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Development of E-Physics Teaching Material Integrated with Augmented Reality and Ethno-Meaningful Learning to Promote Students' 21st Century Skills

Rima Melani Putri[1], Asrizal[2*], Mutiara Nurul Fitri[2]

[1] Magister of Physics Education, Department of Physics, Faculty of Mathematics and Science, Universitas Negeri Padang, Padang, Indonesia.
[2] Department of Physics, Faculty of Mathematics and Science, Universitas Negeri Padang, Padang, Indonesia.

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Corresponding Author:
Asrizal
asrizal@fmipa.unp.ac.id

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Abstract: This study aims to determine the need analysis, validity, and practicality of e-physics teaching material integrated with augmented reality and ethno-meaningful learning to promote students' 21st century skills. The research used a development method based on the Plomp model, and data were analyzed using descriptive statistics. The needs analysis showed that students' 21st-century skills scored 56.59 out of 100, which falls in the very low category. Context analysis of existing physics teaching material, integration of ethnoscience, meaningful learning, and the difficulty level of heat material yielded scores of 50.00, 34.16, 59.44, and 48.22 respectively, indicating low to very low readiness for current implementation. The content validity of the developed teaching material, assessed using Aiken's V, reached 0.78, indicating it is valid. Its practicality score, based on responses from teachers and students, was 87.00 out of 100, categorized as very practical. The findings indicate that the developed e-physics teaching materials are needed, valid, and practical, and are suitable for supporting the physics learning process. However, further studies are required to evaluate their effectiveness in improving 21st-century skills.

Keywords: Augmented reality; E-physics teaching material; Ethnoscience; Meaningful learning; Students' 21st century skills

Introduction

The rapid advancement of technology in the 21st century has transformed many aspects of life, including education (Dito & Pujiastuti, 2021; Firmansyah et al., 2023). Education today is expected to equip students with critical thinking, creativity, problem-solving, and collaboration skills to face future challenges (Asrizal et al., 2018; Dilekçi & Karatay, 2023; Fitri & Asrizal, 2023; Thornhill-Miller et al., 2023). Critical thinking facilitates truth assertion and effective information processing (Obaje, 2025; Susongko et al., 2024), while creative thinking supports the generation of new ideas and innovative problem-solving (Doyan et al., 2020; Kuo et al., 2022). Collaboration also enhances students' social competence and teamwork abilities (Musyaddad et al., 2024). Collectively, these competencies are essential for students to adapt, innovate, and respond effectively to global challenges in the future (Hasnah et al., 2024; Joklitschke et al., 2022; Kubo, 2023; Mohammad, 2025; Xiao, 2024; Zaremohzzabieh et al., 2025).

The 21st century learning demands change so that students are ready to face the challenges of the world. The main focus is on developing critical thinking, creativity, collaboration, and communication skills, which are essential for students in the modern era. The principles of 21st century learning include a student-centered approach, cooperation among students,

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relevance to real-life contexts, and connection to the community. These four principles guide teachers and educational institutions in designing learning processes that are relevant to students' needs. Educational technology also plays a crucial role in optimizing the implementation of these principles in the classroom. Thus, 21st-century learning is not merely about delivering content but an effort to build students' competencies so they are prepared to face real-life challenges (Nurhasanah et al., 2022).

The use of AR-based e-physics teaching material is transforming modern education by providing interactive and relevant learning. E-physics teaching materials are digital learning resources that combine audio-visual content, animations, and simulations, making them effective for conveying complex concepts concisely and enhancing interactivity (Febrianti, 2021; Safitri & Aziz, 2022; Sriwahyuni et al., 2019). The integration of AR enhances this potential by bringing virtual objects into the real environment, deepening conceptual understanding, and increasing student engagement (Aditama et al., 2024; Alfa & Asrizal, 2024; Ismayani, 2020). This innovative approach not only enhances learning outcomes but also cultivates students' curiosity, critical thinking, and readiness to face the evolving challenges of the future.

Integrating e-physics, AR, meaningful learning, and ethnoscience enriches science education. The effectiveness of this technology is further optimized when supported by meaningful learning processes that connect new knowledge with students' cognitive structures, thereby fostering higher-order thinking skills (Putri et al., 2024; Suwandi et al., 2024) and the ethnoscience approach, which integrates local wisdom into learning and has been proven to increase students' interest, motivation, and critical thinking skills (Astari & Sumarni, 2020; Mariamah et al., 2022; Sudarmin & Pujiastuti, 2015). The integration of these four components e-physics, AR, meaningful learning, and ethnoscience not only enriches the science learning experience but also connects it to students' daily lives and addresses the demands of 21st-century education (Fitria et al., 2025; Hikmawati et al., 2020; Rahayu et al., 2023).

