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FRAMEWORK FOR AN APPLIED PHYSICS LEARNING MODULE INTEGRATING STEM AND AUGMENTED REALITY

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ABSTRACT

Purpose – This study addresses the limited quality of Applied Physics learning, which remains largely theoretical and lacks authentic contextual learning experiences for pre-service physics teachers. Integrating Augmented Reality (AR) and STEM through the Applied Physics (PhyARECi-STEM) learning module has the potential to address this need. However, the design of existing STEM learning modules remains suboptimal due to limited expert validation. Therefore, this study aims to develop a framework for the PhyARECi-STEM learning module as a foundation for an innovative 21st-century module.

Methodology – This study employed the Fuzzy Delphi Method (FDM). A total of 31 experts were selected through purposive sampling. Data were collected using a valid and reliable questionnaire and analyzed using fuzzy statistical techniques.

Findings – The findings identified 10 validated fundamental elements of the PhyARECi-STEM learning module, comprising learning outcomes (B.6), learning content (C.5), learning processes (D.1.1, D.2.1, D.2.2.2, D.2.3.3, D.3.2, D.4.1), and learning assessment (E.1.1, E.2.3). All fundamental elements achieved expert consensus exceeding 75%, resulting in validated framework with the potential to support physics problem-solving skills and scientific creativity of pre-service physics teachers.

Novelty – This study proposes a learning module framework constructed from systematically validated fundamental elements and grounded in established educational theories.

Significance – This study provides practical guidance for lecturers and researchers in designing contextual, integrated, and systematic Applied Physics learning. It also strengthens the theoretical foundation for developing the learning modules for pre-service physics teachers and contributes to 21st-century Applied Physics pedagogy.

Keywords: Applied physics, augmented reality, fuzzy Delphi method, STEM approach, learning module.

INTRODUCTION

Applied Physics plays a strategic role in connecting theoretical physics concepts with their real-world applications. As a course that emphasizes the application of physics principles to generate technological solutions, Applied Physics contributes to sectors such as agriculture, renewable energy, medical instrumentation, and digital technology (Babic et al., 2023; del Río et al., 2020; Satanassi et al., 2023). Learning in Applied Physics requires pre-service physics teachers to integrate theory and practice through context-based activities and authentic problem-solving (Zaky et al., 2025). Various efforts have been implemented, ranging from developing simple projects, strengthening multidisciplinary collaboration, identifying collaborative factors, to implementing the Contextual Teaching and Learning model (Fadhilah et al., 2021; Mesutoglu et al., 2024a; Mesutoglu et al., 2024b; Zaky et al., 2025). However, these efforts have not fully provided authentic interdisciplinary experiences or utilized immersive technology, even though pre-service teachers need such interdisciplinary experiences to teach STEM effectively (Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi, 2022b). This situation affects their problem-solving skills and scientific creativity, which have not been optimally developed (Afrizon et al., 2025). Therefore, interdisciplinary Applied Physics learning resources grounded in real-world contexts and integrated with immersive technology are needed to enhance the pedagogical readiness of pre-service physics teachers.

The STEM approach has been widely adopted as a 21st-century educational strategy that integrates STEM disciplines in an interdisciplinary manner to strengthen problem-solving skills, creativity, and innovation. Its implementation varies across countries. In China, STEM emphasizes core literacies and the integration of innovative technologies into student learning and research (Niancai et al., 2024). In the United States, it is positioned as a tool to reduce social disparities based on race, ethnicity, and gender (Palid et al., 2023; Yang et al., 2024). In South Africa, it is linked to the integration of ICT and indigenous knowledge (Nkopodi et al., 2024). Australia emphasizes strengthening workforce competencies as part of its economic development strategy (Xu et al., 2023), while European countries highlight cross-stakeholder collaboration to foster innovation and entrepreneurship (Tabarés & Boni, 2023). Despite these contextual differences, all countries demonstrate that an integrated STEM approach can enhance the relevance of education and strengthen collaborative and problem-solving skills. At the same time, immersive technologies such as Augmented Reality (AR) enrich the STEM learning ecosystem through three-dimensional representations and digital interactions that bridge abstract concepts with physical phenomena. Therefore, the integration of STEM and AR expands pedagogical opportunities while strengthening the foundation of innovation-oriented learning.

In Indonesia, STEM has become part of the national agenda to prepare pre-service teachers for 21st-century challenges. Its implementation is reflected in the national curriculum for secondary and higher education (Kementerian Perencanaan Pembangunan Nasional, 2024; Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi, 2022a). The Kihajar ("Kita Harus Belajar" or we must learn) STEM program facilitates project-based exploration and the use of ICT for students (Pusdatin, 2021, 2022). The STEM approach is also widely applied in research and development (Tuyet et al., 2024), focusing on teaching strategies, media, assessments, and learning modules (Farwati et al., 2021; Nugraha et al., 2023). A key characteristic of STEM is the integration of various disciplines to solve real-world problems thematically (Nugraha et al., 2024; Roehrig et al., 2021a). This integration is implemented through systematic and integrated learning modules (Khotimah et al., 2023). Therefore, integrating STEM into higher education is a strategic step toward equipping pre-service physics teachers to apply STEM effectively in schools.

The readiness of pre-service physics teachers is a key factor in the successful implementation of STEM. Although they demonstrate positive perceptions, interests, and motivation, pre-service teachers still need to strengthen their knowledge and skills to apply STEM effectively (Nugraha et al., 2023). This limitation is influenced by the lack of context-based activities and limited experience with engineering design concepts (Ismet et al., 2020; Nugraha et al., 2023; Widiastuti et al., 2020). Integrating STEM into lectures is one possible solution (Nasrudin et al., 2020), with learning modules serving as an important instructional resource in higher education (Khotimah et al., 2023). Learning modules have been shown to improve learning outcomes (Kariman et al., 2019) and support independent learning (Al Mamun & Lawrie, 2023). However, the availability of STEM learning modules in Indonesia remains limited (Farwati et al., 2021; Ilma et al., 2023), and most are aimed at school students rather than pre-service teachers. Furthermore, the lack of visualization of abstract physics concepts hinders pre-service physics teachers' conceptual understanding (Juandi et al., 2024). Therefore, developing a PhyARECi-STEM learning module framework is urgently needed to strengthen the pedagogical readiness of pre-service teachers.

Previous research on STEM modules has identified two key gaps. First, the determination of module elements often relies on a single data source, such as a needs analysis, which only reveals topic-related challenges (Xue et al., 2023) or limitations in learning resources (Farihah et al., 2021) without detailing the required learning components. In addition, user experience is often limited, making expert involvement necessary to ensure the pedagogical suitability of the module. Second, the validation process remains suboptimal, as many studies validate only the final drafts rather than the design stage (Martaningsih et al., 2022; Pertiwi et al., 2024; Septiadevana & Abdullah, 2024; Zakiyah & Sudarmin, 2022). The lack of design-stage validation results in modules that may not adequately reflect user needs or educational standards. This situation presents an opportunity to simultaneously identify and validate module elements by involving experts from the outset. Experts provide practical insights into the feasibility of module components (Aris et al., 2025) and help ensure the credibility of the content (Montes et al., 2023; Rahayu & Wulandari, 2021). This study develops the PhyARECi-STEM framework for designing innovative modules aligned with educational theory and the needs of pre-service physics teachers. Conceptually, this study contributes by formulating a framework based on fundamental elements validated through expert consensus, to strengthen its theoretical foundation and address the limitations of immersive STEM module design. The two research objectives and their corresponding research questions are presented in Table 1.

Table 1

Research Objectives and Research Questions

Research objectives (RO)	Research questions (RQ)
To identify valid fundamental elements within the components of learning outcomes, content, processes, and assessments required for the development of the PhyARECi-STEM learning module through expert consensus.	What are the valid fundamental elements within the components of learning outcomes, content, processes, and assessments required for the development of the PhyARECi-STEM learning module based on expert consensus?
To design a PhyARECi-STEM learning module framework to support physics problem-solving skills and scientific creativity among pre-service physics teachers.	How can the validated elements be integrated into a framework to support physics problem-solving skills and scientific creativity among pre-service physics teachers?

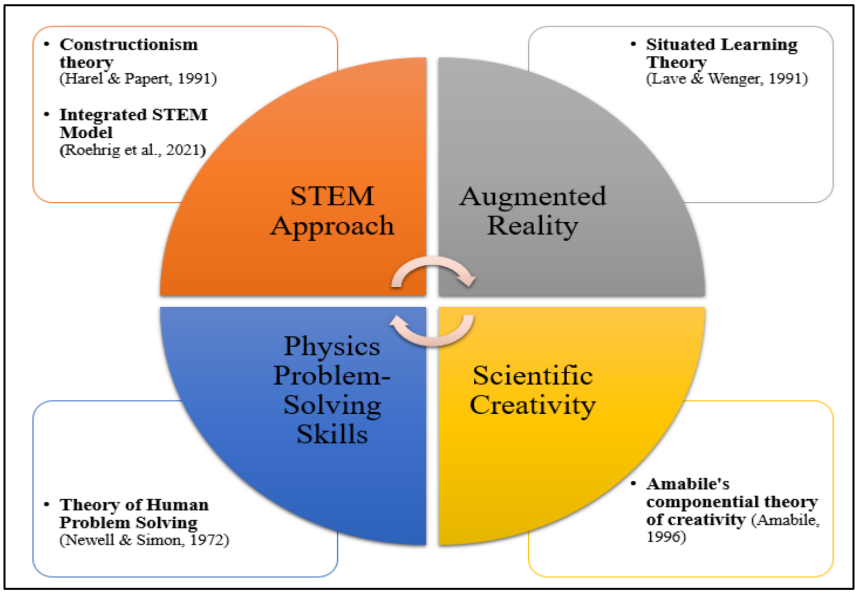
LITERATURE REVIEW

Theoretical Framework

The PhyARECi-STEM module framework was developed by integrating constructionism, the integrated STEM model, situated learning, as well as problem-solving and creativity theories. The integration of these five theoretical foundations forms the conceptual basis for organizing the elements within the four main components of the learning module and establishing the relationships between these components, as illustrated in Figure 1.

Figure 1

Theoretical Framework



Integrated STEM Approach in Teaching and Learning

An integrated STEM approach is applied in the teaching and learning process. This approach combines science and mathematics concepts with the application of technology and engineering principles (Roehrig et al., 2021a). An integrated STEM education framework brings together science, technology, engineering, and mathematics into a coherent learning experience (Ortiz-Revilla et al., 2022; Zhan & Niu, 2023), that promotes essential skills for solving real-world problems (Roberts et al., 2022). The integration of STEM in teaching can take several forms, including disciplinary, multidisciplinary, interdisciplinary, and transdisciplinary approaches (Goos et al., 2023). Therefore, integrated STEM education, which incorporates all STEM disciplines, is crucial for developing the competencies needed to address the challenges of an increasingly complex world.

Science is a fundamental component of the STEM framework, emphasizing the integration of these disciplines to foster the skills needed to address real-world challenges. For example, the application of simple physics concepts can be seen in parabolic motion activities assisted by Scratch to develop 21st-century learning skills (Yulianti et al., 2022), as well as in constructing thermometers to train critical thinking skills (Handayani et al., 2021). Furthermore, solving complex physics problems in real-life contexts is often linked to issues related to the Sustainable Development Goals (SDGs). For example, renewable energy projects involving solar cells can serve as an effort to reduce carbon emissions. Such projects aim to enhance learning outcomes and create meaningful learning experiences (Mayasari et al., 2019; Sukma et al., 2022). In this regard, science makes a significant contribution to the development of essential skills needed to navigate the complexities of modern society.

