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Uncovering culturally responsive teaching to biology problem solving through cultural literacy, environmental literacy, and students' social attitudes

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This section is part of the dissertation and provides a comprehensive theoretical foundation and a review of relevant empirical studies that support the research framework.

ABSTRACT

A culturally responsive teaching approach is an important strategy for fostering meaningful learning by integrating learning materials with cultural contexts to improve concept understanding, social skills and awareness of environmental issues. This study aims to explain the effect of culturally responsive teaching on students' biology problem solving, mediated by cultural literacy, environmental literacy and social attitudes. This study used a quantitative approach with a cross-sectional survey design and structural equation modeling, implemented using Smart Partial Least Squares 3.3.2. The research subjects were 302 students from the biology education and biology study programs at 16 universities in the Sulawesi region, Indonesia. The data collection instrument was a closed-ended Likert-scale questionnaire that had undergone expert validation. The results of the analysis indicated that culturally responsive teaching had a significant effect in increasing cultural literacy, environmental literacy and social attitudes, all of which had a positive impact on biology problem solving.

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Introduction

Culturally responsive teaching (CRT) emphasizes the integration of students' cultural references, experiences and backgrounds into all aspects of the learning process (Gay, 2002). By connecting students' cultural backgrounds with instructional practices, CRT can promote more

meaningful and relevant learning experiences (Villegas & Lucas, 2002). The integration of culture into education can also strengthen students' academic understanding while fostering social awareness and appreciation of cultural diversity (Banks & Banks, 2019). A deeper understanding of learning materials, therefore, is important not only for developing academic competence but also for fostering critical thinking and cross-cultural empathy, which are essential competencies in increasingly multicultural educational contexts (Suprpto et al., 2024). These perspectives indicate that culturally responsive learning should move beyond the inclusion of cultural content as supplementary material and instead position students' cultural knowledge and experiences as resources for constructing meaningful knowledge.

The importance of culturally responsive learning is increasingly relevant in the context of globalization and digitalization. Contemporary education is expected to equip learners with complex thinking skills, social competencies and digital literacy to respond effectively to rapid socio-cultural and technological changes (González-Pérez & Ramírez-Montoya, 2022). At the same time, globalization may create challenges for the continuity of traditional knowledge and cultural identities. Education, cultural documentation, community participation, and supportive policies are therefore important in maintaining traditional identities in the 21st century (Hiswara et al., 2023). Within education, this effort can be realized by integrating local cultural values, traditional knowledge and local wisdom into learning activities. Such integration enables students to recognize the relevance of their cultural heritage while connecting it with contemporary scientific knowledge and real-life challenges.

The integration of culture into science education is particularly important because scientific concepts are often taught in abstract forms that may be disconnected from students' everyday experiences. Connecting scientific knowledge with local contexts can provide meaningful entry points for students to understand concepts, interpret phenomena and apply knowledge to problems in their surroundings. In biology education, local plants and their uses represent a particularly relevant cultural context because communities possess diverse knowledge concerning plant identification, utilization, traditional medicine, food, rituals and environmental management. Bringing such knowledge into the learning process can create opportunities for students to compare local knowledge with scientific explanations, identify similarities and differences and develop a more contextual understanding of biological concepts. Thus, culturally responsive approaches have the potential to position local cultural knowledge not merely as an illustration but as a starting point for scientific inquiry and knowledge construction.

This perspective is closely related to the development of cultural literacy, environmental literacy, social attitudes and biology problem solving. Cultural literacy enables learners to understand, interpret and appreciate cultural knowledge and practices, while environmental literacy supports their ability to understand environmental issues and make responsible decisions (Hungerford & Volk, 1993). Social attitudes are also important because learning requires students to interact, collaborate, respect different perspectives and take responsibility within their social environment. Meanwhile, problem solving enable learners to identify problems, analyze causes, evaluate alternatives and formulate appropriate solutions (Parkin et al., 2004). These competencies are not independent; rather, they can reinforce one another when learning is designed around authentic cultural and environmental contexts.

The relationship among these competencies becomes particularly evident when students are engaged in biological problems that emerge from their immediate cultural and environmental surroundings. For example, learning about local plants can involve students in identifying species, investigating their traditional uses, examining their ecological significance and considering potential threats to their sustainability. Such activities require students to mobilize cultural knowledge, scientific understanding, environmental awareness, social interaction and higher-order thinking simultaneously. Students' ability to analyze, evaluate and solve biological problems therefore requires not only cognitive competence but also an understanding of cultural and environmental contexts and the capacity to collaborate and act responsibly in social settings. This suggests that culturally responsive learning has the potential to provide an integrated learning environment for developing multiple competencies rather than addressing them separately.

Nevertheless, the integration of local culture into biology learning remains challenging. Learning materials frequently emphasize scientific concepts while providing limited opportunities for students to connect these concepts with the cultural knowledge and experiences present in their communities. As a result, students may understand biological concepts at a theoretical level but have fewer opportunities to recognize their relevance to local environmental and cultural issues. Digital learning resources provide an opportunity to address this gap because they can integrate text, images, videos, interactive activities, local examples and contextual problems within a single learning environment. When designed according to culturally responsive principles, digital materials can facilitate independent learning while simultaneously connecting scientific knowledge with students' cultural experiences.

Taken together, the literature suggests that culturally responsive learning can serve as an important pedagogical foundation for connecting students' cultural backgrounds with scientific learning and for developing broader competencies needed in the 21st century. However, the literature also indicates a need for learning resources that systematically integrate cultural knowledge with biological concepts while simultaneously fostering cultural literacy, environmental literacy, social attitudes and biology problem solving. This gap is particularly relevant in plant taxonomy, a field that can be closely connected to local biodiversity and community knowledge of plants. Therefore, developing an e-module based on culturally responsive teaching (CRT) for plant taxonomy represents a promising approach to bridge scientific knowledge with local cultural knowledge and to provide students with contextual learning experiences that support the development of interconnected cognitive, cultural, environmental and social competencies.

Preliminary observations and analyses of learning activities and assessment results indicates that students' biology problem solving, cultural literacy, environmental literacy and social attitudes indicated low levels according to established indicators. In biology learning, assessment results indicated that many students had difficulty identifying biological problems, applying relevant concepts and analyzing data to formulate solutions. In terms of cultural literacy, students demonstrated limited knowledge of cultural diversity, insufficient understanding of local and global cultural contexts and low ability to communicate across cultural differences. Environmental literacy assessments indicated low awareness of environmental issues and limited engagement in environmentally responsible behaviors.

Furthermore, observations of learning interactions revealed low levels of empathy, a high degree of individualistic behavior and minimal participation in collaborative or socially oriented activities. These findings indicate gaps in students' higher-order thinking skills, social awareness and engagement with real-world biological and environmental issues. CRT emphasizes the importance of linking students' experiences and cultural values to the learning process, making it easier for them to understand and apply concepts in biology problem solving.

The objective of this study is to examine the effect of culturally responsive teaching (CRT) on students' biology problem solving and to investigate the mediating roles of cultural literacy, environmental literacy and social attitudes. The contribution of this research lies in its interdisciplinary framework, which integrates biology education, cultural literacy, environmental literacy, social attitudes and biology problem solving within the context of CRT. This study offers a comprehensive model that explains the relationships among these variables, which have often been examined separately in previous research.

Based on the proposed conceptual framework, the research questions are formulated as follows:

1. How does culturally responsive teaching influence students' cultural literacy, environmental literacy and social attitudes?
2. How do cultural literacy, environmental literacy and social attitudes influence students' biology problem solving?
3. How does culturally responsive teaching influence students' biology problem solving?
4. To what extent do cultural literacy, environmental literacy, and social attitudes mediate the relationship between culturally responsive teaching and students' biology problem solving?

Literature Review

Biology Education and Problem Solving

Biology education is expected not only to transfer factual knowledge but also to cultivate students' problem solving, environmental awareness and social attitudes that support responsible scientific action (Gay, 2018; Guerrero, 2020). Conventional curricula often remain abstract and disconnected from students' lived experiences, limiting the development of higher-order thinking skills. Embedding cultural and environmental contexts into biology learning enhances relevance, motivation and engagement, which in turn contribute to better problem solving outcomes.

Problem solving skills are central to learning, reflecting critical, analytical and creative thinking abilities necessary to address real-world challenges. Students with well-developed problem solving can identify problems, gather and analyze information, evaluate alternatives and propose solutions based on scientific reasoning (Mahanal et al., 2022; Nurhayati et al., 2023; Sari et al., 2021). These skills are particularly important for addressing environmental challenges, applying biological knowledge and making decisions that consider ethical, social and ecological implications.

In biology education, connecting learning with students' environmental and cultural experiences can make biological problems more meaningful and encourage students to relate scientific concepts to issues in their surroundings. These findings suggest that biology problem solving can be strengthened when learning integrates cognitive processes with contextual, environmental, cultural and social dimensions. However, the extent to which culturally responsive teaching contributes to biology problem solving, particularly through cultural literacy, environmental literacy and social attitudes, remains insufficiently explored. This gap provides a basis for examining the relationships among these variables in the present study.