The 21st-century learning paradigm finds pertinence in the independent curriculum. The government's implementation of an independent curriculum is an effort to enhance students' 21st-century skills. The learning process in the independent curriculum involves students actively constructing their own knowledge. Furthermore, pedagogical approaches must be tailored to align with students' interests and aptitudes. Consequently, there is a growing need for innovative e-physics teaching materials that can effectively support the cultivation of 21st-century skills. The e-physics teaching materials in question are augmented reality e-physics teaching materials integrated with ethnoscience and meaningful learning.

Government efforts to improve the quality of learning through an independent curriculum have not been optimal. This is in line with the problem findings based on the preliminary study conducted in senior high schools in Bukittinggi city. The analysis revealed three main problems. First, students' 21st century skills are still in the low category. Second, the teaching materials used are not effective according to the needs of the 21st century. In addition, the existing teaching materials tend to be merely informative and have not encouraged students to think critically, creatively, and collaborate in solving problems. Third, the teaching materials used have not facilitated active and contextual learning. Fourth, students have difficulty in understanding heat material, which has an impact on the low understanding of concepts and applications in everyday life.

The main problem in this study is the low level of students' 21st-century skills. The teaching materials used are still conventional in print or simple e-book formats, with minimal interactivity, and do not yet utilize augmented reality (AR) to visualize abstract concepts. Existing AR research generally focuses solely on conceptual understanding without integrating ethno-meaningful learning that connects physics with local culture. Physics education remains rote-learning oriented and does not support the development of 21st-century skills. Meanwhile, in terms of cultural relevance, there are almost no physics teaching materials that highlight local wisdom (ethnoscience) as a bridge between scientific concepts and Indonesian culture, particularly the culture of West Sumatra, making physics content feel distant from students' real-life experiences. Therefore, a solution is needed to address these issues, one of which is through the development of e-physics teaching materials integrated with augmented reality and ethno-meaningful learning, an innovative approach with great potential to enhance students' 21st-century skills in physics education.

This research presents a novelty in the development of e-physics teaching material. This material combines augmented reality (AR) technology with an ethnically meaningful learning approach in the cultural context of West Sumatra. This combination not only makes abstract physics concepts easier to visualize but also links them to local cultural practices, making learning feel relevant and meaningful to students. This innovation is important because most current physics teaching materials remain conventional, rote-learning oriented, and lacking in local context, making them ineffective in fostering 21st-century skills such as critical thinking, creativity, collaboration, and communication. By leveraging AR, students are encouraged to interact directly with the material through immersive learning experiences, while the integration of ethnoscience fosters connections between science and their real-life experiences. This combination not only addresses the gap in teaching materials, but also encourages physics learning innovations that are aligned with the curriculum and 21st century skills.

This research is expected to facilitate the development of students' 21st century skills. The first reason for this research is to address the fundamental challenge posed by the low level of 21st century skills. Second, this research aims to improve students' competence in facing the demands of the 21st century that emphasize 21st century skills. Third, it is expected that this teaching material can increase the potential, quality, and competitiveness of students at the national and international levels. In addition, this research seeks to make a real contribution to the development of educational innovation so that it can be a reference for educators in designing learning that is relevant to the needs of the times.

Several studies are relevant to this research. First, the integration of augmented reality (AR) and CTL digital teaching materials to promote students' 21st century skills (Alfa & Asrizal, 2024). Secondly, the integration of ethno-STEM teaching materials has been identified as a strategy to promote student learning and innovation skills (Agusti et al., 2024). Thirdly, the development of integrated augmented reality (AR)-based digital ethno-STEM instructional materials to enhance students' 21st-century skills has been identified as a crucial area of focus (Zan & Asrizal, 2024). Therefore, innovations that integrate AR, ethnoscience, and meaningful learning are needed to foster 21st century skills.

This research focuses on e-teaching materials, augmented reality (AR), ethnoscience, and meaningful learning. E-teaching materials refer to instructional resources presented in electronic form that incorporate audio and visual elements, making them suitable for use in various learning contexts, including distance learning (Febrianti, 2021; Sriwahyuni et al., 2019). AR is an emerging technology that overlays virtual objects onto the real world, enabling users to interact with these objects as if they were part of their immediate environment (Arena et al., 2022). Ethnoscience emphasizes the integration of local cultural knowledge into science learning, making instruction more relevant and meaningful for students (Jannah et al., 2022; Sari et al., 2023). Meaningful learning, in turn, connects new information with students' prior knowledge and experiences, thereby fostering deeper understanding (Bryce & Blown, 2024; Syaiful et al., 2024). Building on these perspectives, this research aims to develop e-physics teaching material integrated with AR and ethno-meaningful learning to promote students' 21st-century skills. The purpose of the study was to determine the needs analysis, validity, and practicality of the e-physics teaching material integrated with augmented reality and ethno-meaningful learning to promote students' 21st century skills.

Method

This study uses research and development (R&D) methods to produce learning products that can be validated and tested for practicality. This method was chosen because it allows researchers to design products while systematically refining them. The developed product is an e-physics teaching material integrated with augmented reality and ethno-meaningful learning for high school physics material. The research focuses on developing products that meet field needs and are easy to implement in the classroom. With this approach, the research is conducted in a targeted and gradual manner according to the development procedure.