Technology is an essential component of an integrated STEM approach, functioning both as a tool and a subject of study. The role of technology in STEM can be categorized into three aspects: technology as new learning technology, technology as engineering products, and technology as computational participation. A study found that technology in STEM is more often positioned as a product of engineering and learning technology rather than as computational participation (Sivaraj et al., 2019). This condition indicates that STEM research still primarily focuses on the engineering aspect rather than the computational dimension, despite its significant pedagogical potential. One form of computational participation in STEM education is AR, which can visualize abstract scientific concepts (Sivaraj et al., 2020). Research shows that the use of AR in STEM education supports the teaching and learning process and contributes to innovation (Sırakaya & Alsancak Sırakaya, 2022). This suggests that AR can be effectively used as a technological tool in STEM-based learning. Consequently, integrating AR into STEM is pivotal for enhancing the learning experience and preparing pre-service physics teachers for future careers by strengthening their understanding of the scientific principles that drive innovation.

Engineering is a pivotal component of an integrated STEM approach, functioning as a bridge between theoretical knowledge and its practical application. Its role is distinct from that of technology within the STEM field (Simarro & Couso, 2021). In STEM education, engineering is commonly represented through the engineering design process. However, the application of engineering design processes at the university level remains limited, particularly in interdisciplinary science courses (Winarno et al., 2020). After identifying a problem and developing a design solution, the final stage involves creating and refining the solution as a design artifact. These artifacts may take the form of design solutions, prototypes, or drawings

(Arık & Topçu, 2022). Consequently, engineering remains a crucial component of STEM in fostering innovative solutions and developing skilled professionals capable of addressing complex societal problems.

As a foundational discipline that underpins other fields, Mathematics is essential in integrated STEM education. Several studies highlight the vital role of Mathematics in STEM education, such as the application of geometry in house construction (Cumino & Zich, 2021), linear programming in housing development (Arifanti et al., 2021), geometry and angles in solar dryers (Mayasari et al., 2019), understanding and using temperature conversion (Handayani et al., 2021), and algorithmic thinking (Yulianti et al., 2022). In addition, Mathematics extends beyond basic literacy to include conceptual and procedural literacy. It connects mathematical concepts to real-world contexts, such as data analysis (Jackson et al., 2021). In this way, Mathematics is not only a component of STEM disciplines but also an essential factor in the success of STEM education.

The Role of Augmented Reality in STEM and Applied Physics Learning

AR technology has significant potential to enhance STEM learning, particularly in Applied Physics. AR combines the real world with interactive virtual elements, enabling learners to explore abstract phenomena in a more concrete manner. In physics learning, three-dimensional visualizations generated by AR help learners understand complex concepts such as electromagnetic fields, light waves, and particle dynamics in an intuitive and immersive way (Adly et al., 2021; Pittman & LaViola, 2020). AR can improve academic performance, increase motivation, and reduce cognitive load (Mokmin et al., 2024). From a constructionist perspective, AR expands opportunities for exploration and knowledge construction by allowing learners to build and manipulate conceptual representations directly (Harel & Papert, 1991). Meanwhile, from a situated learning perspective, AR creates contextualized learning experiences that closely reflect real-world practice, thereby strengthening the meaning and relevance of learning (Lave & Wenger, 1991). The integration of AR into the STEM approach also aligns with the principles of Roehrig's integrated STEM model, particularly in terms of active engagement and real-world context (Roehrig et al., 2021a). With AR support, pre-service physics teachers not only learn physics concepts but also experience the thought processes of scientists and engineers in authentic settings through simulations, design, and data-driven analysis. Therefore, this technology serves as an important foundation for enriching Applied Physics learning in the STEM context and fostering the development of problem-solving skills and scientific creativity.

STEM Integrated Physics Learning Module

Various studies have shown that STEM-based physics learning modules can improve conceptual understanding, learning motivation, and higher-order thinking skills (Nugraha et al., 2023; Winarno et al., 2020). Such modules play a crucial role in connecting physics theory with technological and engineering applications, particularly in Applied Physics. Project-based approaches and engineering design also contribute to developing a deeper understanding of the relationships between physics variables and their real-life applications. However, several challenges remain. Many STEM modules are developed in a fragmented manner, failing to fully reflect integrative principles (Nugraha et al., 2023; Roehrig et al., 2021b). Technology and engineering aspects are often complementary rather than integral components of instructional design (Wieselmann et al., 2025). Furthermore, assessment systems used in STEM learning still tend to focus on cognitive aspects and technical competency skills, without adequately measuring problem-solving, communication, creativity, or the application of concepts in real-world situations (Mistler, 2025). This condition creates a gap between the intended learning objectives and their practical application. Thus, it is necessary to develop a physics learning module that systematically integrates STEM and AR technologies to enhance learning quality.

The use of learning modules for STEM implementation in Indonesia remains limited (Farwati et al., 2021). Existing modules have been primarily developed for early childhood, elementary, and middle school education programs. STEM-integrated physics learning modules that have been developed are mostly intended for middle school students (Fathurohman et al., 2021; Febriyanti et al., 2018; JR & Sulaiman, 2020; Melisa et al., 2021; Sari et al., 2020; Siew & Ambo, 2020; Yulkifli et al., 2022). In contrast, STEM learning modules for pre-service physics teachers remain limited (Akhsan et al., 2023; Geiger et al., 2018; Handayani et al., 2021). Pre-service physics teachers need STEM modules to build STEM-related skills and interdisciplinary knowledge to support future implementation in schools. In Indonesia, STEM modules for pre-service teachers have been designed in both printed and e-module forms (Nugraha et al., 2023). However, their utilization remains low. Although such learning modules are available in limited quantities, further development is still needed because the existing STEM modules may not fully align with user needs, recent technological advancements, current issues, and the latest curriculum demands. Therefore, the limited use of these learning modules highlights the urgent need to develop and provide STEM learning modules for pre-service physics teachers in Indonesia.

The STEM-integrated physics learning modules developed between 2018 and 2023 have undergone several updates. First, various studies have integrated learning models into STEM learning modules (Fathurohman et al., 2021; Handayani et al., 2021; JR & Sulaiman, 2020; Siew & Ambo, 2020; Yulkifli et al., 2022). Second, the module formats have diversified into print, electronic, and web-based forms. However, existing modules still exhibit several limitations. First, access to these learning modules remains restricted (Geiger et al., 2018). Second, the engineering component in physics learning modules has mostly been presented only as content or literacy, even though this component plays a central role in connecting all STEM disciplines (Fathurohman et al., 2021; Melisa et al., 2021; Nugraha et al., 2023; Yulkifli et al., 2022). This indicates that both the presentation of module content and accessibility still require improvement. In response to these limitations, this study proposes a new module, PhyARECi-STEM, which aligns with the principles of STEM in physics learning. Therefore, the development of a more comprehensive and accessible PhyARECi-STEM learning module framework is needed to address the demands of Applied Physics learning.

METHODOLOGY

The PhyARECi-STEM learning module consists of four components: learning outcomes, learning content, learning process, and learning assessment. The elements of the PhyARECi-STEM learning module were determined using the Fuzzy Delphi Method (FDM). FDM integrates fuzzy theory with the classic Delphi method to reduce ambiguity in expert judgement. The classic Delphi method is widely used in decision-making through expert consensus (Saffie et al., 2016). In this study, the identification and validation of the fundamental elements of the PhyARECi-STEM learning module framework were carried out simultaneously.

Research Instrument and Data Collection

The fuzzy Delphi questionnaire used in this study as the data collection instrument employed a seven-point Likert scale. The use of questionnaires in FDM is essential for structured data collection, as it addresses uncertainty in expert opinions and enhances the validity of research findings (Hasim et al., 2023; Ismail et al., 2019; Yin & Hanif, 2024). This approach simplifies the consensus-building process and ensures that the data generated are reliable and actionable. The use of a seven-point Likert scale in the FDM questionnaire can reduce the ambiguity gap for each acceptance value in expert agreement to only 3.3% compared to 20% when using a five-point Likert scale (Noh et al., 2019). In addition, a larger Likert scale can provide more precise and accurate responses (Chang et al., 2011; Mohd Jamil & Mat Noh, 2021). The questionnaire consisted of five constructs: one related to respondent demographics and four related to module components, namely learning outcomes, learning content, learning process, and learning assessment. In total, the FDM questionnaire comprised 50 elements. These learning module elements were developed based on the TABA Curriculum Model, a literature review, and interviews with experts.

Nine experts validated the FDM questionnaire to ensure that the elements in each component of the learning module were content-appropriate before it was distributed to experts for consensus evaluation. The Content Validity Index (CVI), including the Scale-Level CVI (S-CVI), indicated a validity of 0.99 for relevance and clarity. The reliability of the FDM questionnaire was determined based on the results of a pilot study involving 30 respondents. The analysis showed a Cronbach's alpha (α) value of 0.974. Based on the CVI and Cronbach's alpha values, the FDM questionnaire was considered to have strong content validity and high reliability. Subsequently, the questionnaires were distributed individually via email and WhatsApp to obtain responses from expert participants. The collected data were then entered into Microsoft Excel for data analysis.

Sampling and Selection of Professional Experts

A total of 31 experts were selected for the FDM consensus. The experts involved in the FDM consensus were different from those involved in the instrument reliability study. The recommended number of experts in Delphi studies generally ranges from 10 to 15 participants (Skulmoski et al., 2007). Other studies suggest that Delphi respondents should meet discipline-specific criteria, with sample sizes ranging from 5 to 20 participants (Taylor, 2020). In addition, some studies have reported the use of 16 experts (Markus & Ishak, 2022), while others suggest a broader range of 10 to 50 experts (Al-Rikabi & Montazer, 2024). A large number of experts may also be appropriate when participation is conducted remotely via email or online platforms (Mohd Jamil & Mat Noh, 2021). Therefore, based on these references, the number of experts selected in this study meets the recommended requirements, as the consensus was conducted online via email and social media platforms.

The sampling technique used was purposive sampling, which involves selecting participants based on specific scientific criteria. These criteria include high academic qualifications, expertise in the research area, a minimum of five years of professional experience in the relevant field, willingness to participate with full commitment based on research experience, and absence of personal interests. Research indicates that expert knowledge in the field is essential in Delphi studies (Landeta & Lertxundi, 2024). In addition, data obtained from expert judgement help determine the level of consensus, potential implications and possible outcomes. Experts are defined as individuals with high levels of skill and knowledge (including strong academic qualifications), and extensive experience in the relevant field of study (Kurniawan et al., 2023). They are considered competent if they have at least five years of consistent experience in the area under investigation (Al-Rikabi & Montazer, 2024; Awang et al., 2016; Chua et al., 2024; Markus & Ishak, 2022; Noh et al., 2019). The respondents were also committed to completing the study and had no personal interests, ensuring the study remain unbiased (Noh et al., 2019). The demographic details of the experts involved in the consensus are presented in Table 2.

Table 2

Experts' Demographic Information

Demographic information	Details	N	Percentage
Gender	Male	22	71%
	Female	9	29%
Educational Degree	Master's	0	0%
	Doctor of Philosophy	31	100%
Expertise	Physics Curriculum/Pedagogy	5	16%
	STEM Education/Integrated Science Education	4	13%
	Instrumentation Physics/ Material Physics/ Biophysics/ Climatology/ Earth Physics	12	39%
	Learning Media/ Technology	5	16%
	Physics Learning Assessment	5	16%
Years of Experience	No experience	0	0%
	Less than 5 years	0	0%
	5 – 15 years	6	19%
	16 – 25 years	15	49%
	More than 25 years	10	32%
Academic Position	Staff	1	3%
	Lecturer	0	0%
	Assistant Professor	7	23%
	Associate Professor	11	35%
	Professor	12	39%
Structural Position	Lecturer	18	58%
	Study Program Coordinator	5	16%
	Head of Department/Station	3	10%
	Vice Dean	1	3%
	Dean	2	6%
	Vice-Rector	1	3%
	Rector	1	3%
Institution Location in Indonesia	Sumatera	18	58%
	Java	7	23%
	Borneo	1	3%
	Sulawesi	2	6%
	Bali	1	3%
	Nusa Tenggara	1	3%
	Papua	1	3%
Institution	Public University	29	94%
	Private University	1	3%
	Government Institution	1	3%

Data Analysis

The data were analyzed using the FDM based on triangular fuzzy number and the defuzzification process (Chang et al., 2000; Hasim et al., 2023). The data analysis procedure using the FDM is described as follows.

