage

This stage includes the selection of media, format, and initial product design. The e-module is designed using the Canva application, with a structure consisting of an introduction, learning activities, evaluation, glossary, and bibliography. The learning activities are developed to foster students' collaboration skills through activities such as Bincang Bangku, KolaborAksi, Tantangan Cerdas, and Did You Know? which combine elements of science, technology, engineering, and mathematics in the context of renewable energy.

Develop Stage

The development stage aimed to produce a STEM-based physics e-module suitable for enhancing students' collaboration skills. Three main activities were carried out during this stage: instrument and product validation, e-module design revision, and limited trials.

During the validation stage, three types of validation were conducted by three expert validators, namely validation of the STEM-based physics e-module, validation of the teacher response questionnaire, and validation of the student collaboration skills test instrument. Based on the results of the experts' assessments, feedback, and suggestions, revisions were made to improve the quality and feasibility of the STEM-based e-module.

After the expert validation process was completed and revisions were made, the improved STEM-based physics e-module was tested on a limited scale. The limited trial involved 30 students from class X.B of SMA Muhammadiyah 1 Unismuh Makassar and aimed to determine the effectiveness of the e-module in the learning process as well as to assess the improvement in students' collaboration skills after its implementation.

Disseminate Stage

After completing the limited field trial, the next step was the dissemination of the STEM-based e-module. In this study, dissemination was conducted in a limited scope involving physics teachers from five schools in Makassar City, namely SMA Muhammadiyah 1 Unismuh Makassar, SMAS YP PGRI 3 Makassar, SMKN 10 Makassar, SMAS Mandiri Makassar, and SMAN 17 Makassar. A total of ten physics teachers participated in this dissemination activity.

The purpose of this stage was to introduce and obtain evaluations from physics practitioners to determine the practicality level and potential applicability of the STEM-based e-module in improving students' collaboration skills. The evaluation was conducted using a validated questionnaire instrument, and the feedback obtained was used to analyze the practicality and potential adoption of the developed e-module in other schools.

Research Instruments

The research instruments used consisted of three types, namely a STEM-based e-module validation sheet filled out by experts to assess the suitability of the content, presentation, language, and graphics; a practitioner assessment questionnaire used to assess the practicality of the e-module in physics learning; and a collaboration skills test covering four main indicators, namely cooperation, communication, problem solving, and responsibility, used to measure the effectiveness of the e-module in improving students' collaborative skills.

The selection of these indicators was based on a synthesis of several theoretical frameworks proposed by Roschelle & Teasley (1995), Hull et al. (2009), Brownell et al. (1997), and Greenstein (2011). A comparative review of these studies indicates that these four indicators most comprehensively represent collaborative behavior in STEM-based learning environments.

The cooperation indicator reflects students' ability to actively contribute to group activities, clearly divide tasks, and assist peers who experience difficulties. The communication indicator represents students' capacity to exchange ideas and express opinions effectively within the group. The problem-solving indicator emphasizes students' collective ability to identify and overcome challenges collaboratively. The responsibility indicator reflects individual awareness and commitment to fulfilling assigned roles and completing group tasks thoroughly.

These four indicators are interrelated and mutually reinforcing. Effective communication strengthens cooperation; individual responsibility supports the group's problem-solving process; and together, they form the foundation for assessing students' collaborative competence in STEM learning contexts.

Table 1. Comparison of collaboration skill indicators according to expert

Roschelle & Teasley (1995)	Hull et al. (2009)	Brownell et al. (1997)	Greenstein (2011)	Conclusion (This Study)
Reciprocal involvement of group members	Social interaction	Common goals	Active participation	Cooperation
Coordinated efforts	Cooperation among members	Commitment to collaborate	Productive work	Communication
Shared problem-solving goals	Positive group interaction	Trust and responsibility	Responsibility	Problem solving
–	–	Sharing duties and accountability	Flexibility and mutual respect	Responsibility

Trial Subjects

The test subjects in this study were students of class X.B at SMA Muhammadiyah 1 Unismuh Makassar during the 2024/2025 academic year. A total of 30 students participated in the product testing to evaluate the effectiveness of the STEM-based physics e-module. The study employed a one-group pretest–posttest design, as illustrated in the following figure.