Culturally Responsive Teaching (CRT)

CRT views students' cultural backgrounds as pedagogical assets, linking academic content with cultural practices, values and lived experiences (Gay, 2018; Villegas & Lucas, 2002). Research indicates that CRT increases engagement, strengthens identity and improves academic performance in science classrooms (Barron et al., 2021). In biology education, CRT has been implemented in laboratory-based instruction and higher education contexts to promote inclusivity and deepen conceptual understanding.

Previous studies have shown that culturally responsive learning can support biology problem solving by providing meaningful contexts in which students connect academic concepts with their prior knowledge, cultural experiences and community practices. Keehne et al. (2018) reported that incorporating students' cultural experiences into learning can promote engagement and create opportunities for students to develop reasoning and problem solving. Similarly, Rahmawati et al. (2023) and Indarwati et al. (2024) found that culturally contextualized learning encouraged students to analyze real-life problems, relate scientific concepts to their surroundings and develop appropriate solutions.

These findings suggest that CRT may contribute to biology problem solving not only by improving students' understanding of subject matter but also by making learning more relevant and encouraging students to draw on culturally situated knowledge when addressing problems. Nevertheless, existing studies have largely focused on learning engagement, conceptual understanding, or general higher-order thinking, while empirical evidence examining the direct effect of CRT on measurable biology problem solving abilities remains limited. Therefore, further investigation is needed to determine whether CRT can directly enhance students' biology problem solving abilities and how this effect may be associated with other competencies developed through culturally responsive learning.

Cultural Literacy

Cultural literacy is defined as the ability to recognize, interpret and apply cultural knowledge in learning (Maine et al., 2019; Ochoa et al., 2018). It enables students to contextualize scientific content within familiar cultural narratives and practices. Incorporating cultural perspectives into biology problem solving tasks, such as local agricultural techniques, community health beliefs, or indigenous ecological knowledge, enhances conceptual understanding and critical thinking (Gay, 2018). In biology education, this connection is particularly relevant because local knowledge of plants, agriculture, health and the environment can provide authentic contexts for understanding biological concepts and addressing real-world problems.

Cultural literacy may therefore contribute to biology problem solving by helping students recognize the cultural dimensions of a problem, integrate multiple perspectives, and formulate solutions that are scientifically appropriate while remaining relevant to the local context. However, most previous studies have examined cultural literacy as an educational or sociocultural outcome, rather than investigating its role as a mechanism through which culturally responsive teaching contributes to students' biology problem solving abilities. This indicates a research gap concerning the mediating role of cultural literacy in the relationship between CRT and biology problem solving.

Environmental Literacy

Environmental literacy encompasses knowledge of ecological systems, pro-environmental attitudes and the skills needed for responsible decision-making (McBeth & Volk, 2010; McBride et al., 2013). Both formal and non-formal education significantly influence environmental awareness and behavior (Syamsiah et al., 2024). Problem-based learning (PBL) in environmental contexts has been shown to enhance ecological understanding and the ability to apply biological knowledge to real-world problems (Hollweg et al., 2011; Lewinsohn et al., 2019). Environmental literacy provides a meaningful context for assessing biology problem solving because addressing ecological challenges requires analyzing evidence, evaluating alternatives and making ethically informed decisions.

These findings suggest that environmental literacy can contribute to biology problem solving by providing students with the knowledge, awareness and decision-making skills required to address complex ecological problems. However, previous research has more frequently examined environmental literacy as an outcome of environmental education or as a predictor of environmental behavior, while its role in the relationship between culturally responsive teaching and biology problem solving has received limited empirical attention. This gap highlights the need to investigate whether environmental literacy mediates the effect of CRT on students' biology problem solving.

Social Attitudes

Social attitudes including empathy, cooperation, social responsibility and respect for collective norms, are essential for collaborative scientific problem solving (Bustami et al., 2017; Martínez et al., 2020). Culturally responsive learning environments, these attitudes can be strengthened because students' identities, experiences and cultural perspectives are recognized and valued, creating opportunities for respectful interaction and inclusive classroom discourse. Such social interactions are particularly important in biology problem solving, where students may need to negotiate different interpretations of a problem, evaluate alternative solutions and reach decisions collaboratively.

Thus, social attitudes may contribute to biology problem solving by supporting effective communication, collaboration and responsible decision-making. However, previous studies have predominantly examined social attitudes as outcomes of inclusive or culturally responsive education, with limited attention to their potential role as a mediator linking CRT with students' biology problem solving. This gap warrants further investigation into whether social attitudes function as an important pathway through which CRT contributes to the development of biology problem solving.

Integration of CRT, Literacy and Social Attitudes in Problem Solving

Recent studies provide evidence that culturally responsive approaches can support multiple dimensions of science learning. Culturally responsive and sustaining pedagogies can connect students' cultural experiences with scientific knowledge and create more inclusive science learning environments (Smith et al., 2022). Empirical research has also shown that problem-based culturally responsive learning can significantly improve students' critical thinking and cultural literacy (Ernawati et al., 2026), while culturally responsive transformative teaching has been found to significantly enhance environmental literacy (Wijayanti et al., 2025). In addition, ethnoscience-based learning can strengthen critical thinking and cultural literacy by connecting scientific concepts with local knowledge and cultural practices (Atmojo et al., 2025). These findings suggest that CRT, cultural literacy and environmental literacy can complement one another in developing students' capacity to understand and solve contextual scientific problems. However, previous studies have generally examined these competencies separately or in limited combinations and empirical evidence concerning their interconnected relationships with social attitudes and biology problem solving remains limited. Therefore, examining these relationships within a single model may provide a more comprehensive understanding of how culturally responsive biology education develops students' cognitive, cultural, environmental and social competencies.

Methods

Research Design

This study employs non-experimental quantitative methods (Hair et al., 2021), involving systematic data collection and analysis, to examine the influence of the CRT approach on students' biology problem solving mediated by cultural literacy, environmental literacy and social attitudes. Data were collected using a cross-sectional design to investigate the relationships between the implementation of CRT in learning and students' cultural literacy, environmental literacy, social attitudes and biology problem solving.

Participants and Research Implementation

The participants in this study were undergraduate students from the biology education and biology programs at various state and private universities in the Sulawesi region of Indonesia. The respondents in this research were active students in semesters 2, 4, 6 and 8, as the study was conducted during the even semesters. The research sample was randomly selected and consisted of 302 students, comprising 42 males and 260 females. A total of sixteen universities participated in the study, all offering degree programs in the two fields of Biology Education and Biology. This study employed a survey method to identify the levels of cultural literacy, environmental literacy, social attitudes and biology problem solving among undergraduate students.

Research Instrument

This research used a questionnaire containing 31 statements across 5 variables. Questionnaire statements were developed based on a review of the relevant literature (Androsov & Zhang, 2023; Bustami et al., 2017; Halbert & Chigeza, 2015; McBeth & Volk, 2010; Shahat et al., 2013), as show in Appendix. The questionnaire used was a closed-ended instrument presented as a list of statements with answer choices on a four-point Likert scale: Strongly Agree, Agree, Disagree and Strongly Disagree. The questionnaire went through validated by academic experts for item relevance and alignment with the

research variables. All items met the validity criteria, with scores ranging from 4.25 to 4.50 (≥ 4.0), while the reliability analysis showed Cronbach's alpha values ranging from 0.730 to 0.910 (≥ 0.70), indicating adequate validity and reliability. The questionnaire used consists of two parts: the respondent's identity and statement items.

Data Analysis

The study structural equation modeling (SEM) using SmartPLS 3.3.2. This method is suitable for testing the relationships between independent and dependent variables (Hair et al., 2019). The SEM approach was used to examine the relationships among the CRT approach, cultural literacy, environmental literacy, social attitudes, and biology problem solving abilities. Validity was assessed using outer loadings (>0.60) (Ghozali & Latan, 2015). Reliability and internal consistency were evaluated through Cronbach's alpha (>0.70), rho A (>0.70), composite reliability (>0.70) and convergent validity using the average variance extracted (AVE > 0.50). Discriminant validity was assessed using the Fornell-Larcker criterion and cross-loadings (Barclay & Thomson, 1995; Hair et al., 2019). According to the Fornell-Larcker criterion, the square root of the AVE for each construct (on the diagonal) must exceed its correlations with other constructs (Fornell & Larcker, 1981; Hair et al., 2019). Additionally, each cross-loading should be highest for its respective construct compared to other constructs (Hair et al., 2021). The internal consistency benchmark ranges from 0 to 1. T-tests and F-tests via bootstrapping were performed to determine the significance of path coefficients in the structural model ($T > 1.96$ and $p < 0.05$) at a 95% confidence interval with 5,000 subsamples (Henseler, 2012).

Finding

Based on the results of the SEM analysis, the outer loading values for each variable item which is a student perception indicate that of the 31 statements, 11 did not exceed the threshold of 0.60. This suggests that these items failed to represent the constructs being measured adequately. This could be due not only to inconsistencies in respondents' answers but also to factors such as ambiguous statement wording, misinterpretation of items, or insufficient alignment of certain items with the underlying constructs. The highest outer loading value for each variable item was observed for CRT2 (0.860), CLL5 (0.863), ELL3 (0.843), SOC4 (0.890) and PRO8 (0.828). The values obtained for Cronbach's alpha, rho A and composite reliability for each variable exceed the minimum threshold (0.70) so it can be concluded that the reliability is in the good category. The AVE convergent validity assessment demonstrates that the AVE is greater than 0.50, indicating that the convergent validity criterion is met. In detail, the results of the outer loading analysis, Cronbach's alpha, rho A, composite reliability and AVE are depicted in Table 1.