Step 1: Convert the seven-point linguistic scale into triangular fuzzy numbers (Al-Rikabi & Montazer, 2024; Elliott & Shin, 2002; Hasim et al., 2023; Markus & Ishak, 2022), as presented in Table 3.

Table 3

Seven-Point Linguistic Scale

Linguistic scale	Score	Fuzzy number		
		m_1	m_2	m_3
Extremely Agree	7	0.90	1.00	1.00
Strongly Agree	6	0.70	0.90	1.00
Agree	5	0.50	0.70	0.90
Moderately Agree	4	0.30	0.50	0.70
Disagree	3	0.10	0.30	0.50
Strongly Disagree	2	0.00	0.10	0.30
Extremely Disagree	1	0.00	0.00	0.10

Step 2: Determine the average value of each fuzzy number and place it below the corresponding fuzzy number.

Step 3: Calculate the threshold value, d. This d value is determined using Equation 1.

$$d\,(\tilde{m},\tilde{n}) = \sqrt{\frac{1}{3}\left[(\overline{m_1}-m_1)^2+(\overline{m_2}-m_2)^2+(\overline{m_3}-m_3)^2\right]} \quad (1)$$

Based on Equation 1, $\overline{m_1}$, $\overline{m_2}$, and $\overline{m_3}$ represent the average fuzzy values, whereas m_1, m_2, and m_3 represent the fuzzy values obtained from the respondents' agreement scores. Calculating the threshold value (d) is the first condition that must be satisfied, where d must be less than or equal to 0.20 (Al-Rikabi & Montazer, 2024; Chen, 2000; Cheng & Lin, 2002; Mohd Khalli et al., 2022), indicating that the element has achieved expert consensus.

Step 4: Calculate the percentage of expert consensus by determining the proportion of elements that satisfy the threshold value criterion in Step 3. This represents the second condition that must be met, whereby the percentage of expert consensus must be at least 75.0% (Al-Rikabi & Montazer, 2024; Chen, 2000; Chu & Hwang, 2008; Mohd Khalli et al., 2022).

Step 5: Perform defuzzification by calculating the mean of the fuzzy numbers (Al-Rikabi & Montazer, 2024; Markus & Ishak, 2022; Yusoff et al., 2021). The fuzzy score (A) is calculated using Equation 2.

$$A = \frac{1}{3}\left(m_1 + m_2 + m_3\right) \quad (2)$$

The fuzzy score is the third condition that must be satisfied for an element of the learning module components to be accepted. An element is accepted if its fuzzy score (A) is greater than or equal to the α - cut value of 0.5 (Mohd Khalli et al., 2022; Saido et al., 2018).

Step 6: Rank the elements within each component of the learning module based on the fuzzy score (A) obtained in Step 5. The element with the highest fuzzy score is assigned the highest priority (Al-Rikabi & Montazer, 2024; Saido et al., 2018). This ranking identifies the fundamental elements of the PhyARECi-STEM learning module. In addition, the input and suggestions provided by the expert respondents were also considered.

RESULTS

The research findings identify the valid fundamental elements of the four main components of the PhyARECi-STEM learning module—learning outcomes, content, process, and assessment—based on expert consensus. Furthermore, the findings demonstrate how validated elements are integrated within the framework to support physics problem-solving skills and scientific creativity. The results are presented in two subsections.

RQ1: Fundamental Elements of PhyARECi-STEM Learning Module

Fundamental Elements of Learning Outcomes

Learning outcomes are related to the Course Learning Outcomes (COs) and Sub-COs. A CO is a capability explicitly derived from the Programme Learning Outcomes (PLOs) and specified for a particular course. It describes the knowledge, skills and competencies that students are expected to achieve upon completing the course and is aligned with the course learning materials. The capabilities described by the COs can be measured or observed and represent the intended learning outcomes at each stage of the course. The learning outcomes component comprises six Sub-CO elements for the Applied Physics course, identified through curriculum analysis and interviews with experts. These elements are: (B.1) identifying examples of the application of physics in everyday life. (B.2) analyzing the application of mechanical concepts in agricultural technology and alternative energy; (B.3) analyzing the application of thermodynamic concepts in agricultural technology; (B.4) analyzing the application of electrical and magnetic concepts in digital technology and medical physics; (B.5) analyzing the application of wave and optic concepts to medical physics; and (B.6) solving interdisciplinary Applied Physics problems communicatively, collaboratively, creatively, systematically, innovatively, and responsibly. The findings for learning outcomes component are presented in Table 4.

Table 4

Fundamental Elements of the Learning Outcomes Component of the PhyARECi-STEM Learning Module

Element	Threshold value (d)	Percentage of experts' consensus	Fuzzy score (A)	Decision	Ranking
B.1	0.103	93.5%	0.911	ACCEPTED	2
B.2	0.111	83.9%	0.866	ACCEPTED	5
B.3	0.124	77.4%	0.848	ACCEPTED	6
B.4	0.122	83.87%	0.875	ACCEPTED	3
B.5	0.119	83.87%	0.872	ACCEPTED	4
B.6	**0.118**	**87.10%**	**0.913**	**ACCEPTED**	**1**

Table 4 shows that all six learning outcome elements achieved expert consensus, with threshold (d) values ranging from 0.103 and 0.124, consensus percentages ranging from 77.4% and 93.5%, and fuzzy scores ranging from 0.848 and 0.913. The ranking results showed that element B.6 obtained the highest fuzzy score and was considered valid, as its level of agreement exceeded the 75% consensus threshold. Therefore, element B.6 was designated as a Sub-CO for the PhyARECi-STEM learning module.

Fundamental Elements of Learning Content

Learning content is related to the learning topics and the depth and breadth of the learning materials. The learning content component comprises 14 elements from five sub-topics of the Applied Physics course, together with findings from expert interviews. The first sub-topic concerns the application of mechanical concepts to alternative technology (C.1), consisting of: introduction to mechanical concepts (C.1.1), application of mechanical concepts in agricultural technology (C.1.2), and application of mechanical concepts in alternative energy technologies (C.1.3). The second sub-topic focuses on the application of thermodynamic concepts in agricultural technology (C.2), consisting of: introduction to thermodynamic concepts (C.2.1) and application of thermodynamic concepts in agricultural technology (C.2.2). The third sub-topic addresses the application of electricity and magnetism concepts in digital technology and medical physics (C.3), consisting of introduction to the concepts of electricity and magnetism (C.3.1), application of electricity and magnetism concepts in medical physics technology (C.3.2), and application of electricity and magnetism concepts in digital technology (C.3.3). The fourth sub-topic concerns the application of wave and optics concepts in medical physics (C.4), consisting of: introduction to wave and optics concepts (C.4.1), and application of wave and optics concepts in medical physics technology (C.4.2). The fifth sub-topic focuses on solving problems related to global warming and climate change in a communicative, collaborative, creative, systematic, innovative and responsible manner (C.5), consisting of: global warming symptoms measurement problems and solutions (C.5.1); greenhouse gas problems and solutions (C.5.2); climate change impacts and solutions (C.5.3); and global warming impacts and solutions (C.5.4). The findings for the learning content component are presented in Table 5.

Table 5

Fundamental Elements of the Learning Content Component of the PhyARECi-STEM Learning Module

Element	Threshold value (d)	Percentage of experts' consensus	Fuzzy score (A)	Decision	Ranking
C.1	**Application of mechanics concepts to agricultural technology and alternative energy**				
C.1.1	0.148	83.87%	0.862	ACCEPTED	
C.1.2	0.110	90.32%	0.873	ACCEPTED	4
C.1.3	0.116	93.55%	0.901	ACCEPTED	
C.2	**Application of thermodynamics concepts in agricultural technology**				
C.2.1	0.164	80.65%	0.841	ACCEPTED	5
C.2.2	0.119	87.10%	0.868	ACCEPTED	
C.3	**Application of electricity and magnetism concepts to digital technology and medical physics**				
C.3.1	0.135	87.10%	0.865	ACCEPTED	
C.3.2	0.102	93.55%	0.898	ACCEPTED	2
C.3.3	0.102	93.55%	0.898	ACCEPTED	
C.4	**Application of wave and optics concepts in medical physics**				
C.4.1	0.135	87.10%	0.865	ACCEPTED	3
C.4.2	0.094	96.77%	0.903	ACCEPTED	
C.5	**Solving the problems of global warming and climate change in a communicative, collaborative, creative, systematic, innovative, and responsible manner**				
C.5.1	**0.110**	**90.32%**	**0.892**	**ACCEPTED**	
C.5.2	**0.119**	**87.10%**	**0.887**	**ACCEPTED**	**1**
C.5.3	**0.102**	**93.55%**	**0.898**	**ACCEPTED**	
C.5.4	**0.110**	**90.32%**	**0.892**	**ACCEPTED**	

Table 5 shows that all five learning content subtopics were accepted by experts, with threshold (d) values ranging from 0.094 to 0.164, consensus percentages ranging from 80.65% to 96.77%, and fuzzy scores ranging from 0.841 to 0.903. Based on the average fuzzy score ranking, subtopic C.5 received the highest score and was considered valid because its level of agreement exceeded the 75% consensus threshold. Therefore, subtopic C.5 was designated as the primary learning content in the PhyARECi-STEM learning module framework.

Fundamental Elements of the Learning Process

The learning process involves the use of effective instructional methods that are aligned with the characteristics of the course and implemented through learning activities to develop the specific competencies outlined in the course learning outcomes. The learning process component comprises 20 elements describing four categories of activities related to the integrated STEM approach. These four categories and their corresponding activities were identified through the literature review and expert interviews. The first category focuses on Applied Physics problems as the context for science learning (D.1), comprising: analyzing real-world problem scenarios related to the Applied Physics topics being studied (D.1.1); analyzing newspaper articles and similar sources representing Applied Physics problems in real-world contexts at the beginning of learning (D.1.2); analyzing socio-scientific issues and their implications at the beginning of learning (D.1.3); and analyzing videos depicting real-world problems related to the Applied Physics topics being studied (D.1.4). The second category uses AR as a form of technology literacy (D.2). This category consists of three activities: using AR to deepen understanding of physics concepts (D.2.1); using AR to visualize physics concepts (D.2.2), including visualizing complex physics concepts (D.2.2.1) and visualizing physics concepts that are not directly visible to the eye (abstract) (D.2.2.2). Third, using AR to strengthen multiple representations of physics (D.2.3), representing mathematics with graphs (D.2.3.1), images (D.2.3.2), translating verbal descriptions, images, and graphs into mathematical representations (D.2.3.3), and integrating images, videos, animations, data, graphs, and mathematical equations, and text (D.2.3.4). The third category involves engagement in the Engineering Design Process (D.3), including: ask, imagine, plan, create, and improve (D.3.1); identify and define the problem, gather information, identify possible solutions, create a prototype or model, test the model, reflect and redesign, and communicate (D.3.2); define and research the problem, plan possible solutions, select the best solution, develop a prototype, test, redesign, and communicate (D.3.3); and ask (identify needs and constraints), examine the problem, imagine (develop possible solutions), plan (select promising solutions), create (build prototypes), test and evaluate the prototypes, and improve (redesign as needed) (D.3.4). The fourth category focuses on content integration with Mathematics and other disciplines (D.4), including: implementing project-based problem-solving (D.4.1); producing simple physics experimental apparatus (D.4.2); analyzing cases through case study activities (D.4.3); conducting field studies related to natural phenomena (D.4.4); and applying mathematical thinking skills that extend beyond computation to broader competencies, such as data analysis (D.4.5). The findings for the learning process component are presented in Table 6.