$$O_1 \quad X \quad O_2$$

Figure 2. One-group pretest-posttest design mode

In this design, students were given a pretest before using the e-module and a posttest after learning based on the Situational Judgment Test (SJT). The SJT was chosen because it is suitable for evaluating non-cognitive competencies such as teamwork, communication, responsibility, and problem-solving through contextual scenarios that simulate real-life learning situations. According to a literature review by Muktamiroh et al. (2021), SJT is effective for assessing non-cognitive competencies in the context of education and training, including collaboration skills. This perspective is consistent with Lievens & Motowidlo (2016), who emphasized that SJT demonstrates strong construct validity for assessing collaborative behavior and social responsibility because it involves evaluating individuals' judgments and actions in complex social contexts. Similarly, McDaniel et al. (2007) stated that SJTs capture individual differences in teamwork, communication, and ethical decision-making abilities within realistic educational or professional environments. Therefore, the use of SJT in this study is considered an authentic and contextually relevant instrument for assessing students' collaboration skills comprehensively.

The learning process used the Project Based Learning (PjBL) model integrated into the e-module, with the following stages: problem orientation, project planning, schedule preparation, implementation, presentation of results, and evaluation-reflection. The PjBL model emphasizes learning through projects that promote teamwork, creativity, and reflective problem-solving. Millen & Supahar (2023) confirmed that implementing a PjBL-STEM model in physics learning effectively improved students' creative thinking skills and learning motivation, with effectiveness levels reaching 85 and 68%, respectively. This finding reinforces that combining the PjBL model with STEM-based instruction can develop not only conceptual understanding but also students' engagement, innovation, and collaborative learning skills key competencies for 21st-century education. One of the project activities, themed "Energy-Efficient Generation for a Sustainable Future," was designed to foster cooperation, communication, responsibility, and problem-solving skills.

Data Analysis

Analysis of E-Module Validity Data

The validity of the e-module was analyzed using Aiken's V formula to determine the level of agreement between validators.

$$V = \frac{\sum s}{(n-1)} \tag{1}$$

Explanation :

V = index of rater agreement on the validity of an item

s = The score assigned by each rater minus the lowest score in the category used (s = r –Io, where r is the rater's category score and Io is the lowest score assigned)

r = rater fixed score

Io = Lowest Score

n = Number of raters

c = Number of categories selected by the raters

Aiken's test requirement: after calculation, if V ≥ 0.4, then the expert agreement index is considered valid (Retnawati, 2016).

Analysis of Practitioner Response

The practicality of the e-module was analyzed using the percentage score from the responses of physics teachers:

$$PRS = \frac{\sum A}{\sum B} \times 100\% \tag{2}$$

Explanation

PRS = Percentage of practitioners who responded to the categories stated in the instrument

∑A = Total score obtained for each category stated in the questionnaire

∑B = The maximum score for each category that responded to the questionnaire

with interpretation criteria (Riduwan, 2018): 81–100% (very practical), 61–80% (practical), 41–60% (fairly practical), 21–40% (less practical), and ≤ 20% (impractical).

Analysis of the Effectiveness of E-Module

The effectiveness of the e-module is determined based on the increase in the pretest and posttest scores of students using the N-Gain Score analysis, with the following formula:

$$\text{Gain Score} = \frac{\text{Posttest Score} - \text{Pretest Score}}{\text{Maximum Score} - \text{Pretest Score}} \times 100\% \quad (3)$$

The criteria for improving collaboration skills are obtained in accordance with Table 1.

Table 2. Normalized gain criteria

Limits	Category
$0.70 < g \leq 1.00$	High
$0.30 < X \leq 0.70$	Medium
$0.00 < X \leq 0.30$	Low

Source: Sundayana (2014)

Furthermore, the effectiveness of STEM-based e-module usage is categorized based on the interpretation of the N-gain score obtained and then converted into a percentage (%) as shown in Table 3.