The development model used in this study is the Plomp model. This model was chosen because its stages are comprehensive, systematic, and adaptable to various field conditions (Plomp & Nieveen, 2013). The strength of the Plomp model lies in its integration of theoretical studies and previous research findings in designing relevant products. Therefore, this model is considered appropriate for developing technology-based instructional materials such as e-physics teaching material. The steps of the Plomp shooting model can be seen in Figure 1.

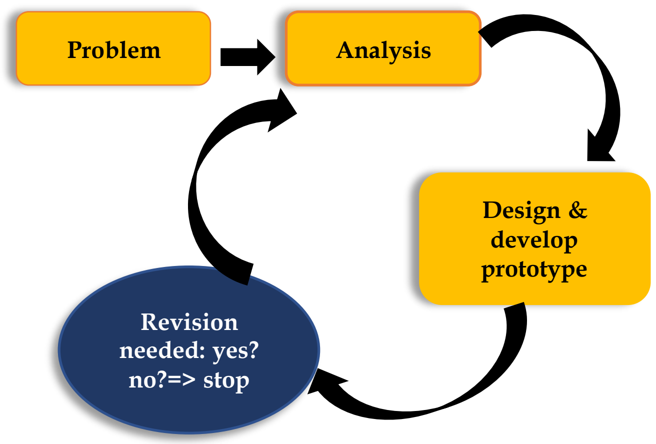

Figure 1. Stages of the Plomp model

The research procedure follows the three main stages of Plomp's model, namely preliminary research, prototyping, and assessment. The preliminary research stage is conducted to analyze learning needs and contexts as the basis for product design. The prototyping stage includes initial design, revision, and repeated evaluation of the product until a suitable prototype is obtained. The assessment stage focuses on testing the practicality of teaching materials through limited trials in the classroom. Each stage is carried out sequentially to ensure that the resulting product is thoroughly tested and aligned with learning needs.

This study used several instruments to collect data related to the developed product. In the preliminary research stage, data was collected using observation sheets, questionnaires, and document analysis to map learning needs. The validity instrument was a validation sheet filled out by experts to assess the suitability of the content, language, and design of the e-physics teaching material integrated with augmented reality and ethno-meaningful learning. Practicality instruments in the form of teacher and student questionnaires were used to evaluate the ease of use and suitability of teaching materials in the classroom. Each instrument was specifically selected to ensure that the data obtained was in line with the research objectives and product development stages.

The population in the initial study consisted of 11th grade students from a high school in Bukittinggi City. In the initial research phase, learning needs and classroom contexts were analyzed using instruments that measured student skills, current teaching materials, and difficulties encountered in learning about heat. The data obtained were analyzed quantitatively using appropriate mathematical formulas to objectively measure the level of learning needs and contextual challenges. These findings served as the basis for designing e-physics teaching materials tailored to students' needs and aligned with the demands of 21st-century learning.

$$\text{Value} = \frac{\text{Score}}{\text{Max Score}} \times 100\% \quad (1)$$

Table 1. Interpretation of needs analysis and context (Widoyoko, 2016)

Criteria	Interval
> 90	Very High
80–90	High
70–79	Enough
60–69	Low
< 60	Very Low

The developed product was validated using a predetermined validation sheet. The validity test was conducted by three physics education lecturers from Universitas Negeri Padang (UNP), each of whom holds a doctorate in physics education and expertise in learning media development and curriculum design. Their professional backgrounds ensured a comprehensive evaluation of the product's content, design, and pedagogical aspects. The data analysis technique used in this study employs Aiken's formula, and validity data is calculated using the following equation (Aiken, 1985).

$$V = \frac{\sum s}{n(c-1)} \quad (2)$$

Table 2. Interpretation of product validity (Aiken, 1985)

Criteria	Interval
≥ 0.6	Valid
< 0.6	Invalid

The practicality of the developed product was assessed by providing it directly to students for use in learning activities. Students then completed a practicality sheet designed to capture their perceptions of usability, clarity, and engagement with the material. Data from these sheets served as the primary instrument for measuring the product’s practicality. The analysis was carried out using a specific formula to calculate practicality scores, as shown in the following equation.

$$\text{Value} = \frac{\text{Score}}{\text{Max Score}} \times 100\% \quad (3)$$

Table 3. Interpretation of product practicality

Criteria	Interval
0–20	Very Less Practical
21–40	Less Practical
41–60	Just
61–80	Practical
81–100	Very Practical

Result and Discussion

Result

Preliminary research constitutes the initial phase in the development of a product. This research provides information about the needs and context of learning. The needs and contexts analyzed include students' 21st-century skills, the context of the teaching materials used, the integration of ethnoscience into teaching materials, the integration of meaningful learning into teaching materials, and students' difficulties with heat-related material. These results serve as a foundation for the development of e-physics teaching material integrated with augmented reality and ethno-meaningful learning.