Table 6

Fundamental Elements of the Learning Process Component of the PhyARECi-STEM Learning Module

Element	Threshold value (d)	Percentage of experts' consensus	Fuzzy score (A)	Decision	Ranking
D.1	**Focusing on Applied Physics Problems as Science Learning Context**				
D.1.1	**0.104**	**93.55%**	**0.908**	**ACCEPTED**	**1**
D.1.2	0.134	80.65%	0.873	ACCEPTED	4
D.1.3	0.103	93.55%	0.901	ACCEPTED	2
D.1.4	0.116	90.32%	0.880	ACCEPTED	3
D.2	**Using Augmented Reality as Technology Literacy**				
D.2.1	**Using Augmented Reality to Deepen Physics Concepts**				
D.2.1	**0.102**	**90.32%**	**0.905**	**ACCEPTED**	**1**
D.2.2	**Using Augmented Reality to Visualize Physics Concepts**				
D.2.2.1	0.093	93.55%	0.914	ACCEPTED	2
D.2.2.2	**0.070**	**96.77%**	**0.935**	**ACCEPTED**	**1**
D.2.3	**Using Augmented Reality to Strengthen Multiple Representations of Physics**				
D.2.3.1	0.118	83.87%	0.891	ACCEPTED	4
D.2.3.2	0.101	90.32%	0.902	ACCEPTED	3
D.2.3.3	**0.093**	**93.55%**	**0.911**	**ACCEPTED**	**1**
D.2.3.4	0.102	90.32%	0.909	ACCEPTED	2

(continued)

Element	Threshold value (d)	Percentage of experts' consensus	Fuzzy score (A)	Decision	Ranking
D.3	**Engagement in Engineering Design Process**				
D.3.1	0.205	61.29%	0.801	REJECTED	
D.3.2	**0.093**	**93.55%**	**0.908**	**ACCEPTED**	**1**
D.3.3	0.129	80.65%	0.889	ACCEPTED	3
D.3.4	0.098	90.32%	0.896	ACCEPTED	2
D.4	**Content integration with Mathematics or Other Disciplines**				
D.4.1	**0.093**	**93.55%**	**0.914**	**ACCEPTED**	**1**
D.4.2	0.120	83.87%	0.895	ACCEPTED	3
D.4.3	0.119	80.65%	0.876	ACCEPTED	4
D.4.4	0.106	87.10%	0.874	ACCEPTED	5
D.4.5	0.098	90.32%	0.896	ACCEPTED	2

Table 6 shows that, according to expert consensus, four learning process activities were identified, with 19 elements accepted and one element rejected. The accepted elements had threshold (d) values ranging from 0.093 to 0.134, consensus percentages ranging from 80.65% to 96.77%, and fuzzy scores ranging from 0.873 to 0.935. Fuzzy score rankings were determined for each activity category. For activity D.1, element D.1.1 obtained the highest score, whereas D.1.2 received the lowest. Activity D.2 comprised three groups, with elements D.2.1, D.2.2.2, and D.2.3.3 obtaining the highest scores. For activity D.3, element D.3.2 received the highest score, whereas D.3.3 received the lowest. In activity D.4, element D.4.1 achieved the highest score, while D.4.4 received the lowest. These six highest-ranked elements were considered valid because the expert agreement level exceeded the 75% consensus threshold. Therefore, these six elements were established as the fundamental elements of the learning process in the PhyARECi-STEM learning module framework.

Fundamental Elements of Learning Assessment

Learning assessment involves evaluating both the learning process and the learning outcomes of pre-service teachers to determine the achievement of the intended learning outcomes. The learning assessment component comprises 10 elements derived from two learning assessment components identified through the literature review and expert interviews. These two components are the types of learning assessment (E.1) and reflection on learning assessment (E.2). The first component, types of learning assessment (E.1), consists of two categories. The first is authentic assessment (E.1.1), which includes written assessment (E.1.1.1), performance assessment (E.1.1.2), portfolio assessment (E.1.1.3), and product assessment (E.1.1.4). The second is diagnostic, formative, and summative assessment (E.1.2), comprising diagnostic assessment (E.1.2.1), formative assessment (E.1.2.2), and summative assessments (E.1.2.3). The second component, reflection on learning assessment (E.2), includes remedial activities (E.2.1), enrichment activities (E.2.2), and follow-up activities (E.2.3). The findings for the learning assessment components are presented in Table 7.

Table 7

Fundamental Elements of the Learning Assessment Component of the PhyARECI-STEM Learning Module

Element	Threshold value (d)	Percentage of experts' consensus	Fuzzy score (A)	Decision	Ranking
E.1	**Types of Learning Assessment**				
E.1.1	**Authentic Assessment**				
E.1.1.1	**0.134**	**80.65%**	**0.873**	**ACCEPTED**	
E.1.1.2	**0.090**	**93.55%**	**0.920**	**ACCEPTED**	
E.1.1.3	**0.083**	**96.77%**	**0.919**	**ACCEPTED**	**1**
E.1.1.4	**0.080**	**96.77%**	**0.926**	**ACCEPTED**	
E.1.2	**Diagnostic, Formative, Summative Assessment**				
E.1.2.1	0.108	90.32%	0.889	ACCEPTED	
E.1.2.2	0.098	90.32%	0.896	ACCEPTED	2
E.1.2.3	0.106	87.10%	0.890	ACCEPTED	
E.2	**Reflection on Learning Assessment**				
E.2.1	0.131	80.65%	0.870	ACCEPTED	3
E.2.2	0.093	93.55%	0.908	ACCEPTED	2
E.2.3	**0.093**	**93.55%**	**0.914**	**ACCEPTED**	**1**

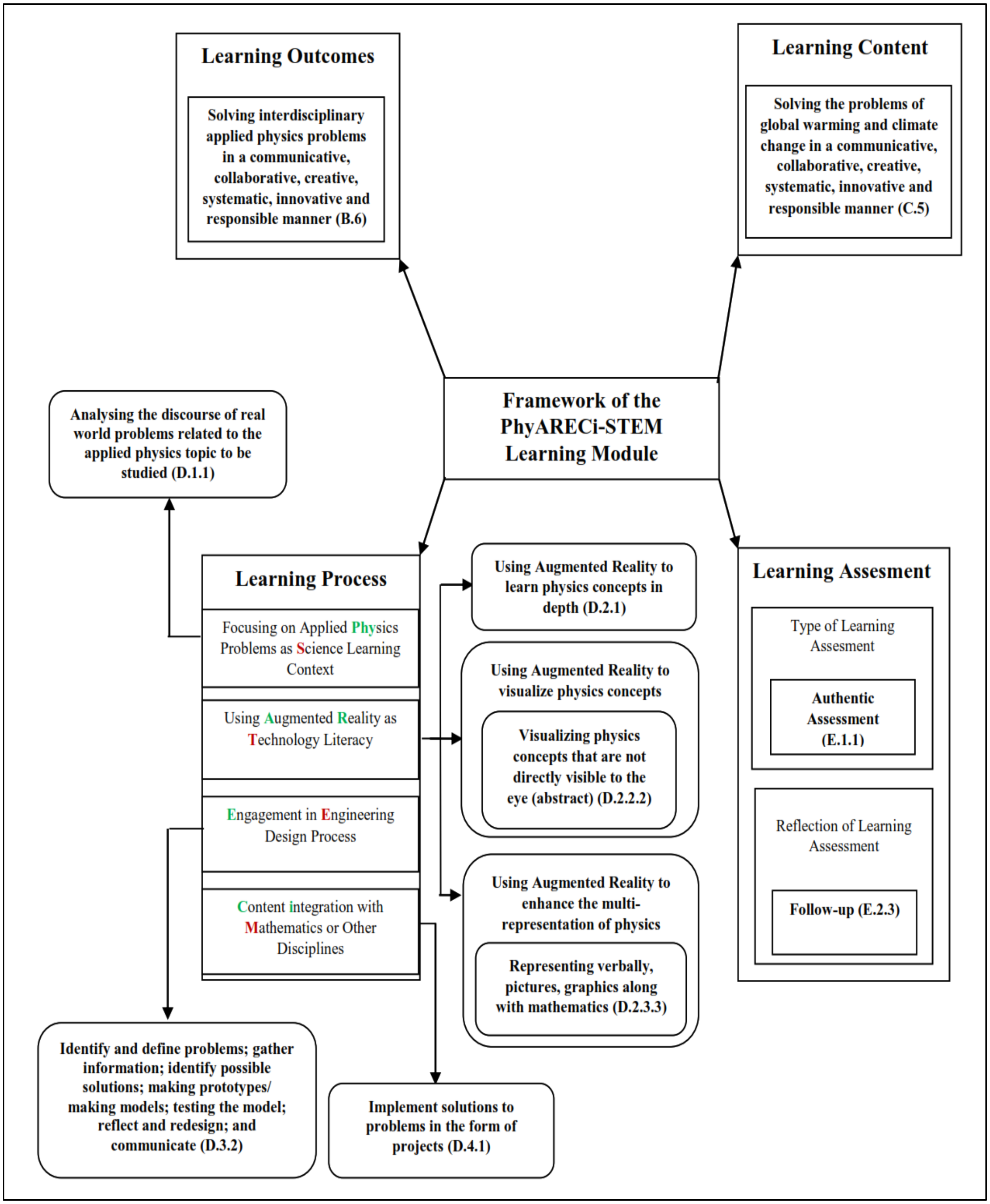
Table 7 shows that all elements in the learning assessment type and learning assessment reflection components were accepted by the experts. These elements had threshold (d) values ranging from 0.080 and 0.134, consensus percentages ranging from 80.65% to 96.77%, and fuzzy scores ranging from 0.870 to 0.926. Fuzzy score rankings were used to assess the representativeness of each element within the learning assessment component. For the learning assessment type, element E.1.1 obtained the highest ranking, whereas E.1.2 received the lowest. Meanwhile, for the learning assessment reflection component, element E.2.3 obtained the highest ranking, whereas E.2.1 received the lowest. Elements E.1.1 and E.2.3 were considered valid because the level of expert agreement exceeded the 75% consensus threshold. Therefore, these two elements were established as the fundamental elements of the learning assessment component in the PhyARECi-STEM learning module framework.

RQ2: Framework of the PhyARECi-STEM Learning Module

The research findings revealed that the PhyARECi-STEM learning module framework comprises 10 fundamental elements validated through expert consensus. These elements collectively represent the four main components of the learning module: learning outcomes, learning content, learning process, and learning assessment. All fundamental elements satisfied the established validity criteria. This indicates that the proposed learning module framework is pedagogically sound, has appropriate content, and supports the integration of technology to achieve the intended Applied Physics learning outcomes. The PhyARECi-STEM learning module framework is presented in Figure 2.