Table 1

The results of the reflective measurement model analysis

Variable	Item variables	Outer loadings	Cronbach's alpha	Rho A	Composite reliability	AVE
Culturally Responsive Teaching	CRT1	0.850	0.788	0.791	0.876	0.702
	CRT2	0.860				
	CRT3	out				
	CRT4	0.803				
Cultural Literacy	CLL1	out	0.848	0.854	0.898	0.688
	CLL2	out				
	CLL3	0.775				
	CLL4	0.847				
	CLL5	0.863				
	CLL6	0.830				
	CLL7	out				

Environmental Literacy	ELL1	0.818	0.712	0.723	0.839	0.636
	ELL2	out				
	ELL3	0.842				
	ELL4	0.727				
Social Attitudes	SOC1	out	0.891	0.900	0.921	0.702
	SOC2	0.678				
	SOC3	0.838				
	SOC4	0.890				
	SOC5	0.881				
	SOC6	0.882				
	SOC7	out				
	SOC8	out				
Problem Solving	PRO1	0.794	0.844	0.847	0.889	0.615
	PRO2	0.769				
	PRO3	out				
	PRO4	0.765				
	PRO5	out				
	PRO6	0.765				
	PRO7	out				
	PRO8	0.828				

Table 2 presents an assessment of the discriminant validity of each variable using the Fornell-Larcker approach. According to the Fornell-Larcker criteria, the square root of AVE for culturally responsive teaching (0.838) is higher than that for cultural literacy (0.540), social attitudes (0.499), environmental literacy (0.484) and biology problem solving (0.424). This indicates that the constructs demonstrate adequate discriminant validity, as each variable explains more variance within its own indicators than it does across indicators of other constructs in the model.

Table 2

Descriptive correlation between variables and AVE (Fornell-Larcker criterion)

Variable	CRT	CLL	ELL	SOC	PRO
CRT	0.838				
CLL	0.540	0.829			
ELL	0.484	0.657	0.797		
SOC	0.499	0.655	0.678	0.838	
PRO	0.424	0.553	0.644	0.660	0.784

Cross-loadings for all variables are presented in Table 3 which shows that each item correlates strongly with its main variable. This finding indicates that each variable has greater variance across measurement items. Overall, discriminant validity for each measurement item was established.

Table 3

Item variable (indicator) cross-loading

	CRT	CLL	ELL	SOC	PRO
CRT1	0.850	0.488	0.401	0.408	0.352
CRT2	0.860	0.431	0.436	0.470	0.376
CRT4	0.803	0.439	0.378	0.373	0.337
CLL3	0.388	0.775	0.499	0.480	0.430
CLL4	0.425	0.847	0.522	0.505	0.412
CLL5	0.502	0.863	0.527	0.562	0.473
CLL6	0.465	0.830	0.621	0.611	0.510
ELL1	0.415	0.561	0.818	0.567	0.528
ELL3	0.461	0.593	0.842	0.554	0.519
ELL4	0.264	0.402	0.727	0.498	0.496
SOC2	0.387	0.427	0.402	0.678	0.489

SOC3	0.439	0.525	0.573	0.838	0.577
SOC4	0.435	0.565	0.581	0.890	0.563
SOC5	0.418	0.609	0.626	0.881	0.572
SOC6	0.414	0.599	0.629	0.882	0.559
PRO1	0.390	0.445	0.566	0.513	0.794
PRO2	0.297	0.351	0.418	0.460	0.769
PRO4	0.288	0.491	0.528	0.532	0.765
PRO6	0.312	0.408	0.462	0.516	0.765
PRO8	0.368	0.459	0.535	0.558	0.828

These results indicated that based on the correlation results, culturally responsive teaching (CRT) positively influences students' cultural literacy (CLL), environmental literacy (ELL), social attitudes (SOC) and biology problem solving (PRO), with the strongest effects observed for cultural literacy and social attitudes and relatively lower effects for biology problem solving. Cultural literacy, in turn, significantly impacts environmental literacy, social attitudes and biology problem solving, serving as an important mediator in students' learning outcomes. Environmental literacy also contributes positively to social attitudes and biology problem solving, while social attitudes, in turn, have a substantial effect on biology problem solving. Overall, the findings suggest that CRT indirectly enhances students' biology problem solving by influencing cultural literacy, environmental literacy and social attitudes, highlighting the interconnected roles of cognitive, cultural and social dimensions in the development of students' competencies.

The results of the R-squared analysis indicated that the contribution of culturally responsive teaching to cultural literacy was 29.1%, the contribution of culturally responsive teaching and cultural literacy to environmental literacy was 45.5% and the contribution of culturally responsive teaching, cultural literacy and environmental literacy towards social attitudes was 54.8%. In contrast, the contribution of culturally responsive teaching, cultural literacy, environmental literacy and social attitudes towards biology problem solving was 51.2%. These results indicate that while the influence between the variables is relatively strong, other factors also contribute to enhancing students' biology problem solving.

Table 4 presents a summary of descriptive and inferential statistics for the measured variables, including means, standard deviations, t-values and p-values. These statistics provide an overview of the central tendency, variability and significance of the observed data, facilitating the interpretation of the relationships and differences among the variables.

Table 4

Data description: Mean, standard deviation, T-values and p-values

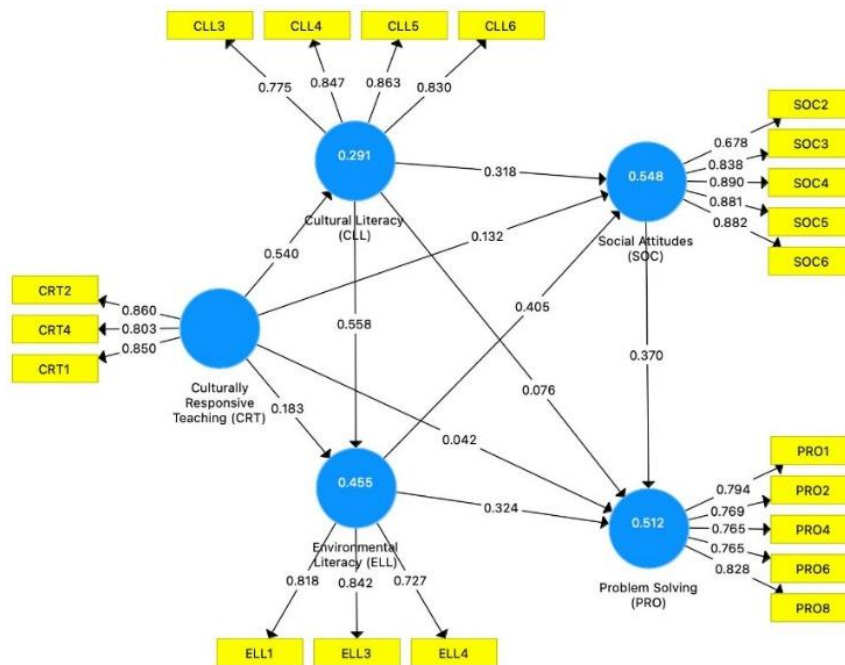
	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (O/STDEV)	P Values
CRT -> CLL	0.540	0.539	0.071	7.610	0.000
CRT -> ELL	0.183	0.184	0.065	2.829	0.005
CRT -> SOC	0.132	0.134	0.053	2.494	0.013
CRT -> PRO	0.042	0.045	0.059	0.709	0.479
CLL -> ELL	0.558	0.559	0.065	8.631	0.000
CLL -> SOC	0.318	0.320	0.065	4.908	0.000
CLL -> PRO	0.076	0.079	0.066	1.139	0.255
ELL -> SOC	0.405	0.401	0.063	6.399	0.000
ELL -> PRO	0.324	0.322	0.068	4.776	0.000
SOC -> PRO	0.370	0.366	0.062	5.979	0.000

Figure 2 illustrates the structural model showing the relationships among culturally responsive teaching (CRT), cultural literacy (CLL), environmental literacy (ELL), social attitudes (SOC) and biology

problem solving (PRO). The model presents the path coefficients between latent constructs and their observed indicators, highlighting both direct and indirect effects of CRT on students' competencies in biology problem solving, literacy and social attitudes.

Figure 2

SEM analysis results (Source: SmartPLS 3.3.2)



Discussion

The analysis indicates the relationships between culturally responsive teaching (CRT) and various aspects of student learning. CRT demonstrates notable associations with cultural literacy (CLL), environmental literacy (ELL) and social attitudes (SOC). In contrast, the direct effect of CRT on students' biology problem solving (PRO) appears to be low and not statistically significant, suggesting that any influence of CRT on biology problem solving may occur indirectly through variables such as CLL, ELL and SOC. Overall, the findings highlight how CRT is connected to multiple dimensions of learning, with potential indirect pathways affecting students' biology problem solving.