Results of Needs and Context Analysis

The first needs analysis related to students' 21st century skills. This initial study was conducted at a high school in Bukittinggi. The skills analyzed included critical thinking, creativity, communication, and collaboration. The instruments used included test instruments to test critical and creative thinking skills. Instruments to assess collaboration and communication skills used performance assessment instruments. The results of the analysis of students' 21st century skills are shown in Table 4.

Table 4. Analysis student's 21st century skill

Student's 21st Century Skill	Value	Category
Critical thinking	50.60	Very Low
Creativity thinking	42.75	Very Low
Communication	68.00	Low
Collaboration	65.00	Low

Based on the data in Table 4, students' 21st century skills can be explained. The value of students' critical thinking skills is 50.60 in the very low category. The value of students' creative thinking skills is 42.75 in the very low category. The value of students' communication skills is 68.00 in the low category. The value of student collaboration skills is 65.00 in the low category. The average value of students' 21st century skills is 56.59 in the low category. Based on the results of the analysis, it can be concluded that students' 21st century skills are still in the low category.

The second analysis relates to analyzing the context of the teaching materials used. There were three teaching materials analyzed. The analysis was carried out on four components of teaching materials. The components analyzed include self-instructional, self-contained, adaptive, and user friendly. The analysis becomes the basis for evaluating the suitability of teaching materials with 21st century learning characteristics. The results of the context analysis of teaching materials are shown in Table 5.

Table 5. Analysis of e-physics teaching material (Prastowo, 2015)

Component	Average Value
Self-instructional	55.00
Self-contained	73.33
Adaptive	25.00
User friendly	46.67
Average	50.00

Based on Table 5, the results of the context analysis of the teaching materials used can be explained. The value of the self-instructional component is 55.00 in the very low category. The value of the self-contained component is 73.33 in the sufficient category. The value of the adaptive component is 25.00 in the very low category. The user-friendly component shows a value of 46.67, which is included in the very low category. The average value of physics e-teaching materials analysis is 50.00 which are included in the very low category. The lowest indicator is found in teaching materials that cannot be applied under any conditions. Based on the results of the analysis, it shows that the e-physics teaching materials used by educational institutions today are not in accordance with optimal teaching materials.

The third context analysis is related to the integration of ethnoscience in the teaching materials used. There are four components of ethnoscience that can be observed. The ethnoscience components analyzed include containing local culture (CLC), connecting material with local culture (MLC), there are examples of local culture (ELC), and integration of ethnoscience with 21st century skills (ECS). The results of the analysis of the ethnoscience context in teaching materials are shown in Figure 2.

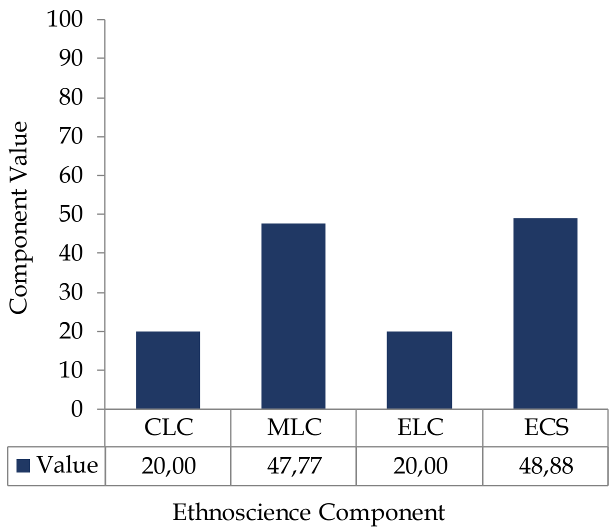

Figure 2. Analysis integration of ethnoscience

Based on Figure 2, the integration of ethnoscience in teaching materials can be explained. The value of the teaching material component containing local culture is 20.00 in the very low category. The component value of connecting material with local culture is 47.77 in the very low category. The value of the component of having examples of local culture in teaching materials is 20.00 in the very low category. The value of the ethnoscience integration component with 21st century skills is 48.88 in the very low category. The average value of the analysis results is 34.16 in the very low category. Based on the results of the analysis, it shows that the integration of ethnoscience in teaching materials is still low.

The fourth needs analysis is the integration of meaningful learning in teaching materials. Four components were analyzed. Components of meaningful learning include initial cognitive structure (CS), meaningful learning intention (ML), logical elaboration (LE), and advance organizer (AO). This analysis aims to determine the extent to which the elements of meaningful learning have been applied in teaching materials. The findings of this analysis become a reference in developing teaching materials that are more contextual and relevant to students' needs. The results of the meaningful learning integration analysis are shown in Figure 3.