Figure 2

Framework of the PhyARECi-STEM Learning Module Based on Expert-Validated Fundamental Elements



DISCUSSION

RQ1: Fundamental Elements of the PhyARECi-STEM Learning Module

Fundamental Element of Learning Outcomes

The learning outcomes component comprises six elements validated through expert consensus, with element B.6 receiving the highest fuzzy score (Table 4). Element B.6 focuses on solving interdisciplinary Applied Physics problems in a communicative, collaborative, creative, systematic, innovative, and responsible manner. This finding confirms that communication and collaboration are fundamental to interdisciplinary STEM problem-solving, as they facilitate pre-service physics teachers' conceptual understanding and the development of their STEM identity (Stewart, 2022; Wells et al., 2025). However, communication and collaboration alone are insufficient without the support of a systematic and innovative interdisciplinary framework. Consistent with previous research, interdisciplinary interactions foster creativity, although such creativity is often guided by structured learning processes (Chang et al., 2022). Furthermore, an innovative culture combined with a systematic approach strengthens decision-making by encouraging consideration of ethical, social, and cultural dimensions in STEM contexts (Ammar et al., 2024; Ong et al., 2024; Steffensen, 2024). Consequently, pre-service physics teachers are better prepared to become reflective aand responsible professionals who can address real-world problems from an interdisciplinary perspective while considering the broader implications of their work.

Fundamental Elements of Learning Content

The learning content component comprises 14 elements across five sub-topics of the Applied Physics course that were validated through expert consensus, with sub-topic C.5 receiving the highest fuzzy score (Table 5). Sub-topic C.5 focuses on solving problems related to global warming and climate change. This content addresses contemporary global challenges (Abbass et al., 2022; Bonneuil et al., 2021), supports the achievement of the Sustainable Development Goals (SDGs) (Arora & Mishra, 2023; Saleem et al., 2024), and aligns with the Indonesian Merdeka Curriculum (Tang, 2024). These findings are consistent with previous research indicating that Applied Physics learning modules should emphasize authentic real-world problems (Roehrig et al., 2021b) and solutions to both global and local issues (Donmez, 2020). Therefore, global warming and climate change constitute essential learning content for the PhyARECi-STEM learning module.

Fundamental Elements of the Learning Process

The learning process component comprises 19 elements grouped into four learning activities related to the integrated STEM approach, all of which were validated through expert consensus (Table 6). These four categories of learning activities are discussed as follows. The first category focuses on using discourse analysis (D.1.1) to present Applied Physics problems as the context for science learning (D.1). Among the D.1 elements, discourse analysis (D.1.1) received the highest fuzzy score. This finding is consistent with previous research demonstrating that the analysis of real-world context-based discourse promotes cross-disciplinary thinking and higher-order cognitive skills more effectively than conventional media (Bendraou, 2024). Furthermore, STEM-integrated discourse has been shown to facilitate the application of scientific knowledge and reasoning in solving authentic real-world problems (Arık & Topçu, 2022; Reynante et al., 2020; Siverling et al., 2017). Therefore, discourse analysis provides an effective instructional strategy for engaging pre-service physics teachers with authentic real-world issues while establishing meaningful contexts for science learning.

Second, using AR as technology literacy (D.2) is divided three activities: using AR to deepen physics concepts (D.2.1), using AR to visualize physics concepts (D.2.2), and using AR to strengthen multiple representations of physics (D.2.3). Activity D.2.1 is consistent with previous research demonstrating the effectiveness of AR in deepening understanding of physics concepts, including Newton's laws, electricity, and mechanics (Ferdiman et al., 2023; Hedenqvist et al., 2023; Ropawandi et al., 2022). In Activity D.2.2, the visualization of physics concepts that cannot be directly observed emerged as the most prominent element. This finding is supported by studies showing that AR can realistically represent abstract concepts, promote conceptual exploration, and enhance engagement in active learning (Radu et al., 2023). However, the effectiveness of AR should be carefully managed, particularly when teaching complex topics that may increase learners' cognitive load (Thees et al., 2020). Activity D.2.3 emphasizes the use of multiple representations (verbal, visual, graphical, and mathematical representations) are essential for enabling pre-service physics teachers to communicate scientific ideas comprehensively within integrated STEM learning environments (Nugraha et al., 2023). Therefore, the findings highlight the essential role of AR as a technology literacy component.

Third, engagement in the Engineering Design Process (D.3) identified element D.3.2 as the highest-ranked activity, comprising the following stages: identify and define the problem, gather information, identify possible solutions, create a prototype or model, test the model, reflect and redesign, and communicate. Compared with other engineering design elements, D.3.2 includes two additional stages (gather information and communicate) which distinguish it from other models. The gathering information stage plays an essential role in the engineering design process by strengthening problem-solving, fostering innovation, and developing critical thinking and interdisciplinary collaboration (Nurtanto et al., 2020). Meanwhile, the communication stage ensures that proposed solutions align with users' needs while promoting shared understanding among team members (Lin et al., 2021). These findings are consistent with previous studies emphasizing the importance of actively engaging pre-service teachers throughout the entire engineering design process, including experiencing failure, reflecting on outcomes, and progressively refining solutions (Chien et al., 2023; Jolly, 2017; Nugraha et al., 2023; Siverling et al., 2019; Stretch & Roehrig, 2021). The Engineering Design Process lies at the core of integrated STEM education because it serves as the integrative mechanism that connects the STEM disciplines and transforms scientific knowledge into meaningful real-world solutions (Donmez, 2020; Nugraha et al., 2023). Therefore, the validated fundamental elements of the Engineering Design Process have strong potential to equip pre-service physics teachers with the competencies needed to solve complex problems, develop innovative solutions, and collaborate effectively across disciplines.

Finally, content integration with mathematics or other disciplines (D.4) identified implementing problem solutions through projects (D.4.1) as the highest ranked element. This finding is consistent with previous research highlighting project-based learning as an effective approach for promoting thinking, learning, and the integration of knowledge and skills across STEM disciplines (Bungum & Mogstad, 2024; Lin et al., 2023). Furthermore, integrated STEM education emphasizes the connection between research and practice in higher education, enabling pre-service teachers to explore, integrate and apply interdisciplinary knowledge through project-based learning in interdisciplinary courses (Zhan & Niu, 2023). Therefore, implementing problem solutions through projects provides an effective learning activity for integrating STEM content while fostering interdisciplinary learning among pre-service physics teachers.

Fundamental Elements of Learning Assessment

The learning assessment comprises 10 elements across two learning assessment components: assessment type (E.1) and reflection on learning assessment (E.2), as shown in Table 7. Within the assessment type component, authentic assessment (E.1.1) emerged as the fundamental element. This finding is consistent with previous research indicating that written assessments remain essential for measuring students' knowledge and skills (Gao et al., 2020). However, written assessments alone are insufficient and should be complemented by other forms of assessment. Consistent with earlier studies, performance, portfolio, and product assessments enable educators to monitor the learning process, creativity, and the depth of learning outcomes within the context of teacher education (DeCoito & Estaiteyeh, 2022; McArthur, 2023; Wilson, 2021; Yakob et al., 2021). Within the reflection on learning assessment component, follow-up (E.2.3) emerged as the fundamental element. This finding is also consistent with previous research showing that continuous feedback and appropriate follow-up activities strengthen STEM competency development and promote long-term learning readiness (Cantlon et al., 2024; Karamustafaoğlu & Pektaş, 2023; Neher-Asylbekov & Wagner, 2023). Therefore, the assessment elements identified through expert consensus are well-aligned with the principles of STEM and AR-integrated learning and provide a comprehensive approach to assessing both learning processes and learning outcomes.

RQ2: Framework of the PhyARECi-STEM Learning Module

The PhyARECi-STEM learning module framework has the potential to support pre-service physics teachers in mastering Applied Physics concepts and developing their STEM identity through the integration of authentic contexts, interdisciplinary content, AR, engineering design, and creative problem-solving activities. The integration of AR into the learning content and learning process provides situated learning experiences through 3D visualizations and contextual environments that simulate professional practice, consistent with situated learning theory (Lave & Wenger, 1991). Throughout the learning process, pre-service physics teachers design and produce prototypes or other learning artifacts, thereby embodying the principles of constructionism (Harel & Papert, 1991). The framework also reflects the characteristics of Roehrig's integrated STEM model, which emphasizes meaningful integration across STEM disciplines while addressing authentic real-world problems (Roehrig et al., 2021a). Furthermore, learning activities that broaden the scope of problem exploration through AR integration and apply heuristic strategies and goal-based analysis have the potential to enhance physics problem-solving skills (Newell & Simon, 1972). Likewise, learning activities that incorporate domain-relevant skills, creative processes, task motivation, and supportive social environments (the Engineering Design Process) have the potential to foster scientific creativity (Amabile, 1996). The framework also incorporates authentic assessment and continuous follow-up activities, which can strengthen STEM competencies and enhance learning readiness. Collectively, these findings have important pedagogical implications, as the proposed learning module framework provides lecturers with a validated and adaptable guide for designing Applied Physics learning that integrates STEM and AR. Therefore, the PhyARECi-STEM learning module framework was constructed from expert-validated fundamental elements intended to support physics problem-solving skills and scientific creativity among pre-service physics teachers.

CONCLUSION AND RECOMMENDATION

The findings indicate that the fundamental elements of the PhyARECi-STEM learning module satisfied the threshold value, expert consensus percentage, and fuzzy score criteria. These validated elements encompass the four main components of the module: learning outcomes, learning content, learning process, and learning assessment. The findings underscore the importance of systematically identifying and validating fundamental elements during module development, as many existing STEM learning modules have undergone limited expert validation. This study contributes to the field by proposing the PhyARECi-STEM learning module framework, which is constructed from systematically validated fundamental elements and grounded in established educational theories. Theoretically, the framework advances the development of Applied Physics learning by integrating the STEM approach and AR, with the potential to support the physics problem-solving skills and scientific creativity of pre-service physics teachers. Practically, the study provides a structured and validated framework that can guide lecturers and curriculum developers in designing STEM- and AR-integrated learning modules. The study was limited to expert-consensus-based framework development and did not empirically evaluate implementation, usability, or effects on pre-service physics teachers' problem-solving skills and scientific creativity. Future research should therefore develop the module from the proposed framework and evaluate its feasibility and effectiveness with intended users.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

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REFERENCES

Abbass, K., Qasim, M. Z., Song, H., Murshed, M., Mahmood, H., & Younis, I. (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environmental Science and Pollution Research*, *29*(28), 42539–42559. https://doi.org/10.1007/s11356-022-19718-6

Adly, M., Nasser, N., & Sharaf, N. (2021). PHYAR: Introducing a mixed/augmented reality platform for physics concepts. *Proceedings of the 13th International Conference on Computer Supported Education (CSEDU 2021), 2*, 338–345. https://doi.org/10.5220/0010496103380345

Afrizon, R., Mohtar, L. E., & Mohd Azmi, M. S. (2025). When studying applied physics: What problems are there, and do pre-service physics teachers need? *International Journal of Advances in Applied Sciences, 14*(3), 650–661. https://doi.org/10.11591/ijaas.v14.i3.pp650-661

Akhsan, H., Putra, G. S., Wiyono, K., Romadoni, M., & Furqon, M. (2023). Development of a STEM-based introduction to quantum physics module on the sub-subject of potential variations in the physics education study program. *Jurnal Penelitian Pendidikan IPA*, *9*(9), 7408–7412. https://doi.org/10.29303/jppipa.v9i9.3577

Al-Rikabi, Y. K., & Montazer, G. A. (2024). Designing an e-learning readiness assessment model for Iraqi universities employing fuzzy Delphi method. *Education and Information Technologies*, *29*, 2217–2257. https://doi.org/10.1007/s10639-023-11889-0

Al Mamun, M. A., & Lawrie, G. (2023). Student-content interactions: Exploring behavioural engagement with self-regulated inquiry-based online learning modules. *Smart Learning Environments*, *10*(1), 1–31. https://doi.org/10.1186/s40561-022-00221-x

Amabile, T. M. (1996). *Creativity in context: Update to the social psychology of creativity*. Westview Press.