Table 3. Categorization of N-Gain score effectiveness interpretation

Persentage (%)	Category
> 76	Effective
56–75	Fairly Effective
40–55	Less Effective
< 40	Not Effective

Sumber: Widoyoko (2009)

Result and Discussion

This study aimed to develop a STEM-based physics e-module that focuses on improving the collaboration skills of high school students. The development process was carried out using the 4D model (Define, Design, Develop, and Disseminate), which included the stages of needs analysis, product design, expert validation, practicality testing, and effectiveness testing conducted with class X.B students at SMA Muhammadiyah 1 Unismuh Makassar. The research results are presented based on three main focuses in accordance with the problem formulation, namely the validity, practicality, and effectiveness of the STEM-based e-module.

Validity of STEM-Based E-Modules

The validity of STEM-based e-modules was obtained through the assessment of three expert validators on four main aspects, namely content, presentation, language, and graphics, using Aiken's V index. The results of the analysis showed that all aspects had high validity scores.

The average overall validity index was 0.93, which is classified as highly valid. This means that the developed e-module has met the standards of content, presentation, language, and graphics. The validators provided input to enrich the examples of technology application in everyday contexts, so that the Technology aspect in STEM is more contextual.

This finding is in line with the opinion of Borg & Gall (1983), who emphasized that the validation of educational development products must ensure consistency between learning objectives, content, and the context of application. This e-module has fulfilled this principle because the content and activities designed are in line with physics competencies and the learning outcomes of the independent curriculum.

Table 4. Validation Results of STEM-Based E-Module Content

Aspect	Obtained Score	Ideal Score	Validation Index	Category
Content suitability	152	168	0.87	valid
Presentation suitability	102	108	0.93	valid
Language suitability	115	120	0.94	valid
Graphics suitability	140	144	0.96	valid
Average			0.93	valid

Source: processed primary data (2025)

The content is considered highly relevant because the e-module not only presents theory about renewable energy, but also links it to real-world applications in everyday life, such as the use of solar and wind energy. The integration of the four dimensions of STEM is clearly evident in each learning activity. The Science aspect is reflected through activities analyzing energy concepts and their application to natural phenomena, while the Technology aspect is manifested through the introduction of the use of physical technologies such as dynamos and energy conversion devices. Furthermore, the Engineering aspect appears in the "KolaborAksi" project activity, which guides students to design simple energy-saving devices as a form of engineering principle application. Meanwhile, the Mathematics aspect is seen in the activities of calculating energy efficiency and analyzing the data from experiments conducted by students. The integration of these four aspects makes this STEM-based e-module not only informative but also applicable and contextual in building a meaningful understanding of physics concepts.

This integration shows that the e-module has fulfilled the principles of integrative learning as stated by Rochmad (2022) and Afriana et al. (2016) that good STEM learning must present real contexts and foster interdisciplinary interactions.

The linguistic aspect of the e-module is also valid due to the use of communicative, clear language that is appropriate for the developmental level of the students. The language in the e-module is considered capable of motivating students to actively think, ask questions, and discuss in accordance with the characteristics of 21st-century learning, which demands two-way communication. The graphic aspect also received the highest score because the layout, color selection, font type, and illustrations support the readability and visual comfort of the students aligns with the findings of Yunita et al. (2024), who confirmed that the Canva-based STEM e-module provides an appealing and interactive interface that enhances students' interest and engagement in learning physics.

Figure 3. Display of the STEM-based physics e-module on renewable energy developed using canva

Thus, the validity results show that the developed STEM-based e-module is very suitable for use in physics learning, in terms of content, presentation, language, and graphics. These results are consistent with the research by Syahiddah et al. (2021) and Ngabekti et al. (2019), which states that systematically structured STEM-based e-modules can improve the quality of science learning and facilitate collaboration. Furthermore, Aditia et al. (2024) found that Ethno-STEM-based science e-modules achieved "very valid" results in both material and media aspects, with practicality scores of 80 for students and 85.5 for teachers.

The Practicality of STEM-Based E-Modules

The practicality aspect aims to determine the extent to which the e-module is easy to use by teachers and students in learning activities. The assessment was carried out by 10 physics teachers in Makassar City, including 1 teacher from SMA Muhammadiyah 1 Unismuh Makassar. The results of the analysis show an average assessment score of 96.6%, which is categorized as very practical.

The assessment shows that the e-module is easy to implement in physics learning. Teachers assessed that the content of the e-module was in line with learning outcomes, the steps of the activities were systematically arranged, and the media used was easily accessible. Interactive components such as QR codes, PhET simulation videos, and digital worksheets were considered capable of increasing student engagement in an active and collaborative manner.