In more detail, CRT demonstrates a significant influence on cultural literacy, environmental literacy and social attitudes ($p < 0.005$). This occurs because CRT links the subject matter to students' local cultural contexts, encouraging active involvement, cross-cultural understanding and sensitivity to environmental and social issues. Hutchison & McAlister-Shields (2020) observe that CRT helps students strengthen their cultural identity and integrate it into the learning process, creating a sense of ownership and relevance in what they learn. Blanchet-Cohen & Reilly (2013) argue that embedding local values and cultural perspectives in biology education increases students' awareness of the ecological impact of both traditional and modern practices, leading to stronger engagement in sustainable action. Similarly, Nurbatra & Masyhud (2022) found that CRT fosters student agency by providing flexibility in choosing culturally relevant topics and promoting inclusive discussions across diverse backgrounds.

Furthermore, the findings demonstrate that cultural literacy significantly influences both environmental literacy and social attitudes ($p < 0.005$). Students who are familiar with local norms, traditions and wisdom tend to respect biodiversity, conserve natural resources and appreciate multicultural coexistence. Veisi et al. (2018) demonstrated that cultural and social dynamics shape students' environmental awareness and their behaviors toward ecological preservation. Similarly,

Leung et al. (2011) highlighted that individuals' understanding of environmental issues is deeply embedded in their sociocultural frameworks, affecting how they interpret and respond to ecological knowledge. In line with this, Jegede & Fraser (1989) emphasized that socio-cultural values influence students' dispositions toward science learning, thereby affecting their motivation and readiness to apply scientific concepts in real-life contexts.

Environmental literacy, in turn, has a significant effect on both social attitudes and biology problem solving ($p < 0.005$). This suggests that students comprehend the interconnections between human activity and environmental systems. They not only develop environmentally responsible behaviors but also cultivate collaborative and empathetic social attitudes. Such dispositions prepare students to approach complex problems holistically, incorporating ecological, cultural and social perspectives. Consequently, this nurtures higher-order biology problem solving that are contextualized and sustainable. Tran et al. (2024) support this conclusion by showing that integrating social issues into the biology curriculum increases both student engagement and the application of biological knowledge to real-world challenges. Wahyuningtyas (2022) also emphasizes that culture-based instructional modules can enhance relevance and stimulate critical reflection, serving as an effective strategy for bridging cultural experiences and scientific inquiry.

The results further indicate that social attitudes significantly affect biology problem solving ($p < 0.005$). This finding indicates that students who are more open to diverse perspectives, empathetic toward others and collaborative in nature are better equipped to address complex, multidimensional problems. These interpersonal and intrapersonal qualities complement cognitive skills in devising effective and innovative solutions. Therefore, social attitudes serve as an important mediating bridge between culturally responsive pedagogy and the cultivation of higher-order thinking skills.

The study also indicates that CRT and cultural literacy do not directly influence biology problem solving ($p > 0.005$). This outcome suggests that while CRT and CLL lay the foundation for identity development, inclusivity and empathy. They may not directly train students in analytical reasoning or systematic problem solving. Instead, their role is more supportive, shaping dispositions and contextual awareness that subsequently facilitate biology problem solving through other mediating competencies such as environmental literacy and social collaboration. The absence of a direct effect may also reflect instructional design, in which CRT-based activities tend to emphasize awareness, discussion and cultural engagement rather than explicit practice in logical reasoning or biology problem solving.

However, evidence from previous studies indicates that integrating CRT is integrated with more strategy-oriented approaches. such as problem-based learning (PBL), it can significantly enhance students' biology problem solving. Ernawati et al. (2024) demonstrated that the synergy between CRT and PBL creates an inclusive and contextualized learning environment that simultaneously strengthens cultural literacy, fosters critical thinking and improves biology problem solving. This implies that CRT alone may not be sufficient to develop biology problem solving directly. However, it becomes highly effective when combined with active learning models that emphasize inquiry, critical reflection and real-world application.

Taken together, the literature indicates that CRT can strengthen students' cultural literacy, environmental literacy and social attitudes by connecting scientific learning with their cultural experiences, local environments and social interactions (Ladson-Billings, 1995; Gay, 2018; Aronson & Laughter, 2016). These competencies are interconnected with problem solving because students need to interpret contextual information, analyze evidence, consider different perspectives and develop responsible solutions to biological and environmental problems (McBride et al., 2013; Freeman et al., 2014; Tanner, 2017). Thus, integrating CRT with inquiry- or problem-based learning may enhance both the socio-cultural relevance and cognitive demands of biology learning. However, limited empirical research has examined the relationships among CRT, cultural literacy, environmental literacy, social attitudes, and biology problem solving simultaneously, highlighting the need for an integrated model of culturally responsive biology education.

Conclusion and Limitations

Based on the results of the analysis. It can be concluded that culturally responsive teaching (CRT) has a significant influence on students' cultural literacy, environmental literacy and social attitudes. However, its influence on biology problem solving is indirect. The significant influence of CRT on cultural literacy facilitates students' active involvement and contextual understanding of cultural and environmental values, thus encouraging the formation of social attitudes and environmental literacy. Strong cultural literacy has been shown to contribute significantly to environmental literacy and social attitudes. At the same time, environmental literacy and social attitudes play an important role in significantly improving students' biology problem solving. Even though CRT and cultural literacy do not directly show a significant influence on biology problem solving, this approach remains relevant because it can create a foundation of values and an inclusive learning context, which, when combined with strategies such as problem-based learning (PBL), proves to be effective in fostering critical thinking skills and sustainable biology problem solving.

This study has several limitations that may affect the generalizability and interpretation of the findings. The limitations of the study, namely, first, the use of a cross-sectional survey design limits the ability to capture the dynamics of change or long-term causal relationships between variables. Second, the sample included 16 universities in Sulawesi; the results may not generalize to other regions in Indonesia with different levels of cultural diversity. In addition, the data were obtained entirely through a closed questionnaire, which may limit the depth of understanding of students' experiences and perceptions of the application of CRT in the learning context.

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Appendix

Statement of each variable in the research instrument

Item Variables	Item Statement
CRT1	The classroom learning environment supports the diversity of students' cultures and backgrounds.
.CRT2	The learning methods used by lecturers help develop students' knowledge and skills.
CRT3	Students are not allowed to relate the learning material to their cultural background.
CRT4	Classroom learning helps me see the relationships between subject matter and cultural values.
CLL1	I understand that culture influences the way students respond to learning materials.
CLL2	I am not able to analyze the cultural bias that appears in the learning process.
CLL3	I am interested in learning about other cultures through learning in class.
CLL4	I appreciate the cultural differences that my classmates bring to the learning process.
CLL5	Cultural diversity enriches the learning experience in the classroom.
CLL6	I can interact with classmates from other cultures without causing misunderstandings.
CLL7	I do not feel responsible for helping create an inclusive learning environment.
ELL1	I understand basic environmental concepts, such as climate change, recycling, and biodiversity
ELL2	I am unable to analyze environmental problems and formulate effective solutions.
ELL3	I care about environmental issues and contribute to preserving nature.
ELL4	I actively take environmentally friendly actions on campus.
SOC1	I do not always express my opinions honestly in the learning process.
SOC2	I always arrive on time for every learning activity.
SOC3	I show a positive and enthusiastic attitude in participating in learning activities
SOC4	I feel responsible for ensuring that my group completes the assignment.
SOC5	I respect my classmates' differences of opinion during learning activities
Item Variables	Item Statement
SOC6	I actively collaborate with my group of friends in completing learning tasks.
SOC7	I do not dare to take the initiative in learning activities, such as leading discussions
SOC8	I cannot always accept my classmates' different cultural backgrounds.
PRO1	I can recognize problems relevant to biology.
PRO2	I can explain biological problems using appropriate terms.
PRO3	I cannot formulate criteria for success in solving biological problems.
PRO4	I can gather information from various sources to solve biological problems.
PRO5	I am not always able to choose the most effective solution to a biological problem.
PRO6	I can review information used to solve biological problems.
PRO7	I am unable to evaluate the advantages and disadvantages of each chosen solution.
PRO8	I can evaluate whether the implemented solution has achieved the expected results.

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Team-based projects incorporating eco-friendly packaging and conservation principles to improve students' sustainability awareness in environmental chemistry courses

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ABSTRACT

It's clear that understanding sustainability is super essential for dealing with the environmental problems we face now and will face later. But we still don't know how to teach it in colleges, mainly in environmental science and chemistry education classes. This study tries to create a lecture program for environmental chemistry using team projects focused on eco-friendly packaging and saving resources. This is because we need better ways to teach sustainability. The study uses a research and development method, following the ADDIE model (which is just a way to plan how to prepare something). They got info from 124 college students in environmental chemistry, and the program they made has lesson plans, how the team projects should work, and ways to grade them. The effectiveness of the program was assessed using normalized gain (N-Gain) and paired sample t-test analysis. While the program demonstrated high validity (92.5%) and practicality (95%), and produced a moderate improvement in students' sustainability awareness (N-Gain = 0.6, $p < 0.05$), certain limitations remain. The research was conducted within a single institution and over a relatively short period, limiting the generalizability and long-term insights of the findings. Future research should explore the scalability of this approach across diverse educational settings and investigate the sustained impact of such programs on students' attitudes and behaviors towards sustainability.