Ammar, M., Al-Thani, N. J., & Ahmad, Z. (2024). Role of pedagogical approaches in fostering innovation among K-12 students in STEM education. *Social Sciences and Humanities Open*, *9*, Article 100839, 1–13. https://doi.org/10.1016/j.ssaho.2024.100839

Arifanti, D. R., Thalhah, S. Z., Mafidapuspadina, M., & Muzaini, M. (2021). Pengembangan lembar kerja peserta didik berbasis STEM untuk meningkatkan kemampuan kreativitas matematika. *AKSIOMA: Jurnal Program Studi Pendidikan Matematika*, *10*(4), 2710-2725. https://doi.org/10.24127/ajpm.v10i4.4258

Aris, N. M., Ibrahim, N. H., & Halim, N. D. A. (2025). Design and Development Research (DDR) approach in designing design thinking chemistry module to empower students' innovation competencies. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *44*(1), 55–68. https://doi.org/10.37934/araset.44.1.5568

Arık, M., & Topçu, M. S. (2022). Implementation of engineering design process in the K-12 science classrooms: Trends and issues. *Research in Science Education*, *52*(1), 21–43. https://doi.org/10.1007/s11165-019-09912-x

Arora, N. K., & Mishra, I. (2023). Sustainable development goal 13: Recent progress and challenges to climate action. *Environmental Sustainability*, *6*(3), 297–301. https://doi.org/10.1007/s42398-023-00287-4

Awang, S., Ahmad, S., Alias, N., & Dewitt, D. (2016). Design of an instructional module on basic life support for homeschooled children. *Cogent Education*, *3*(1). https://doi.org/10.1080/2331186X.2016.1188439

Babic, S., McNiven, A. L., Bezjak, A., Balogh, J. M., Mah, K., & Tsao, M. N. (2023). Evolution and evaluation of a structured applied physics course for radiation oncology and radiation physics trainees. *Journal of Cancer Education*, *38*(3), 813–820. https://doi.org/10.1007/s13187-022-02190-8

Bendraou, R. (2024). Critical pedagogy: Investigating critical thinking skills and active citizenship through discourse analysis in a Moroccan EFL textbook. *International Journal of English Language Studies*, *6*(1), 98–109. https://doi.org/10.32996/ijels.2024.6.1.10

Bonneuil, C., Choquet, P. L., & Franta, B. (2021). Early warnings and emerging accountability: Total's responses to global warming, 1971–2021. *Global Environmental Change*, *71*, 1–10. https://doi.org/10.1016/j.gloenvcha.2021.102386

Bungum, B., & Mogstad, E. (2024). Building and programming a weather station: Teachers' views on values and challenges in a comprehensive STEM project. *Research in Science and Technological Education*, *42*(2), 450–466. https://doi.org/10.1080/02635143.2022.2103108

Cantlon, J. F., Becker, K. T., & DeLong, C. M. (2024). Computational thinking during a short, authentic, interdisciplinary STEM experience for elementary students. *Journal for STEM Education Research*, *7*(3), 425–443. https://doi.org/10.1007/s41979-024-00117-0

Chang, P. L., Hsu, C. W., & Chang, P. C. (2011). Fuzzy Delphi method for evaluating hydrogen production technologies. *International Journal of Hydrogen Energy*, *36*(21), 14172–14179. https://doi.org/10.1016/j.ijhydene.2011.05.045

Chang, P. T., Huang, L. C., & Lin, H. J. (2000). The fuzzy Delphi method via fuzzy statistics and membership function fitting and an application to the human resources. *Fuzzy Sets and Systems*, *112*(3), 511–520. https://doi.org/10.1016/S0165-0114(98)00067-0

Chang, T. S., Wang, H. C., Haynes, A. M., Song, M. M., Lai, S. Y., & Hsieh, S. H. (2022). Enhancing student creativity through an interdisciplinary, project-oriented problem-based learning undergraduate curriculum. *Thinking Skills and Creativity*, *46*, 1–10. https://doi.org/10.1016/j.tsc.2022.101173

Chen, C. T. (2000). Extensions of the TOPSIS for group decision-making under fuzzy environment. *Fuzzy Sets and Systems*, *114*(1), 1–9. https://doi.org/10.1016/j.asoc.2014.10.013

Cheng, C.-H., & Lin, Y. (2002). Evaluating the best main battle tank using fuzzy decision theory with linguistic criteria evaluation. *European Journal of Operational Research*, *142*(1), 174–186. https://doi.org/10.1016/S0377-2217(01)00280-6

Chien, Y. H., Liu, C. Y., Chan, S. C., & Chang, Y. S. (2023). Engineering design learning for high school and college first-year students in a STEM battlebot design project. *International Journal of STEM Education*, *10*(1). https://doi.org/10.1186/s40594-023-00403-0

Chu, H. C., & Hwang, G. J. (2008). A Delphi-based approach to developing expert systems with the cooperation of multiple experts. *Expert Systems with Applications*, *34*(4), 2826–2840. https://doi.org/10.1016/j.eswa.2007.05.034

Chua, C., Kosnin, A. M., & Yeo, K. J. (2024). Fuzzy Delphi method for A-level mathematics technological pedagogical and content knowledge module. *International Journal of Evaluation and Research in Education*, *13*(1), 441–453. https://doi.org/10.11591/ijere.v13i1.25982

Cumino, C., & Zich, U. (2021). Geometry to build models, models to visualize geometry. *Digital Experiences in Mathematics Education*, *7*, 149–166.https://doi.org/10.1007/s40751-020-00080-6

DeCoito, I., & Estaiteyeh, M. (2022). Online teaching during the COVID-19 pandemic: Exploring science/STEM teachers' curriculum and assessment practices in Canada. *Disciplinary and Interdisciplinary Science Education Research*, *4*, Article 8. https://doi.org/10.1186/s43031-022-00048-z

del Río, J. A., Russell, J. M., & Juárez, D. (2020). Applied physics in Mexico: Mining the past to predict the future. *Scientometrics*, *125*(1), 187–212. https://doi.org/10.1007/s11192-020-03639-7

Donmez, I. (2020). STEM education dimensions: From STEM literacy to STEM assessment. In S. Idin (Ed.), *Research highlights in education and science* (pp. 154–170). ISRES Publishing.

Elliott, K. M., & Shin, D. (2002). Student satisfaction: An alternative approach to assessing this important concept. *Journal of Higher Education Policy and Management*, *24*(2), 197–209. https://doi.org/10.1080/1360080022000013518

Fadhilah, F., Effendi, Z. M., & Ridwan. (2021). Development of contextual teaching and learning (CTL) models in applied physics courses. *International Journal of Multicultural and Multireligious Understanding*, *8*(3), 364–375. https://doi.org/10.18415/ijmmu.v8i3.2425

Farihah, M. J., Norawi, A. M., & Jahan, A. N. (2021). Game-based STEM module development for KSSM science teachers. *Journal of Turkish Science Education*, *18*(2), 249–262. https://doi.org/10.36681/tused.2021.63

Farwati, R., Metafisika, K., Sari, I., Sitinjak, D. S., Solikha, D. F., & Solfarina, S. (2021). STEM education implementation in Indonesia: A scoping review. *International Journal of STEM Education for Sustainability*, *1*(1), 11–32. https://doi.org/10.53889/ijses.v1i1.2

Fathurohman, A., Susiloningsih, E., & Arianti, A. (2021). Physics module based on STEM problem based learning on Newton's motion law material for senior high school. *Journal of Physics: Conference Series*, *1869*(1), Article 012155. https://doi.org/10.1088/1742-6596/1869/1/012155

Febriyanti, E., Indrawati, Supeno, Sutarto, & Mahardika, I. K. (2018). The effectiveness of the module-based STEM (Science, Technology, Engineering, Mathematics) to study physics at vocational high school. *International Journal of Advanced Research*, *6*(5), 1367–1370. https://doi.org/10.21474/ijar01/7168

Ferdiman, B., Al Akbar, H., Faturrahman, M. R., & Maulana, F. I. (2023). Development of augmented reality application in physics through Newton's laws and object interaction. *Procedia Computer Science*, *227*, 699–708. https://doi.org/10.1016/j.procs.2023.10.574

Gao, X., Li, P., Shen, J., & Sun, H. (2020). Reviewing assessment of student learning in interdisciplinary STEM education. *International Journal of STEM Education*, *7*(1). https://doi.org/10.1186/s40594-020-00225-4

Geiger, V., Mulligan, J., Date-Huxtable, L., Ahlip, R., Heath Jones, D., Julian May, E., Rylands, L., & Wright, I. (2018). An interdisciplinary approach to designing online learning: Fostering pre-service mathematics teachers' capabilities in mathematical modelling. *ZDM - Mathematics Education*, *50*(1–2), 217–232. https://doi.org/10.1007/s11858-018-0920-x

Goos, M., Carreira, S., & Namukasa, I. K. (2023). Mathematics and interdisciplinary STEM education: Recent developments and future directions. *ZDM - Mathematics Education*, *55*(7), 1199–1217. https://doi.org/10.1007/s11858-023-01533-z

Handayani, E. S., Yuberti, Saregar, A., & Wildaniati, Y. (2021). Development of STEM-integrated physics e-module to train critical thinking skills: The perspective of preservice teachers. *IOP Conference Series: Earth and Environmental Science*, *1796*(1). https://doi.org/10.1088/1742-6596/1796/1/012100

Harel, I., & Papert, S. (1991). *Constructionism: Research reports and essays, 1985-1990*. Ablex Publishing Coorporation Norwood.

Hasim, M. A., Jabar, J., Sufian, A., Ibrahim, N. F., & Khalid, F. A. (2023). Employing fuzzy Delphi techniques to validate the components and contents of e-learning antecedents and usage behavior towards e-learning performance. *European Journal of Educational Research*, *12*(1), 467–480. https://doi.org/10.12973/eu-jer.12.1.467

Hedenqvist, C., Romero, M., & Vinuesa, R. (2023). Improving the learning of mechanics through augmented reality. *Technology, Knowledge and Learning*, *28*(1), 347–368. https://doi.org/10.1007/s10758-021-09542-1

Ilma, A. Z., Wilujeng, I., Widowati, A., Nurtanto, M., & Kholifah, N. (2023). A systematic literature review of STEM education in Indonesia (2016-2021): Contribution to improving skills in 21st century learning. *Pegem Egitim ve Ogretim Dergisi*, *13*(2), 134–146. https://doi.org/10.47750/pegegog.13.02.17

Ismail, N. K., Mohamed, S., & Hamzah, M. I. (2019). The application of the fuzzy Delphi technique to the required aspect of parental involvement in the effort to inculcate positive attitude among preschool children. *Creative Education*, *10*(12), 2907–2921. https://doi.org/10.4236/ce.2019.1012216

Ismet, Darmawijayo, Aisyah, N., Nawawi, E., Yusup, M., & Meilinda. (2020). How to support pre-service teachers' conceptual understanding using hyperthermia as STEM context: A case study in sciences education department Universitas Sriwijaya. *Journal of Physics: Conference Series*, *1480*(1), Article 012072. https://doi.org/10.1088/1742-6596/1480/1/012072

Jackson, C., Mohr-Schroeder, M. J., Bush, S. B., Maiorca, C., Roberts, T., Yost, C., & Fowler, A. (2021). Equity-oriented conceptual framework for K-12 STEM literacy. *International Journal of STEM Education*, *8*(1), 1–16. https://doi.org/10.1186/s40594-021-00294-z

Jolly, A. (2017). *STEM by design: Strategies and activities for grades 4-8*. Routledge.