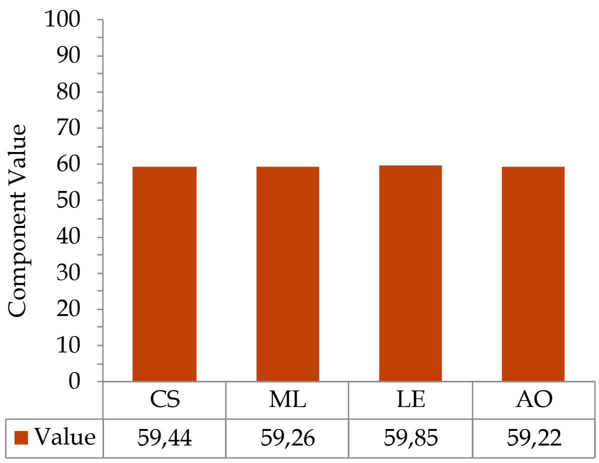

Figure 3. Analysis integration of meaningful learning

Based on Figure 3, the integration of meaningful learning in teaching materials can be explained. The value of the initial cognitive structure component is 59.44 in the very low category. The value of the meaningful learning intention component is 59.26 in the very low category. The value of the logical elaboration component is 59.85 in the very low category. The value of the advance organizer component is 59.22 in the very low category. The average value of meaningful learning integration in learning is 59.44 in the very low category. Based on the analysis, it shows that the integration of meaningful learning in teaching materials still low.

The last needs analysis is related to students' difficulties with heat material. The analysis was conducted through a questionnaire instrument containing questions related to heat material. The analysis results showed a score of 48.22 in the very low category. Based on the results of the analysis, it shows that students still have difficulty in understanding the heat material. Students face challenges in this material due to their inability to distinguish various quantities of heat. In addition, students also face challenges in understanding physics concepts due to lack of motivation and engagement in the learning process. Therefore, it is necessary to find solutions to facilitate students in understanding heat material.

Validity Test Results of E-Teaching Material

In light of these findings, it is evident that there are significant issues that require attention. The prevailing level of 21st-century skills among students is suboptimal. In order to address the challenges of the 21st century, it is imperative that learning be more adaptive, dynamic, and incorporate real-world contexts. The integration of technological elements, such as electronic learning materials, is imperative in contemporary educational methodologies. One potential avenue for achieving this objective is the development of augmented reality physics e-physics teaching materials that are integrated with ethnoscience and meaningful learning. The implementation of such materials would serve to facilitate students' development of 21st-century skills. The e-physics teaching materials developed can be displayed as follows.

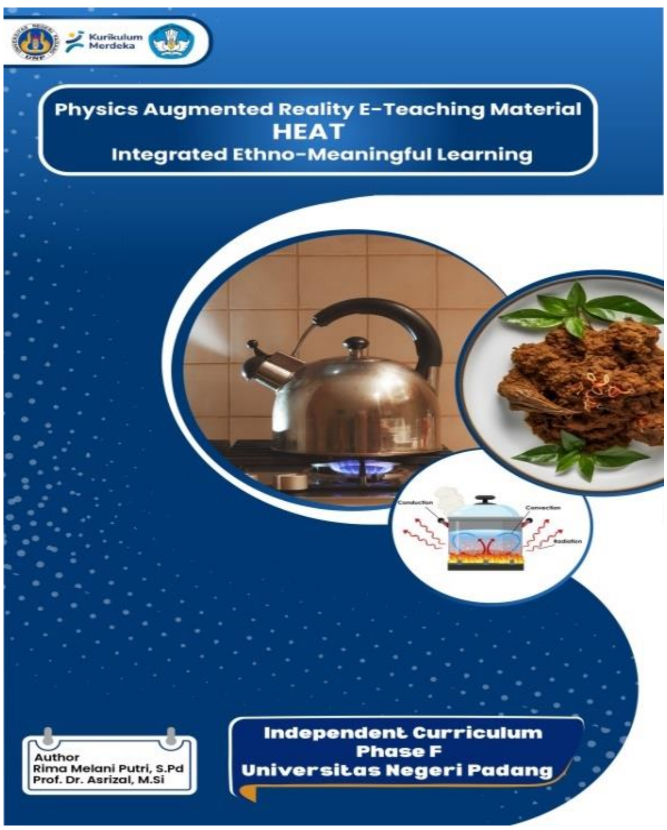

Figure 4. Cover of e-physics teaching material

The cover of the e-learning material contains the following elements: the title of the e-learning material, the subject matter to be studied, and the characteristics of the e-learning material, the purpose of the e-learning material, the name of the author, and the name of the supervisor. The objective of the cover is to attract the reader's attention and effectively convey the content of the e-learning material. The cover features images of local wisdom from West Sumatra pertinent to the subject matter, along with an image of heat transfer serving as a representation of the content within the e-learning material. The cover incorporates augmented reality (AR), meaningful learning, and ethnoscience. The cover's design, featuring a blue and white background, aims to enhance its visual appeal and engage the reader.