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Introduction

As is known, plastic, which started being used around 50 years ago, has now become an inseparable part of human life. It is estimated that between 500 million and 1 billion plastic bags are used each year globally, amounting to around 1 million bags per minute. To produce them, 12 million

barrels of oil are needed annually, and 14 million trees are cut down. Excessive plastic consumption results in vast amounts of plastic waste. As it is not made from biological compounds, plastic is non-biodegradable. It is estimated that plastic takes 100 to 500 years to fully decompose (Putra & Wahid, 2021; Maida et al., 2020).

Plastic bag waste pollutes the soil, water, oceans, and even the air. Plastic bags are made from ethylene, a gas produced by distilling oil. Oil, gas, and coal are non-renewable natural resources, so increasing plastic use depletes these resources faster. Plastic is mostly made of polyvinyl polymers. These polymers come from polychlorinated biphenyls (PCBs), which look a lot like DDT. It takes anywhere from 100 to 500 years for plastic to break down in the ground (Febrianta & Yuwono, 2022; Enfrin et al., 2021; Kik et al., 2020).

Plastic waste management requires a mix of policy, technology, and behavior change, with education for sustainable development (ESD) as a key driver in developing the right attitudes and skills. It will help the individual gain the ability to be able to act and take decisions that can help in ensuring environmental integrity through means such as minimizing the use of plastics, encouraging recycling, and finding new ways of managing waste. Through inclusion of the concepts of sustainability in educational curriculum, it will help the individual assess their daily decisions which may have an effect on the environment such as the use of plastics, hence being able to effect change in their environment. Therefore, education regarding the environment and conservation plays a vital role in addressing the issue of pollution, climate change, and resource management (Khairina et al., 2020; Amin et al., 2020).

Environmental chemistry focuses on the interactions between chemicals and their environment, whether naturally occurring or artificial. At present, as global connections strengthen and sustainability is prioritized, it is increasingly essential for students of chemistry and related disciplines to become acquainted with environmental chemistry and the principles of ESD (Agbedahin, 2019; Bascopé et al., 2019).

ESD is a way of teaching that includes subjects on keeping things going, such as environmental, social, and financial issues, as part of learning (Sinakou et al., 2019; Kioupi & Voulvoulis, 2019). Education based on ESD aims to help students develop their understanding, knowledge, attitudes, and skills so they can address issues and build a future that lasts. For instance, in an environmental chemistry course, group projects on using eco-friendly packaging and conservation can help students learn more about sustainability.

Sustainability awareness is what people know, how they feel, and what they do to keep environmental, economic, and social systems going strong (Wamsler, 2020; Rieckmann, 2018). It encompasses three areas: cognitive (sustainability issue and solution knowledge), affective (attitude, values, and concern for sustainability), and behavioral (actual or planned sustainable behavior) (Evans, 2019; Bascopé et al., 2019). It consists of several indicators, including knowledge of sustainability principles, positive attitude, behavioral intentions, and critical thinking for solving sustainability-related problems.

Learning about sustainability awareness is imperative for students, as they are future leaders, entrepreneurs, and decision-makers who will shape society and address ongoing global challenges (Abulibdeh et al., 2024; Khan, 2023; Motzer et al., 2021). Sustainability awareness educates students about intertwined environmental, social, and economic challenges, cultivating responsibility and willingness to act (Ningsih & Akhyar, 2024). Sustainability awareness empowers students to adopt sustainable practices, make informed decisions, and develop solutions that support the sustainable development and conservation of natural resources. Sustainability awareness also equips students to contribute to a world that will increasingly focus on sustainable goals, preparing them for their individual growth, employability, and potential to introduce constructive changes in society (Rieckmann, 2018; Wamsler, 2020; Evans, 2019). Teamwork that integrates eco-friendly packaging and conservation in environmental chemistry can help mitigate the adverse effects of plastic packaging that doesn't break down (Moshkbid et al., 2024; Matarazzo et al., 2020).

To meet the requirement of enhanced awareness of sustainability in environmental chemistry education, there is a need for innovative methods of learning. The current research centers on team-based projects (TBPs), which engage students in solving problems and performing practical activities

like designing environment-friendly packaging and formulating conservation strategies. Contemporary studies encourage the application of learning and project-based approaches to facilitate understanding of sustainability by students.

Several important questions are investigated in the study. First, what level of improvement in students' understanding of sustainability can be achieved using a team-based lecture course on environmental chemistry with an emphasis on the design of environmentally friendly packaging and conservation? Secondly, what is the students' reaction to implementation of the proposed instruction approach that is team-based projects in environmental chemistry education?

Course development research for an Environmental Chemistry course on eco-friendly packaging technology will be done to integrate environmental chemistry concepts, conservation concepts, and eco-friendly packaging technologies within the higher education syllabus. The motivation to integrate eco-friendly packaging technology comes from its multi-disciplinary characteristics as well as its applicability towards addressing practical environmental issues. Eco-friendly packaging technology will serve as a real-world means of imparting chemical concepts such as biodegradation, green synthesis, and life cycle analysis while sensitizing students about the concept of sustainability and innovation in everyday practice.

There have been previous endeavors that have touched on various aspects pertinent to such integration. Pratiwi et al. (2023) and Mitarlis et al. (2023), for instance, have noted the salutary impacts of conservation-themed chemistry education on students' pro-environmental behavior and cognitive understanding of sustainability. Maidou et al. (2019) and Man et al. (2023) have summarized the application of green chemistry principles and project-based learning to enhance sustainability competencies. So too, Anthony Jnr (2021) has highlighted the role of sustainability thinking towards responsible innovation, while Kanapathy et al. (2020) and Janakiraman et al. (2021) have briefly touched on eco-innovation in packaging and its role towards environmental literacy. What, however, has yet to be accomplished despite such valuable endeavors is to bring together all of environmental chemistry, conservation values, eco-friendly packaging technology, and Education for Sustainable Development (ESD) into a single, systematically conceived course program.

Thus, the novelty and latest contribution of this study lie in its holistic integration of science content knowledge, sustainability values, and technological breakthroughs, encapsulated within the context of environmentally friendly packaging in a framed environmental chemistry course. It not only addresses the cognitive aspects of learning chemistry but also enhances students' affective and behavioral abilities relevant to ESD targets.

There has been particular emphasis on universities in preparing leaders and professionals who are sustainability aware (Abulibdeh et al., 2024; Khan, 2023; Motzer et al., 2021). Interdisciplinary, project-based methods are increasingly advised for integrating sustainability across curricula, encouraging active participation and deeper understanding (Sinakou et al., 2019; Kioupi & Voulvoulis, 2019). Empirical research indicates that they lead to transformative learning and broader implementation of sustainable behaviors (Wamsler, 2020; Bascopé et al., 2019). In spite of all the progress, most science curricula, including environmental chemistry, are poorly represented by holistic models that incorporate team-based tasks, conservation values, and practical work, such as environmentally friendly packaging, explicitly (Mitarlis et al., 2023; Kanapathy et al., 2020; Man et al., 2023).

The concept of eco-friendly packaging is a natural platform for teaching sustainability because it combines environmental problems with the use of scientific knowledge in practice. There are a number of recent research results indicating that bioplastics and biodegradable materials, such as starch, cellulose, chitosan, alginate, and biomass-based materials, can serve as good substitutes for traditional plastic products provided that their environmental impact depends on their performance, manufacturing process, and life cycle (Khalid & Arif, 2022; Van Roijen & Miller, 2022; Wang et al., 2022). Project and cooperative learning methods used in higher education are capable of transforming sustainability problems in reality into educational experience, which is associated with students' teamwork and sustainability skills development (Birdman et al., 2022; Guerra et al., 2022). Thus, projects of eco-friendly packaging are not only product development activities but also can be considered as

interdisciplinary educational platforms.

The concept of sustainability awareness is not limited to student awareness of environmental concerns but involves student attitudes, values and readiness to apply such awareness in sustainable practices. Recent research in higher education suggests that students may have strong sustainability knowledge, but less effective attitudes and behaviors which point to the importance of learning approaches that integrate awareness and practice (Farliana et al., 2024; Ovais, 2023). For effective sustainability education, it is important to focus on experiential and practice-based learning methods, rather than traditional teaching, since sustainable knowledge is related to developing specific sustainability competencies such as systems thinking, critical thinking, collaboration and solving of sustainability problems (Lozano et al., 2022; Brundiers et al., 2021; Kioupi & Voulvoulis, 2022). Thus, it would be relevant to implement sustainability awareness in team-based projects such as sustainable packaging.

Team-based projects provide a structured pedagogical approach for engaging students in authentic sustainability problems through shared responsibility, collaboration, and collective problem-solving. Research in higher education shows that well-designed project-based learning can strengthen collaboration, student autonomy, real-world application, and sustainability competencies (Birdman et al., 2022; Konrad et al., 2021). Effective teamwork also depends on meaningful peer interaction and appropriate instructor facilitation, which support communication, interpersonal competence, and the integration of diverse perspectives (Konrad et al., 2021; Bolstad et al., 2023). In sustainability-oriented projects, interdisciplinary collaboration enables students to connect scientific knowledge with complex environmental problems and develop feasible solutions through inquiry and reflection (Paristiowati et al., 2022; Domingues, 2025). Thus, team-based projects centered on eco-friendly packaging can provide an integrated mechanism for connecting sustainability awareness, environmental chemistry, collaborative inquiry, problem-solving, and sustainable action.