JR, J. J. R., & Sulaiman, F. (2020). The development of integrated STEM-PBL physics module for learning classical mechanics in secondary education. *Solid State Technology*, *63*(6), 19410–19433. https://solidstatetechnology.us/index.php/JSST/article/view/8174

Juandi, T., Kaniawati, I., Samsudin, A., Verawati, N. N. S. P., & Zahara, L. (2024). Learning problems of prospective teachers in lectures modern physics during the COVID-19 pandemic. *KnE Social Sciences*, *2024*, 1221–1238. https://doi.org/10.18502/kss.v9i13.16064

Karamustafaoğlu, O., & Pektaş, H. M. (2023). Developing students' creative problem solving skills with inquiry-based STEM activity in an out-of-school learning environment. *Education and Information Technologies*, *28*(6), 7651–7669. https://doi.org/10.1007/s10639-022-11496-5

Kariman, D., Harisman, Y., Sovia, A., & Prahmana, R. C. I. (2019). Effectiveness of guided discovery-based module: A case study in Padang city, Indonesia. *Journal on Mathematics Education*, *10*(2), 239–250. https://jme.ejournal.unsri.ac.id/index.php/jme/article/view/3791

Kementerian Perencanaan Pembangunan Nasional. (2024). *Ringkasan eksekutif peta jalan pendidikan Indonesia tahun 2025–2045*.

Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi. (2022a). *Pedoman penerapan kurikulum dalam rangka pemulihan pembelajaran* (Kepmendikbudristek No. 56 Tahun 2022).

Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi. (2022b). *Standar proses pada pendidikan usia dini, jenjang pendidikan dasar, dan jenjang pendidikan menengah* (Permendikbudristek No. 16 Tahun 2022)

Khotimah, R. P., Adnan, M., Che Ahmad, C. N., & Murtiyasa, B. (2023). The effectiveness of the STEMDISLEARN module in improving students' critical thinking skills in the differential equations course. *Cogent Education*, *10*(2). https://doi.org/10.1080/2331186X.2023.2220233

Kurniawan, D., Samsura, D. A. A., & van Deemen, A. M. A. (2023). Exploring expertise criteria of university academics. *Journal of Social Studies Education Research*, *14*(4), 75–107. https://www.learntechlib.org/p/224811/

Landeta, J., & Lertxundi, A. (2024). Quality indicators for Delphi studies. *Futures and Foresight Science*, *6*(1). https://doi.org/10.1002/ffo2.172

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge University Press.

Lin, K. Y., Lu, S. C., Hsiao, H. H., Kao, C. P., & Williams, P. J. (2023). Developing student imagination and career interest through a STEM project using 3D printing with repetitive modeling. *Interactive Learning Environments*, *31*(5), 2884–2898. https://doi.org/10.1080/10494820.2021.1913607

Lin, K. Y., Wu, Y. T., Hsu, Y. T., & Williams, P. J. (2021). Effects of infusing the engineering design process into STEM project-based learning to develop preservice technology teachers' engineering design thinking. *International Journal of STEM Education*, *8*(1), 1–15. https://doi.org/10.1186/s40594-020-00258-9

Markus, L., & Ishak, M. Z. (2022). Development of the Secondary School Quantum Physics-STEM (SSQP-STEM) instructional module for physics teachers: A Fuzzy Delphi Method (FDM) approach. *International Research Journal of Education and Sciences,* *6*(2), 16-29. https://www.masree.info/wp-content/uploads/2022/10/Development-Of-The-Secondary-School-Quantum-Physics-Stem-SSQP-Stem-Instructional-Module-For-Physics-Teachers-A-Fuzzy-Delphi-Method-FDM-Approach.pdf

Martaningsih, S. T., Maryani, I., Prasetya, D. S., Prwanti, S., Sayekti, I. C., Aziz, N. A. A., & Siwayanan, P. (2022). STEM problem-based learning module: A solution to overcome elementary students' poor problem-solving skills. *Pegem Journal of Education and Instruction*, *12*(4), 340–348. https://doi.org/10.47750/pegegog.12.04.35

Mayasari, T., Susilowati, E., & Winarno, N. (2019). Practicing integrated STEM in renewable energy projects: Solar power. *Journal of Physics: Conference Series*, *1280*(5), Article 052033. https://doi.org/10.1088/1742-6596/1280/5/052033

McArthur, J. (2023). Rethinking authentic assessment: Work, well-being, and society. *Higher Education*, *85*(1), 85–101. https://doi.org/10.1007/s10734-022-00822-y

Melisa, M., Susilowati, E., & Dewantara, D. (2021). Development of electronic modules based on STEM to train students' creativity: Validity and practicality analysis. *Berkala Ilmiah Pendidikan Fisika*, *9*(3), 335. https://doi.org/10.20527/bipf.v9i3.10440

Mesutoglu, C., Bayram-Jacobs, D., Vennix, J., Limburg, A., & Pepin, B. (2024a). Exploring multidisciplinary teamwork of applied physics and engineering students in a challenge-based learning course. *Research in Science and Technological Education*, *42*(3), 639–657. https://doi.org/10.1080/02635143.2022.2154334

Mesutoglu, C., Bayram, D., Vennix, A., & Limburg, A. (2024b). Boundary interactions of applied physics and mechanical engineering students in a challenge-based learning course. *European Journal of Engineering Education*, *49*(4), 752–768. https://doi.org/10.1080/03043797.2024.2326438

Mistler, W. (2025). Formal assessment in STEM higher education: A general analysis and recommendations for improvement. *The Journal of Technology Studies*, *50*(1), 42–52. https://doi.org/10.21061/jts.429

Mohd Jamil, M.R & Mat Noh, N. (2021). *Kepelbagaian metodologi dalam penyelidikan reka bentuk dan pembangunan* (3rd ed.). Qaisar Prestige Resources.

Mohd Khalli, M. N., Sintang, S., & Kamu, A. (2022). The framework of socio-religious harmony in Sabah, East Malaysia: An application of fuzzy Delphi method. *Heliyon*, *8*(8), 1–10. https://doi.org/10.1016/j.heliyon.2022.e09976

Mokmin, N. A. M., Hanjun, S., Jing, C., & Qi, S. (2024). Impact of an AR-based learning approach on the learning achievement, motivation, and cognitive load of students on a design course. *Journal of Computers in Education*, *11*(2), 557–574. https://doi.org/10.1007/s40692-023-00270-2

Montes, R., Zuheros, C., Morales, J., Zermeño, N., Duran, J., & Herrera, F. (2023). Design and consensus content validity of the questionnaire for b-learning education: A 2-tuple fuzzy linguistic Delphi based decision support tool. *Applied Soft Computing*, *147*, Article 110755. https://doi.org/10.1016/j.asoc.2023.110755

Nasrudin, D., Rochman, C., Suhendi, H. ., Helsy, I., Rasyid, A., Aripin, I., Utama, W., & Mayasri, A. (2020). STEM education for pre-service teacher : Why and how? *Journal of Physics: Conference Series*, *1563*(1), Article 012039. https://doi.org/10.1088/1742-6596/1563/1/012039

Neher-Asylbekov, S., & Wagner, I. (2023). Effects of out-of-school STEM learning environments on student interest: A critical systematic literature review. *Journal for STEM Education Research*, *6*(1), 1–44. https://doi.org/10.1007/s41979-022-00080-8

Newell, A., & Simon, H. A. (1972). *Human problem solving*. Prentice-Hall.

Niancai, L., Zhuolin, F., & Qi, W. (2024). *Education in China and the world: Achievements and contemporary issues*. Springer Nature. https://doi.org/10.1007/978-981-99-5861-0

Nkopodi, N., Jakovljevic, M., & Photo, P. (2024). Criteria for enhancing student wellbeing in STEM classrooms: ICT and indigenous knowledge in South African higher education. *Discover Education*, *3*, Article 152. https://doi.org/10.1007/s44217-024-00251-2

Noh, N. M., Siraj, S., Halili, S. H., Jamil, M. R. M., & Husin, Z. (2019). Aplikasi teknik fuzzy Delphi terhadap keperluan elemen teknologi sebagai wadah dalam pembelajaran berasaskan pemikiran reka bentuk. *Asia Pacific Journal of Educators and Education*, *34*, 129–151. https://doi.org/10.21315/apjee2019.34.7

Nugraha, M. G., Kidman, G., & Tan, H. (2023). Pre-service teacher in STEM education: An integrative review and mapping of the Indonesian research literature. *Eurasia Journal of Mathematics, Science and Technology Education*, *19*(5), Article em2262. https://doi.org/10.29333/ejmste/13155

Nugraha, M. G., Kidman, G., & Tan, H. (2024). Interdisciplinary STEM education foundational concepts: Implementation for knowledge creation. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(10), Article em2523. https://doi.org/10.29333/ejmste/15471

Nurtanto, M., Pardjono, P., Widarto, W., & Ramdani, S. D. (2020). The effect of STEM-EDP in professional learning on automotive engineering competence in vocational high school. *Journal for the Education of Gifted Young Scientists*, *8*(2), 633–649. https://doi.org/10.17478/JEGYS.645047

Ong, Y. S., Koh, J., Tan, A. L., & Ng, Y. S. (2024). Developing an integrated STEM classroom observation protocol using the productive disciplinary engagement framework. *Research in Science Education*, *54*(1), 101–118. https://doi.org/10.1007/s11165-023-10110-z

Ortiz-Revilla, J., Greca, I. M., & Arriassecq, I. (2022). A theoretical framework for integrated STEM education. *Science and Education*, *31*(2), 383–404. https://doi.org/10.1007/s11191-021-00242-x

Palid, O., Cashdollar, S., Deangelo, S., Chu, C., & Bates, M. (2023). Inclusion in practice: A systematic review of diversity-focused STEM programming in the United States. *International Journal of STEM Education*, *10*, Article 2. https://doi.org/10.1186/s40594-022-00387-3

Pertiwi, N. P., Saputro, S., Yamtinah, S., & Kamari, A. (2024). Enhancing critical thinking skills through STEM problem-based contextual learning: An integrated e-module education website with virtual experiments. *Journal of Baltic Science Education*, *23*(4), 739–766. https://doi.org/10.33225/jbse/24.23.739

Pittman, C., & LaViola, J. J. (2020). PhyAR: Determining the utility of augmented reality for physics education in the classroom. *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 761–762. https://doi.org/10.1109/VRW50115.2020.00231

Pusdatin. (2021). *Petunjuk teknis kihajar STEM tahun 2021*. Kementerian Pendidikan dan Kebudayaan.

Pusdatin. (2022). *Petunjuk teknis kihajar STEM tahun 2022*. Kementerian Pendidikan dan Kebudayaan.