E-physics teaching materials are integrated with ethnoscience and meaningful learning. E-physics teaching material contains local culture of West Sumatra. The material is linked to local culture that is close to students. E-physics teaching materials are also integrated with meaningful learning. Meaningful learning is limited to meaningful learning indicators. This step is useful for developing 21st century skills. Learning objectives (TP) are derived from learning outcomes (CP). E-physics teaching material contains one learning outcome (CP), namely heat.

E-physics teaching materials demonstrate that the educational process commences with conditions that are analogous to students' lives, incorporating ethnoscience and comprising videos and images that facilitate student comprehension. The integration of e-physics teaching materials with ethnoscience and meaningful learning steps is a distinctive feature of the program. The following steps are to be followed by students in order to ensure the meaningfulness of the learning process.

This augmented reality physics e-learning material, integrated with ethnoscience and meaningful learning, has the potential to facilitate students' critical thinking, creativity, collaboration, and communication skills. This shows the instructional content of the e-learning material, which provides clear guidance on the application of each skill. The cultivation of critical thinking is facilitated by the posing of questions, and creative thinking is achieved by encouraging students to generate ideas through the instructions provided in the e-physics teaching materials. Collaboration and communication are promoted through group discussion activities and the presentation of discussion outcomes. The e-physics teaching materials were created using the Canva application in PDF format, then made interactive with the assistance of the Flippdf Corporate application. The Assembler.edu application was utilized for augmented reality integration.

Next, the e-physics teaching materials were subjected to a rigorous evaluation process to ascertain their validity and practicality. The validity test comprised four components: material substance, visual communication, learning design, software usage, and meaningful learning integration. The validation was carried out by three physics lecturers from the Faculty of Mathematics and Natural Sciences at UNP. The validation results are displayed in Table 6.

Table 6. Results of the validation of AR physics e-physics material

Aspects	Validity Value	Criteria
Material substance	0.81	Valid
Learning design	0.79	Valid
Visual communication	0.81	Valid
Utilization of software	0.80	Valid
Meaningful learning	0.79	Valid
Ethnoscience	0.69	Valid

Based on the data presented in Table 6 shows the results of the validation of e-physics teaching material. The validation value of the material substance component is 0.81 in the valid criteria. The value of the learning design component is 0.79 in the valid criteria. The value of the visual communication component is 0.81 in the valid criteria. The value of the software utilization component is 0.81 in the valid criteria. The value of the meaningful learning component is 0.79 in the valid criteria. The value of the ethnoscience component is 0.69 in the valid criteria. The average value obtained from the six aspects of validity is 0.78 in the valid criteria. Based on the analysis, e-physics teaching materials integrated with augmented reality and ethno-meaningful learning is valid.

Practicality Test Results of E-Teaching Material

The subsequent stage of the process is the implementation of a practical test to assess the efficacy of augmented reality physics e-physics teaching materials. The practicality test was administered to students. At this stage, students employed augmented reality physics e-physics teaching materials in their learning. The practicality test is composed of several components, including usefulness, ease of use, attractiveness, clarity, cost-effectiveness, and AR-EM. The initial findings from the practicality test were derived from one to one evaluation.

Table 7. Practicality e-learning material augmented reality one to one evaluation

Aspects	Practicality Value	Criteria
Usability	85.55	Very practical
Ease of use	80.00	Practical
Attractiveness	78.67	Practical
Clarity	85.33	Very practical
Cost-effectiveness	89.33	Very practical
AR-EM	86.66	Very practical

One-to-one practicality was conducted on three Bukittinggi high school students. The instrument used is a practicality instrument. Practicality indicators include usability, ease of use, attractiveness, clarity, cost effectiveness, and augmented reality and ethno-meaningful learning (AR-EM). The results of the one-on-one evaluation analysis are shown in Table 7.

Based on the data in Table 7, the practicality of the e-physics teaching material can be explained. The scores for the indicators of usability ease of use, attractiveness, clarity, cost effectiveness, and augmented reality and ethno-meaningful learning ranged from 78.67 to 89.33 in the practical to very practical criteria. The average practicality score for each criterion is 84.22 in the highly practical category. Based on the results of the individual practicality analysis, the e-physics teaching material integrated with augmented reality and ethno-meaningful learning developed is practical for use in the learning process.

The second practicality is small group evaluation. Small group practicality was also conducted on nine Bukittinggi high school students. The instrument used is also a practicality instrument. Practicality indicators are the same as the one-on-one practicality instrument. This instrument was given to nine students after they received learning using e-physics teaching material integrated with augmented reality and ethno-meaningful learning. The results of the small group evaluation analysis are shown in Table 8.