Although the above possibilities have been identified, very little research has actually focused on incorporating team-based project learning along with conservation and environmental chemistry through eco-friendly packaging in environmental chemistry education. This calls for developing an instruction model which will involve students in solving real-world environmental issues by incorporating scientific investigation, collaboration, conservation, and sustainability. Therefore, this paper will focus on developing and evaluating an integrated instruction model, which involves all of the above-mentioned concepts along with environmental chemistry, conservation, eco-friendly packaging technology, and sustainability awareness in an integrated team-based project model. What makes the proposed research unique is its explicit integration of these concepts, which have been approached separately in most cases in previous research. This is especially true because of the continued environmental challenges caused by plastic packaging technology due to its non-biodegradable nature.

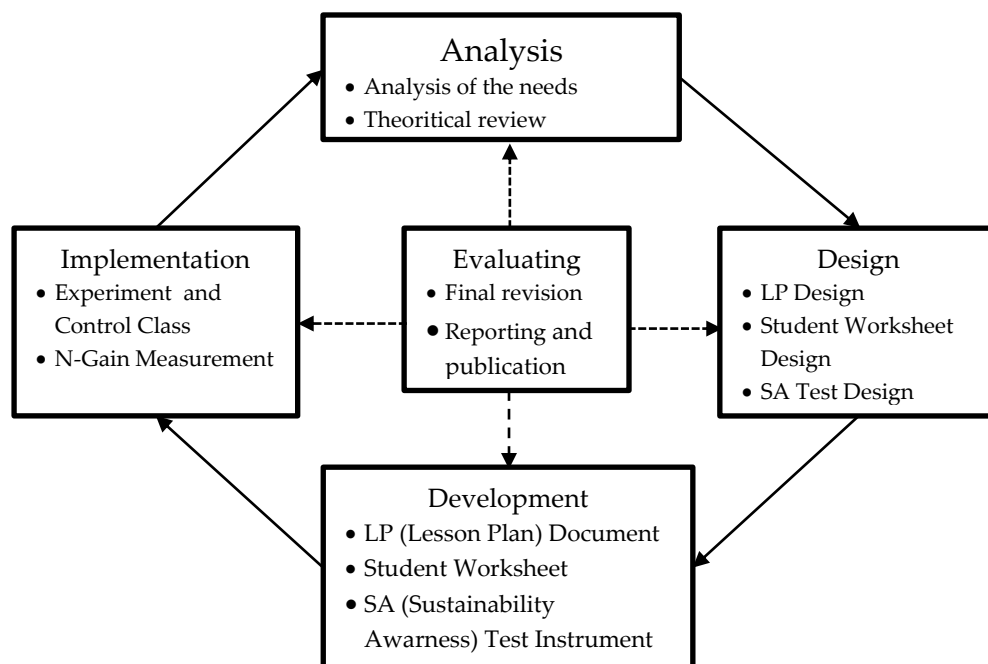
Higher education, particularly courses such as environmental chemistry, is crucial for equipping students with scientific knowledge and sustainability awareness. Therefore, this study aims to contribute to learning innovation by embedding eco-friendly packaging technology as a contextual entry point to help students critically understand and address the negative environmental impacts of plastics while cultivating their competencies in Education for Sustainable Development (ESD).

Method

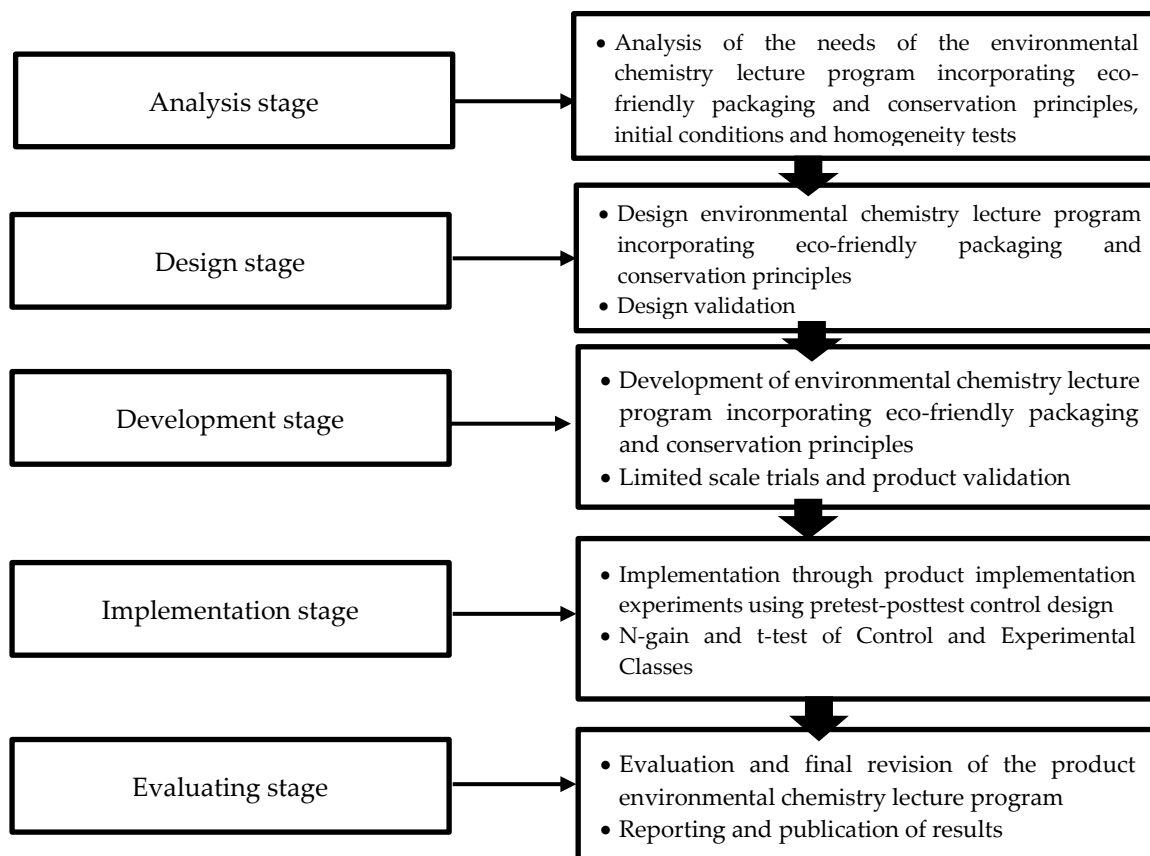
Research and development methods using the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation), according to Branch (2009), have been carried out to develop an environmental chemistry lecture program that provides insight into environmentally friendly packaging technology and conservation to improve students' ESD competencies. The subjects of this study were students in the Chemistry Education and Environmental Science Study Program at the Faculty of Mathematics and Natural Sciences, Semarang State University.

Figure 1

The ADDIE model adapted from Branch (2009)



This development procedure follows the ADDIE instructional research and development procedure, which aims to produce an environmental chemistry lecture program product that provides insight into environmentally friendly packaging technology and conservation to improve students' ESD competencies. ADDIE is a development model consisting of five stages, namely Analysis, Design, Development, Implementation, and Evaluation. The R and D stages with the ADDIE model in this study are shown in Figure 2.

Figure 2*ADDIE Design Implementation Flow for Lecture Program Development*

The stages in developing an environmentally conscious environmental chemistry course program focused on eco-friendly packaging technology to enhance sustainability awareness include the following: Analysis, this stage involves conducting a needs analysis, identifying problems (needs), carrying out task analysis, and determining the research sample. At this stage, the environmentally conscious environmental chemistry course program, focused on eco-friendly packaging technology to enhance sustainability awareness, is created. The design is then evaluated and improved before being realized in the final product. At this stage, the product design is still conceptual and will form the foundation for the next development process.

The development phase translates the conceptual design into a complete environmentally conscious environmental chemistry course program centered on eco-friendly packaging technology and sustainability awareness. Development involves developing such components as the course syllabus, learning outcomes, teaching materials, project instructions, student worksheets, assessment tools, and learning resources. Learning activities will be planned according to the nature of the topic of environmental chemistry where chemical concepts will be linked with practical environmental issues especially regarding plastic pollution, material selection, biodegradability, waste handling, and environmental consequences of packaging. Implementation of the course will involve group projects where students will have to identify environmental issues concerning packaging, study the chemical and environmental properties of other materials, develop environmentally friendly packaging prototypes, and evaluate the properties and the environmental aspects of the solutions. After that, the developed course program will be tested in a limited scale within the classroom environment in order to check the feasibility and practicability of the course program as well as its compliance with the specified learning outcomes.