In terms of design, teachers assessed that the e-module was visually appealing, the language was easy to understand, and the instructions for use were clear. High practicality was also demonstrated by the ability of teachers and students to access the e-module without the need for additional training. This shows that the product developed is not only functional but also efficient in its use in the digital classroom.

Table 5. Percentage of practitioners' assessment of stem-based e-modules

Indicator	Score Obtained	Ideal Score	Score Percentage (%)	Category
E-Module Content Coverage	116	120	96.7	Very Practical
E-Modules Focused on Collaboration Skills	154	160	96.2	Very Practical
Advantages of E-Modules	235	240	97.9	Very Practical
Practicality of E-Modules	191	200	95.5	Very Practical
Average			96.6	Very Practical

Source: processed primary data (2025)

This practicality supports Trianto (2015) view that effective teaching materials must be adaptive to user needs and the learning environment. In addition, the integration of Project Based Learning (PjBL) syntax in the e-module makes learning activities more focused and collaborative. Each stage, from problem identification, planning, project implementation, to evaluation, trains students to work together, communicate ideas, and share responsibilities.

Input from practitioners was minimal, consisting mainly of suggestions to include a greater variety of sample questions and to make slight improvements to the concept map flow for better systematic organization. Overall, these practicality results support the findings of Mustafa et al. (2020), who reported that STEM-based e-modules supported by interactive media possess a high level of applicability and effectively facilitate collaborative learning. This result is also consistent with Masykur et al. (2024), who reported a teacher practicality level of 81%, indicating that STEM-based e-modules are highly feasible and easy to use in classroom learning. Similarly, Zahra et al. (2025) found that STEM–PjBL–based e-modules achieved high practicality and received positive responses from both teachers and students.

Effectiveness of STEM-Based E-Modules

The effectiveness of the e-module was measured through improvements in students' collaboration skills using a Situational Judgment Test (SJT) consisting of 24 questions. The test was administered twice, before (pre-test) and after (post-test) learning using the e-module. The results of the analysis of students' collaboration skills before and after using the STEM-based e-module can be seen in Table 6.

The pretest and posttest results are shown in Figure 4. The results of the N-gain Score analysis can be seen in Table 7.

Of the 30 students who were the subjects of the study, the average N-Gain score was 0.84, which is in the high category, with an N-Gain percentage of 84%, indicating that learning using STEM-based e-modules is effective in improving collaboration skills.

Table 6. Results of the analysis of student collaboration skills test scores

Parameter	Pretest Score	Postest Score
Maximum Ideal Score	96	96
Minimum Ideal Score	0	0
Maximum Empirical Score	90	96
Minimum Empirical Score	39	75
Average Score	74.1	91.6

Source: processed primary data (2025)

This improvement was reflected in changes in student behavior during learning. Students were more active in discussions, worked in groups, and contributed to projects such as energy-saving campaigns (KolaborAksi). Project activities enabled them to integrate science and technology concepts with critical thinking and teamwork skills.