Radu, I., Huang, X., Kestin, G., & Schneider, B. (2023). How augmented reality influences student learning and inquiry styles: A study of 1-1 physics remote AR tutoring. *Computers & Education: X Reality*, *2*, Article 100011. https://doi.org/10.1016/j.cexr.2023.100011

Rahayu, P., & Wulandari, I. A. (2021). Defining e-portfolio factor for competency certification using fuzzy Delphi method. *Procedia Computer Science*, *197*, 566–575. https://doi.org/10.1016/j.procs.2021.12.174

Reynante, B. M., Selbach-Allen, M. E., & Pimentel, D. R. (2020). Exploring the promises and perils of integrated STEM through disciplinary practices and epistemologies. *Science and Education*, *29*(4), 785–803. https://doi.org/10.1007/s11191-020-00121-x

Roberts, T., Maiorca, C., Jackson, C., & Mohr-Schroeder, M. (2022). Integrated STEM as problem-solving practices. *Investigations in Mathematics Learning*, *14*(1), 1–13. https://doi.org/10.1080/19477503.2021.2024721

Roehrig, G. H., Dare, E. A., Ellis, J. A., & Ring-Whalen, E. (2021a). Beyond the basics: A detailed conceptual framework of integrated STEM. *Disciplinary and Interdisciplinary Science Education Research*, *3*(1), 1–18. https://doi.org/10.1186/s43031-021-00041-y

Roehrig, G. H., Dare, E. A., Ring-Whalen, E., & Wieselmann, J. R. (2021b). Understanding coherence and integration in integrated STEM curriculum. *International Journal of STEM Education*, *8*, Article 2. https://doi.org/10.1186/s40594-020-00259-8

Ropawandi, D., Halim, L., & Husnin, H. (2022). Augmented reality (AR) technology-based learning: The effect on physics learning during the COVID-19 pandemic. *International Journal of Information and Education Technology*, *12*(2), 132–140. https://doi.org/10.18178/ijiet.2022.12.2.1596

Saffie, N. A. M., Shukor, N. A. M., & Rasmani, K. A. (2016). Fuzzy Delphi method: Issues and challenges. *2016 International Conference on Logistics, Informatics and Service Sciences (LISS).* IEEE. https://doi.org/10.1109/LISS.2016.7854490

Saido, G. A. M., Siraj, S., DeWitt, D., & Al-Amedy, O. S. (2018). Development of an instructional model for higher order thinking in science among secondary school students: A fuzzy Delphi approach. *International Journal of Science Education*, *40*(8), 847–866. https://doi.org/10.1080/09500693.2018.1452307

Saleem, A., Anwar, S., Nawaz, T., Fahad, S., Saud, S., Ur Rahman, T., Khan, M. N. R., & Nawaz, T. (2024). Securing a sustainable future: The climate change threat to agriculture, food security, and sustainable development goals. *Journal of Umm Al-Qura University for Applied Sciences, 11*, 595-611. https://doi.org/10.1007/s43994-024-00177-3

Sari, M. R., Sutarto, S., Sudarti, S., Indrawati, I., & Budiarso, A. S. (2020). STEM-CP (sains, technology, engineering mathematics-contextual problem) based physics module to increase student literacy skills at vocational high school. *Pancaran Pendidikan*, *9*(1), 57–66. https://doi.org/10.25037/pancaran.v9i1.271

Satanassi, S., Branchetti, L., Fantini, P., Casarotto, R., Caramaschi, M., Barelli, E., & Levrini, O. (2023). Exploring the boundaries in an interdisciplinary context through the family resemblance approach: The dialogue between physics and mathematics. *Science and Education*, *32*(5), 1287–1320. https://doi.org/10.1007/s11191-023-00439-2

Septiadevana, R., & Abdullah, N. (2024). Designing a STEM project-based learning module for scientific literacy and critical thinking elementary school students. *Jurnal Pendidikan Sains Indonesia*, *12*(3), 662–682. https://doi.org/10.24815/jpsi.v12i3.38255

Siew, N. M., & Ambo, N. (2020). The scientific creativity of fifth graders in a STEM project-based cooperative learning approach. *Problems of Education in the 21st Century*, *78*(4), 627–643. https://doi.org/10.33225/pec/20.78.627

Simarro, C., & Couso, D. (2021). Engineering practices as a framework for STEM education: A proposal based on epistemic nuances. *International Journal of STEM Education*, *8*(1). https://doi.org/10.1186/s40594-021-00310-2

Sivaraj, R., Ellis, J., & Roehrig, G. (2019). Conceptualizing the T in STEM: A systematic review. *Proceedings of the Society for Information Technology & Teacher Education International Conference* (pp. 1245–1254). Association for the Advancement of Computing in Education.

Sivaraj, R., Ellis, J. A., Wieselmann, J. R., & Roehrig, G. H. (2020). Computational participation and the learner-technology pairing in K-12 STEM education. *Human Behavior and Emerging Technologies*, *2*(4), 387–400. https://doi.org/10.1002/hbe2.220

Siverling, E. A., Guzey, S. S., & Moore, T. J. (2017, October). Students' science talk during engineering design in life science-focused STEM integration units. *2017 IEEE Frontiers in Education Conference (FIE)* (pp. 1-9). IEEE. https://doi.org/10.1109/FIE.2017.8190670

Siverling, E. A., Suazo-Flores, E., Mathis, C. A., & Moore, T. J. (2019). Students' use of STEM content in design justifications during engineering design-based STEM integration. *School Science and Mathematics*, *119*(8), 457–474. https://doi.org/10.1111/ssm.12373

Sırakaya, M., & Alsancak Sırakaya, D. (2022). Augmented reality in STEM education: A systematic review. *Interactive Learning Environments*, *30*(8), 1556–1569. https://doi.org/10.1080/10494820.2020.1722713

Skulmoski, G. J., Hartman, F. T., & Krahn, J. (2007). The Delphi method for graduate research. *Journal of Information Technology Education*, *6*(1), 1–21. https://doi.org/10.1007/3-540-47847-7_10

Steffensen, L. (2024). Developing responsible citizenship through integrated STEM education activities. In J. Anderson, & K. Makar (Eds.), *The contribution of mathematics to school STEM education: Current understandings* (pp. 295–311). https://doi.org/10.1007/978-981-97-2728-5_17

Stewart, C. O. (2022). STEM identities: A communication theory of identity approach. *Journal of Language and Social Psychology*, *41*(2), 148–170. https://doi.org/10.1177/0261927X211030674

Stretch, E. J., & Roehrig, G. H. (2021). Framing failure: Leveraging uncertainty to launch creativity in STEM education. *International Journal of Learning and Teaching*, *7*(2), 123–133. https://doi.org/10.18178/ijlt.7.2.123-133

Sukma, M., Halim, A., & Evendi, E. (2022). Implementation of e-learning module based on science technology engineering mathematics on solar cells topic. *JIPF(Jurnal Ilmu Pendidikan Fisika)*, *7*(1), 60–70. https://doi.org/dx.doi.org/10.26737/jipf.v7i1.2237

Tabarés, R., & Boni, A. (2023). Maker culture and its potential for STEM education. *International Journal of Technology and Design Education*, *33*(1), 241–260. https://doi.org/10.1007/s10798-021-09725-y

Tang, K. (2024). Climate change education in Indonesia's formal education: A policy analysis. *Npj Climate Action*, *3*(1), 1–11. https://doi.org/10.1038/s44168-024-00143-z

Taylor, E. (2020). We agree, don't we? The Delphi method for health environments research. *Health Environments Research and Design Journal*, *13*(1), 11–23. https://doi.org/10.1177/1937586719887709

Thees, M., Kapp, S., Strzys, M. P., Beil, F., Lukowicz, P., & Kuhn, J. (2020). Effects of augmented reality on learning and cognitive load in university physics laboratory courses. *Computers in Human Behavior*, *108,* Article 106316. https://doi.org/10.1016/j.chb.2020.106316

Tuyet, T. L. T., Thi, K. N., Duc, H. T., Giao, X. T. T., Thi, N. V., Tuong, V. H. K., Nhu, U. D. T., & Mai, A. L. T. (2024). STEM education in primary schools of Southeast Asian countries: An analysis of scientific publications in the Scopus database from 2000 to 2022. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(4). https://doi.org/10.29333/ejmste/14432

Wells, R. S., Chen, L., Kimball, E., Annan, B., Auerbach, S. M., & Fermann, J. T. (2025). Improving the perceived utility value of teamwork and collaboration among STEM undergraduates. *International Journal of Science and Mathematics Education*, *23*(2), 515–536. https://doi.org/10.1007/s10763-024-10471-5

Widiastuti, I., Budiyanto, C. W., & Ramli, M. (2020). Pre-service teacher conceptions of integrated STEM using the engineering design approach. In *2020 IEEE International Conference on Teaching, Assessment, and Learning for Engineering (TALE)* (pp. 106–111). IEEE. https://doi.org/10.1109/TALE48869.2020.9368382

Wieselmann, J. R., Menon, D., Price, B. C., Johnson, A., Asim, S., Haines, S., & Morison, G. (2025). What is STEM? Preservice elementary teachers' conceptions of integrated STEM education. *Teaching and Teacher Education*, *165*, Article 105108. https://doi.org/10.1016/j.tate.2025.105108

Wilson, K. (2021). Exploring the challenges and enablers of implementing a STEM project-based learning programme in a diverse junior secondary context. *International Journal of Science and Mathematics Education*, *19*(5), 881–897. https://doi.org/10.1007/s10763-020-10103-8

Winarno, N., Rusdiana, D., Samsudin, A., Susilowati, E., Ahmad, N., & Afifah, R. M. A. (2020). The steps of the Engineering Design Process (EDP) in science education: A systematic literature review. *Journal for the Education of Gifted Young Scientists*, *8*(4), 1345–1360. https://doi.org/10.17478/jegys.766201

Xu, L., Fang, S. C., & Hobbs, L. (2023). The relevance of STEM: A case study of an Australian secondary school as an arena of STEM curriculum innovation and enactment. *International Journal of Science and Mathematics Education*, *21*(2), 667–689. https://doi.org/10.1007/s10763-022-10267-5

Xue, X., Ahmad, N. J., & Liu, X. (2023). The development and validation of an EDP-STEM module-taking heat transfer, mechanics, and buoyancy as examples. *Journal of Turkish Science Education*, *20*(4), 649–668. https://doi.org/10.36681/tused.2023.037

Yakob, M., Hamdani, H., Sari, R. P., Haji, A. G., & Nahadi, N. (2021). Implementation of performance assessment in STEM-based science learning to improve students' habits of mind. *International Journal of Evaluation and Research in Education*, *10*(2), 624–631. https://doi.org/10.11591/ijere.v10i2.21084

Yang, H. W., Harradine, C., Lim, C. I., Clements, D. H., Vinh, M., & Sarama, J. (2024). Reporting and analyzing demographics in U.S.-American early STEM intervention literature: A systematic review. *Early Childhood Education Journal*, *53*(6), 2287-2301. https://doi.org/10.1007/s10643-024-01739-0

Yin, T. T., & Hanif, H. (2024). Fuzzy Delphi method: A step-by-step guide to obtain expert consensus on MUETBot functionalities. *International Journal of Academic Research in Business and Social Sciences*, *14*(4), 1097–1104. https://doi.org/10.6007/ijarbss/v14-i4/21307

Yulianti, D., Sugianto, & Ngafidin, K. M. (2022). Scratch assisted physics learning with a STEM approach in the pandemic era to develop 21st century learning skills. *Jurnal Pendidikan IPA Indonesia*, *11*(1), 185–194. https://doi.org/10.15294/jpii.v11i1.32607

Yulkifli, Y., Yohandri, Y., & Azis, H. (2022). Development of physics e-module based on integrated project-based learning model with ethno-STEM approach on smartphones for senior high school students. *Momentum: Physics Education Journal*, *6*(1), 93–103. https://doi.org/10.21067/mpej.v6i1.6316

Yusoff, A. F. M., Hashim, A., Muhamad, N., & Hamat, W. N. W. (2021). Application of fuzzy Delphi technique to identify the elements for designing and developing the e-PBM PI-Poli module. *Asian Journal of University Education*, *17*(1), 292–304. https://doi.org/10.24191/ajue.v17i1.12625

Zakiyah, N. A., & Sudarmin. (2022). Development of e-module STEM integrated ethnoscience to increase 21st century skills. *International Journal of Active Learning*, *7*(1), 49–58. https://journal.unnes.ac.id/nju/ijal/article/view/34410/12633

Zaky, M., Alit, K., & Untara, A. (2025). Enhancing student creativity in applied physics through RO filter and heating filament learning media development. *Ideguru: Jurnal Karya Ilmiah Guru*, *10*(1), 635–641. https://doi.org/10.51169/ideguru.v10i1.1539

Zhan, Z., & Niu, S. (2023). Subject integration and theme evolution of STEM education in K-12 and higher education research. *Humanities and Social Sciences Communications*, *10*(1), 1–13. https://doi.org/10.1057/s41599-023-02303-8