The process of evaluation is done systematically to gauge the validity, practicality, and preliminary success of the newly designed course program. Firstly, an FGD of experts is carried out to evaluate whether the course program, its objectives, environmental chemistry knowledge, conservation knowledge, eco-friendly packaging project, the learning activities, and the assessment tools conform to the theoretical framework and the nature of higher education. Expert feedback is analyzed and the course program revised prior to its actual implementation. Secondly, survey responses of the students are collected after completion of the learning activities to gauge student perceptions about the clarity, relevancy, feasibility, level of engagement, collaborative learning, and contribution of project activities to awareness of sustainability. Evaluation results based on the experts' and student feedbacks are triangulated to establish areas of strength as well as areas needing revision of the course program. The revisions made represent the final environmentally conscious environmental chemistry course program design.

Participants

The sample consists of four classes, two classes from the Chemistry Education program and two from the Environmental Science program, comprising a total of 124 undergraduate students enrolled in the Environmental Chemistry course during the even semester of 2024. These students are in their 4th semester and have previously completed prerequisite courses in general chemistry and basic environmental science, making them pedagogically and cognitively prepared for the integration of eco-friendly packaging technology in the course. The sample was selected purposively based on key considerations, including student academic background, learning objectives, and the thematic relevance of sustainable packaging to their respective fields. This selection aims to ensure that the program implementation can optimally foster students' sustainability awareness, scientific understanding, and application of environmentally responsible practices.

Data Collection Tools

The data collection tools in this study were systematically developed based on the stages of the ADDIE model to ensure alignment with the research objectives. During the Analysis phase, data were collected through three main instruments: (1) a student needs analysis questionnaire to assess students' prior knowledge and perceptions related to environmental chemistry and sustainability, (2) semi-structured interview guidelines for lecturers to explore their perspectives on integrating eco-friendly packaging technology in the course, and (3) a literature review checklist to identify gaps in existing curricula and instructional practices.

In the Design phase, instruments were developed to support instructional development and to measure students' initial competencies in practice. These included (1) lesson plan and lecture module validation sheets, which experts reviewed to ensure alignment with sustainability principles in a practical context, and (2) a pretest instrument on sustainability awareness, designed using validated items that measure dimensions such as students' understanding of environmental issues, attitudes toward sustainability, and knowledge of eco-friendly packaging. This pretest served as a practical baseline for students' sustainability awareness prior to their participation in the course.

Before implementing the environmental chemistry course program, which incorporates team-based projects on eco-friendly packaging and conservation principles, a pretest was administered to assess students' initial sustainability awareness. Pretest was made up of 20 multiple choice questions, where five of them covered each of four indicators, which included knowledge of sustainability concepts, attitude towards sustainability practices, behavioral intention of sustainability, and critical thinking and problem solving. The questions were created in accordance with the operational definitions of the four indicators and were rated by five experts in a five-point scale. Content validity was assessed using Aiken's V coefficient, with item-level values ranging from 0.85 to 0.95 ($M = 0.90$), indicating satisfactory content validity. The instrument was subsequently pilot-tested with 30 students with characteristics comparable to those of the target sample. Item analysis showed point-biserial correlations ranging from 0.35 to 0.61, difficulty indices ranging from 0.53 to 0.73, and discrimination indices ranging from 0.37 to 0.60. Each of the 20 items fulfilled the pre-set requirements and remained

included, while reliability was calculated using the KR-20 coefficient which gave the value of 0.89. Students were allowed 60 minutes for testing, and the results from the pretest formed the quantitative baseline that will be compared with the posttest performance of the students to measure their improved knowledge on sustainability.

Quantitative data from the surveys and pretests were analyzed descriptively and inferentially, while qualitative data from interviews were analyzed thematically. These combined instruments and methods provided a comprehensive understanding of the learning context and the impact of the course design.

For the developmental and implementation phases, the instructional learning materials, multimedia and activities were created and tested. Post-tests and surveys were also used to evaluate the degree to which students learned and the level of their engagement with the program. Feedback from experts was also obtained for improving the learning materials. At last, numerical and feedback instruments were used to measure the success of our program. The number-oriented data comprised test scores to evaluate students' knowledge of sustainability issues. On the other hand, feedback from surveys and group discussions helped assess the effectiveness and usefulness of the lecture program.

Data Analysis

We analyzed the data using both quantitative and qualitative methods. The number-based part assessed how well students understood sustainability. We did this by comparing their scores before and after the teaching, using a formula by Hake (2002a, 2002b).

$$N\text{-Gain} = \frac{\text{Posttest Score} - \text{Pretest Score}}{\text{Maximum Score} - \text{Pretest Score}}$$

Where:

Posttest Score: The score obtained after learning.

Pretest Score: The score obtained before learning.

Maximum Score: The highest possible score

Here is the N-Gain Interpretation Categories:

Table 1

The N-Gain interpretation categories

Category	N-Gain Range
High	N-Gain ≥ 0.7
Medium	$0.3 \leq \text{N-Gain} < 0.7$
Low	N-Gain < 0.3

We used a paired-samples t-test to compare average grades before and after the program to determine whether our green lecture series made a real difference. This test works well when looking at two sets of data connected, like pre-and post-test results, to see if a teaching method is any good (Creswell & Creswell, 2017).

We ran a t-test on the pre- and post-test scores to determine whether the lecture series increased students' awareness of sustainability. We set our cutoff for a real difference (alpha) at 0.05, which is standard for education research (Fraenkel, Wallen, & Hyun, 2012). To better understand how much the lecture series changed things, we also figured out the effect size using Cohen's d. This indicates whether the change was small (0.2), medium (0.5), or large (0.8), according to Cohen (1988). The t-test results and the effect size give us a clearer idea of what the program did.

Thematic analysis was applied to the student feedback and discussions within the groups. Thus, we were able to identify the themes associated with students' experiences and impact on their perception of the issue of sustainability (Braun & Clarke, 2006). We analyzed, categorized, and interpreted the feedback in order to find out how effective the instruction process was and how motivated students were towards the packaging.

Several sources of data were used to ensure the credibility of the research findings. We analyzed surveys, group discussions, and expert opinions (Creswell & Poth, 2018). Such an approach provides for credibility and reliability of the research findings. A combination of numbers and narratives provided us with a better insight into the effectiveness of the lecture program.

Results and Discussion

This research was a collaborative project on eco-friendly packaging and conservation for an environmental chemistry class. The goal was to raise students' awareness of sustainability, and the project was meticulously planned using the ADDIE model, with each team member contributing their expertise.

At each stage of the ADDIE model, we developed tools to gather data. The initial phase involved a comprehensive student needs analysis facilitated through surveys, lecturer interviews, and group discussions. These discussions were instrumental in identifying gaps in current teaching methods and in shaping the program to meet students' educational needs.

During the group discussions, considerations on the choice of the appropriate sample for the program tests were discussed. Among the aspects considered during the sample choice included the nature of the students, their learning requirements, and the relevance of the packaging technology to the environment. The choice of sample made in this regard would mean that the program will make the learners more sustainable. This is in line with current trends on the need for sustainability-oriented higher education programs that are linked to students' competencies and learning needs as sustainability competencies develop better through learning that addresses practical real-life issues (Redman & Wiek, 2021; Bianchi et al., 2022; Leal Filho et al., 2023; Yakar-Pritchard et al., 2024).

Aside from the sample determination, the FGD was also used to measure the initial conditions of the students who will be used as the subjects for this study. Initial conditions of the students include their basic knowledge about ESD and environmentally friendly packaging technology. This information was used to serve as the basis for developing an appropriate learning strategy. Homogeneity test of the sample has also been done and based on the results, it can be seen that the samples possess relatively homogeneous characteristics and thus it will be easy to determine the outcome of the implementation of the program. The need to assess the sustainability knowledge of the students is further emphasized by the recent studies which state that even though university students have positive environmental attitude, they lack sustainable knowledge (Alvarez-Risco et al., 2022; Redman & Wiek, 2021; Farliana et al., 2024; Aquan et al., 2025).

From the test carried out on the homogeneity on the sample classes within the Chemistry and Environmental Science Education Study Programmes, the findings were that the data satisfied the homogeneity requirement. The test was carried out to ensure that the variables measured within the sample classes shared similar fundamental characteristics such as the level of knowledge about the concepts of education for sustainable development (ESD) and the environmentally friendly packaging technology. The test results showed that there was a probability of 0.45 ($p > 0.05$). The result is significant since the comparable characteristics allow for a better interpretation of differences within the sample classes as a result of the instruction programme and not because of significant differences before carrying out the test as recommended by other researchers (Redman et al., 2021; Kioupi & Voulvoulis, 2022; Xiao et al., 2024; Null et al., 2024).

These findings prove that the selected classes are relatively homogeneous in terms of the variables that were analyzed. Therefore, they can be considered an appropriate proxy for the full-scale program. Such homogeneity will help prevent external factors from affecting the effectiveness of the learning process. It will also contribute to ensuring that the outcome will be more relevant. Consequently, the assessment of homogeneity is one of the crucial steps that should be done prior to implementing the full-scale program (Braithwaite et al., 2018; Kraft, 2020).