Table 8. Practicality e-learning material augmented reality small group evaluation

Aspects	Practicality Value	Criteria
Usability	90.22	Very practical
Ease of use	89.78	Very practical
Attractiveness	88.44	Very practical
Clarity	92.89	Very practical
Cost-effectiveness	92.44	Very practical
AR-EM	87.68	Very practical

Based on the data in Table 8, the practicality results of the small group can be explained. The values of the indicators of usability ease of use, attractiveness, clarity, cost effectiveness, and augmented reality and ethno-meaningful learning obtained scores ranging from 87.68 to 92.89 in the very practical criteria. The average practicality value of the small group was 90.24 in the very practical criteria as well. Based on the results of the practicality analysis in the small group, the e-physics teaching material integrated with augmented reality and ethno-meaningful learning developed are practical for use in teaching.

The third practicality is field test practicality. The practicality of the field test was also carried out on Bukittinggi High School students. Practicality indicators are the same as one-on-one and small group practicality instruments. This instrument is given to students after they receive learning using e-physics teaching material integrated with augmented reality and ethno-meaningful learning. The results of the field test practicality analysis are shown in Table 9.

Table 9. Practicality of field test of e-physics teaching material

Aspects	Practicality Value	Criteria
Usability	85.00	Very practical
Ease of use	89.00	Very practical
Attractiveness	87.00	Very practical
Clarity	87.00	Very practical
Cost-effectiveness	89.00	Very practical
AR-EM	86.00	Very practical

Based on the data in Table 9, the practicality of the field test can be explained. The values of the indicators of usability, ease of use, attractiveness, clarity, cost effectiveness, and augmented reality and ethno-meaningful learning scores ranging from 85.00 to 89.00 in the very practical criteria. The average practicality score of the field test is 87.00 within the highly practical criteria. Based on the practicality analysis results of the field test, the e-physics teaching material integrated with augmented reality and ethno-meaningful learning developed are practical for use in teaching and have the potential to support the development of students' 21st-century skills.

Discussion

The results achieved in this study are in line with the research objectives. The three results are the outcomes of the analysis of the needs, validity, and feasibility of e-physics teaching materials integrated with augmented reality and ethno-meaningful learning. The first result achieved in this study is the analysis of the needs and context of developing e-physics teaching materials integrated with augmented reality and ethno-meaningful learning. The results of the needs analysis and context include students' 21st-century skills, the context of the teaching materials used, the integration of ethnoscience into the teaching materials, the integration of meaningful learning into the teaching materials, and students' difficulties with heat-related material. The results of the analysis of students' 21st-century skills indicate that they are still in the low category. The findings of this preliminary study are consistent with the findings of previous research. Previous research also shows that students' 21st century skills are still low. The results showed that students' 21st century skills were still relatively underdeveloped (Ibrahim et al., 2021; Irawan et al., 2022; Lestari & Apsari, 2022). This lack of 21st century skills is due to the limited space and opportunities for students to think. Furthermore, this phenomenon is influenced by the lack of student-centered learning methodologies (Chusna et al., 2024; Kurniawan, 2024).

The results of the analysis of teaching materials show that the materials currently in use are not optimal and do not meet the needs of the 21st century. Teaching materials that are suitable for the 21st century increasingly emphasize the integration of technology, such as e-teaching materials. According to Prastowo (2015) e-teaching materials consist of four criteria, namely self-instruction, independence, adaptability, and ease of use. The integration of technology in teaching materials is crucial to making the learning process more engaging, interactive, and relevant to 21st-century needs, as well as enhancing student motivation and learning outcomes (Akram et al., 2022; Kalyani, 2024; Rintaningrum, 2023). On the other hand, many teaching materials provided in schools do not meet these criteria. Therefore, the development of e-teaching materials is not merely an option but an urgent necessity to improve the quality of education in the 21st century.

The results of the analysis of the integration of ethnoscience and meaningful learning in teaching materials show that it is still low. The integration of ethnoscience and meaningful learning is also very important in teaching materials. The integration of ethnoscience in 21st-century learning enhances critical thinking skills and the relevance of learning to students' real-life experiences (Harjono et al., 2025; Herayanti et al., 2025; Pieter & Risamasu, 2024). The inclusion of ethnoscience makes student learning more contextual, meaningful, and supportive of local cultural preservation (Jannah et al., 2022; Nugraheni & Pratomo, 2025; Suciyati et al., 2021). The integration of meaningful learning into the learning process is crucial as it enhances students' overall understanding, motivation, and skills (Lestari et al., 2023; Syaiful et al., 2024). Meaningful learning helps students connect new knowledge with previous experiences or knowledge, making the material easier to understand, remember, and apply in real life (Mystakidis, 2021; Nurhasanah et al., 2022; Silva, 2020). Therefore, it is important to integrate ethnoscience and meaningful learning into education, particularly in instructional material.

The results of the latest needs analysis indicate that students have difficulty understanding heat-related material. Students still face challenges in mastering heat-related material. This issue is influenced by students' interest and motivation in learning physics. As indicated by various research findings, interest, motivation, and concentration in physics learning are still lacking (Jannah et al., 2022; Salassa et al., 2023). One of the factors contributing to the challenges faced in physics education is the inadequate use of learning media and methodologies (Winarti, 2021). Therefore, there is a need for teaching materials that can facilitate 21st-century learning needs integrated with technology such as AR, as well as integrated ethno-science and deep learning. This indicates the need to develop e-physics teaching materials integrated with augmented reality and ethno-meaningful learning to assist in the physics learning process.