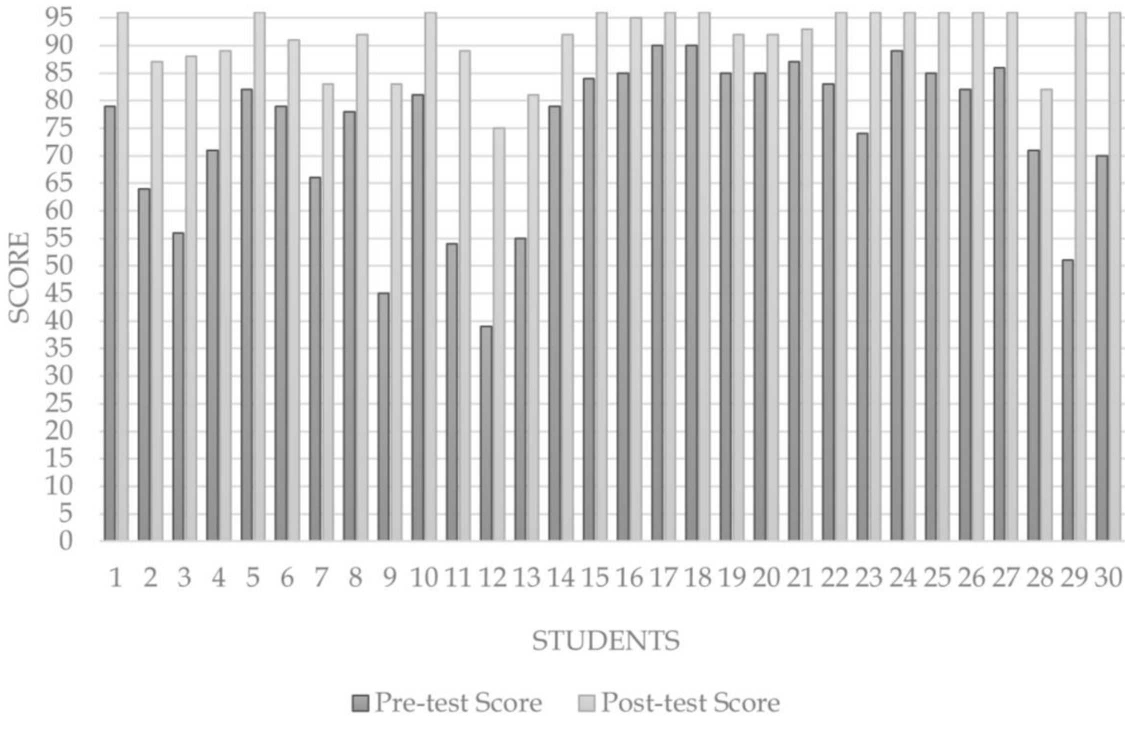

Figure 4. Pre-test and Post-test of Student Collaboration Skills (Source: processed primary data, 2025)

Table 7. Analysis of normalized gain (N-Gain) in collaboration skills of grade X.B students at SMA Muhammadiyah 1 Unismuh Makassar

Limits	Category	Number of Student	Average N-Gain	Average N-Gain (%)
$g \geq 0.7$	High			
$0.3 \leq g < 0.7$	Medium	30	0.84	84
$g < 0.3$	Low			

Source: processed primary data (2025)

These results are in line with Greenstein (2011) research, which states that project-based learning can develop collaborative skills through social interaction, effective communication, and group responsibility. Similarly, Asrizal et al. (2022) found that physics electronic teaching materials integrated with STEM significantly improve students' 21st-century skills particularly critical thinking, creativity, and communication while also promoting interactive and collaborative learning environments. Asrizal et al. (2024) further confirmed that the STEM-Smart Physics E-Module successfully enhanced students' conceptual understanding as well as their 4C skills, including communication and collaboration, through the integration of digital technology in STEM-based learning. The alignment of these findings reinforces that technology-enhanced STEM e-modules can effectively foster both cognitive and collaborative competencies.

These findings also support Suryadi's view in Asriani et al. (2025) that teaching materials are considered effective if they can foster student activity and positive responses during learning. The success of improving collaboration is also reinforced by the contextual characteristics of the e-module. By linking the concept of renewable energy to real life, students not only learn physics concepts but also understand their social and ecological relevance. This is in line with Rochmad (2022) theory, which emphasizes that integrative approaches such as STEM help students think systemically, reflectively, and cooperatively.

Thus, the STEM-based e-module has proven to be valid, practical, and effective as innovative teaching material that can improve students' collaboration skills in physics learning. Learning, which was previously individualistic, has become more interactive, participatory, and teamwork-oriented.

Conclusion

The development of the STEM-based physics e-module aimed at improving students' collaboration skills resulted in three main findings. The expert validation showed an average Aiken's V index of 0.93, indicating that the e-module was valid and suitable for use in learning. The practicality assessment by ten physics teachers obtained an average score of 96.6%, categorized as very practical. The effectiveness test using the N-Gain analysis produced an average score of 0.84 (high category), demonstrating that the e-module was effective in enhancing students' collaboration skills. Therefore, the STEM-based physics e-module can be considered valid, practical, and effective as an innovative learning medium for supporting collaborative physics learning in high schools.

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Author Contributions

N: Conceptualization, methodology, writing original draft preparation, formal analysis, investigation, visualization, writing—review and editing; M.A. & K.: Validation, supervision, and resources. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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