The second result of this study is the validity of e-physics teaching materials integrated with augmented reality and ethno-meaningful learning. The validity of the developed product was tested by experts to obtain the validity level of the teaching materials. The results of data analysis from the validity instrument indicate that the value of each component is in the valid category. The validity components include content substance, instructional design, visual communication, software utilization (Kemendiknas, 2010), meaningful learning, and ethnoscience. All six validation aspects have an Aiken's V value greater than 0.6, which is generally considered valid (Aiken, 1985). Based on the validity results, the e-physics instructional materials integrated with augmented reality and ethno-meaningful learning are deemed valid. The e-valid instructional materials can be used to support the learning process. Previous studies have indicated that valid e-integrated ethno-AR instructional materials can be used to support learning (Daulay & Asrizal, 2024; Ridha & Virijai, 2024; Virijai & Asrizal, 2023). Valid interactive ethno-meaningful learning materials can be used in learning (Efrisa et al., 2025). E-physics teaching materials can be used in physics learning (Zan & Asrizal, 2024). Thus, valid e-physics teaching materials integrated with augmented reality (AR) and ethno-meaningful learning can be used and can optimize the learning process.

The third result of this study is the practicality of e-physics teaching materials integrated with augmented reality and ethno-meaningful learning. The results of the data analysis from the practicality instrument indicate that the value of each component is in the very practical category. The practicality components include usability, ease of use, appeal, clarity, cost-effectiveness (Novit et al., 2023; Rahmayani & Asrizal, 2023; Virijai & Asrizal, 2023), and AR-EM. Based on the practicality results, the e-physics instructional materials integrated with augmented reality and ethno-meaningful learning are deemed highly practical and can be used in learning. Practical e-physics instructional materials can be easily used in the learning process (Abdullah et al., 2024; Asrizal et al., 2022). Practical digital teaching materials integrated with ethno-AR can be easily used in learning (Agusti et al., 2024; Fitri et al., 2024; Ridha & Virijai, 2024; Virijai & Asrizal, 2023). Thus, practical e-physics teaching materials integrated with augmented reality and ethno-meaningful learning can be used to optimize the learning process.

Based on the analysis of e-physics teaching materials integrated with augmented reality and ethno-meaningful learning to promote students' 21st century skills, these e-physics teaching materials are needed, valid, and very practical. The developed e-physics teaching material can be used as a support tool in the learning process. Previous studies supporting these findings indicate that technology-based teaching materials that are valid and practical can be utilized in the learning process (Afriyanti et al., 2021; Latif & Talib, 2021; Nazifah & Asrizal, 2022). E-teaching materials can enhance critical thinking and student learning outcomes (Irawan et al., 2022). E-teaching materials can also improve students' 21st-century skills and new literacy (Asrizal et al., 2022).

Teaching materials integrated with augmented reality and ethnoscience also support 21st-century learning needs. Digital teaching materials integrated with augmented reality can facilitate students' 21st-century skills (Alfa & Asrizal, 2024). E-modules integrated with ethnoscience can enhance students' 21st-century skills (Fitri & Asrizal, 2023). Electronic teaching materials integrated with ethnoscience can enhance students' critical thinking (Lestari & Apsari, 2022). Digital teaching materials integrated with ethno-science and augmented reality can facilitate students' 21st-century skills (Fitri & Asrizal, 2023; Virijai & Asrizal, 2023; Zan & Asrizal, 2024). Thus, e-physics teaching materials integrated with augmented reality and ethno-meaningful learning can facilitate the development of students' 21st-century skills.

Conclusion

Based on data from research and development of e-physics teaching materials integrated with augmented reality and ethno-meaningful learning, three main results can be concluded. First, e-physics teaching materials integrated with augmented reality and ethno-meaningful learning is needed to support physics learning. Second, these e-physics teaching materials are suitable for use in physics learning activities because they meet the assessment criteria of experts with valid criteria. Third, these e-physics teaching materials are practical for use in physics learning, based on evaluations by teacher practitioners and students, with a rating of very practical. The findings indicate that these e-physics teaching materials can support the physics learning process. For future research, it is recommended to conduct an effectiveness test to evaluate the impact of these e-physics teaching materials on students' 21st-century skills and other learning outcomes.

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Author Contributions

R.M.P., contributed in developing the product, collecting data, analyzing data, and writing the draft article; A., as the supervisor who has managed the research activities from conceptualizing the research idea to writing, reviewing, and editing the article; M.N.F., contributed to the editing of the article. All authors have read and approved the published manuscript.

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Conflicts of Interest

The authors have declared that no conflict of interest exists in the conduct of research and the subsequent publication of scientific results.

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