Moreover, the homogeneity analysis found out that such characteristics as educational background, age, and learning experience were not statistically significant in terms of the differences

among the sample classes. This finding is methodologically important because establishing comparable baseline characteristics can strengthen the interpretation of changes in sustainability-related outcomes by reducing concerns that observed differences are primarily attributable to pre-existing differences among the participating groups (Redman et al., 2021; Kioupi & Voulvoulis, 2022; Xiao et al., 2024). Because of these results, we could proceed to the next stage of the program with greater confidence in interpreting the outcomes of the intervention.

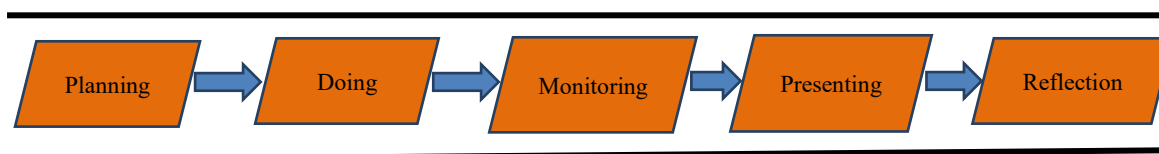
The FGD results indicated that two classes from the Chemistry and Environmental Science Education Programs at the Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang, were selected as the test groups. This choice was based on an assessment of the program requirements and the students' initial conditions. With the homogeneity test completed, the selected classes were considered sufficiently comparable to support the implementation and evaluation of the ESD program. Such alignment between students' initial conditions, intended learning outcomes, and instructional design is consistent with recent higher-education ESD research emphasizing that sustainability programs should be systematically designed and evaluated according to students' competencies and learning needs (Brundiers et al., 2021; Kioupi & Voulvoulis, 2022; Hammer & Lewis, 2023). This provides a reasonable basis for evaluating the program outcomes and assessing their potential relevance to the broader target population.

During the planning stage, we developed lesson plans and class modules that incorporate eco-friendly packaging technology and sustainability ideas. We used tools like pretests to gauge where students stood with their sustainability smarts. These pretests gave us a starting point for seeing how well the program works. Putting these learning tools to use meant using a variety of resources, like videos and interactive activities that engage people. In bringing all of these elements together, there is a lot that has been done in ensuring that the learning of the students improves. In doing so, this is in line with current science education studies which suggest that contextualized project-based learning and systematically organized environmental learning projects could lead to improved analytical and engagement abilities, as well as helping students make connections between their scientific knowledge and sustainability concerns in the world (Syawaludin et al., 2022; Lutfauziah et al., 2023).

We designed team projects for the environmental chemistry lectures that use eco-friendly packaging and focus on conservation. The goal was to get students more aware of how to be sustainable. We call this the environmentally friendly packaging technology conservation-focused environmental chemistry lecture program. You can see the design in Figure 3.

Figure 3

The design of the environmental chemistry lecture program team-based projects incorporating eco-friendly packaging and conservation principles to improve students' sustainability awareness



During the design stage, we created team projects for the environmental chemistry lecture series that incorporated eco-friendly packaging and conservation principles. This was all done to get students thinking more about sustainability. We ended up with a semester plan, a step-by-step guide for the team projects, teaching stuff for the chemistry course, and a way to evaluate the lectures. This design is consistent with recent evidence that sustainability-oriented chemistry education benefits from student-centered, project-based, and contextually relevant learning strategies that connect disciplinary knowledge with authentic environmental problems (Aydin Gunbatar et al., 2025; Yakar-Pritchard et al., 2024; Wan Nor Azmi et al., 2024).

In the course of development and implementation of our project, we have been working hard to test it and make improvements to it. We gave post-tests to find out what knowledge the students

have gained and evaluate the effectiveness of the approach used. In addition, we carried out surveys among the students to get their feedback and learn about their engagement in the program. The expert groups helped us improve the teaching material and ensured that it is correct and serves its purpose. All these results of the testing and the feedback provided have helped us evaluate the progress of our project. The combination of cognitive measures and feedback is supported by the latest reviews of green and sustainable chemistry education (Aydin Gunbatar et al., 2025; Ginting & Budiasih, 2025; Suiirbay, 2025).

We created an environmental chemistry lecture program based on the use of eco-friendly packaging technology. We did this by designing a framework for team project work in class, a semester learning schedule, process of conducting team projects, teaching materials for the course, and an assessment scheme. Integration of packaging technology and environmental chemistry is conceptually relevant because current literature on green chemistry education highlights the need for embedding chemical ideas into environmental issues and application of active learning techniques to foster students' knowledge of both science and sustainability (Ginting & Budiasih, 2025; Aydin Gunbatar et al., 2025).

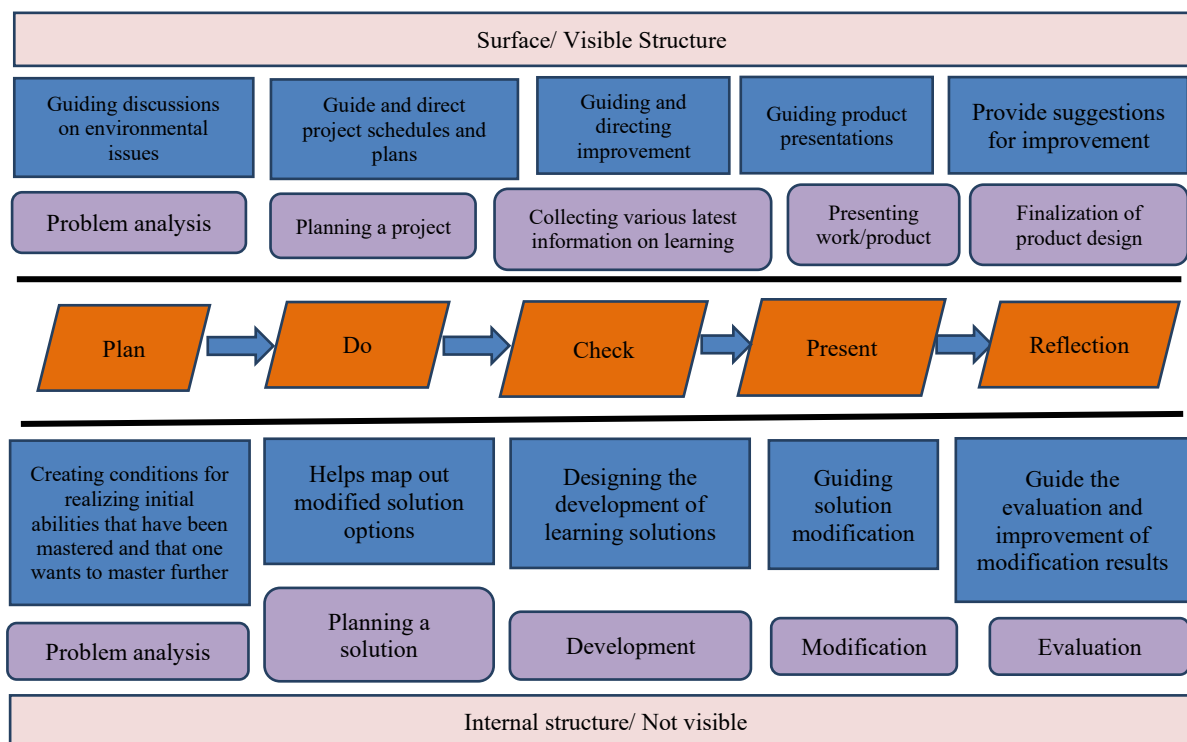
Next, the program's feasibility, in terms of its suitability for teamwork on sustainable packaging and protection, was assessed. The objective was to ensure that the program met all criteria required for it to be efficient and useful in the classroom. This assessment was conducted by three experts in environmental chemistry, sustainable education, and green technologies who verified if the information provided was accurate, the learning approach was appropriate and the program had potential for wider usage. Participation of the experts in multiple related fields corresponds with the modern research on sustainability education, which stresses the importance of alignment between disciplinary content, pedagogical approach, sustainability skills, and assessment methods in designing an ESD curriculum (Brundiers et al., 2021; Aydin Gunbatar et al., 2025; Wan Nor Azmi et al., 2024).

The results revealed that the course is very reliable and valuable. It scored 92.5% for appropriateness, which means that it correlates highly with student learning outcomes. In addition, it earned a 95% score for usability, which means that the course is easy to apply in practice. Taking all the scores into account, we expect that the lectures on environmental chemistry will contribute to the development of protection and green technology skills among students. This result is in line with the findings of recent systematic reviews, according to which properly constructed sustainability and green chemistry curricula could serve as an excellent basis for combining environmental awareness, active learning, and sustainability competencies in chemistry courses (Yakar-Pritchard et al., 2024; Suiirbay, 2025).

This experiment took place in the autumn of 2024/2025 among 124 students enrolled in the environmental chemistry course at Semarang State University. This pilot test aimed to assess the newly designed lecture course integrating group work and emphasis on environmental packaging and protection concepts. The experiment was based on the application of a one-shot case study approach using the method of structured experimental activities implemented into the existing curriculum. Semarang State University was selected as a research institution due to the commitment of this educational organization to the sustainability issue and its reputation as an innovator in environmental studies in Indonesia. Furthermore, Semarang State University is known to provide its students with an Environmental Chemistry course within its Chemistry Education program.

Figure 4

Development of syntax in the environmental chemistry lecture program team-based projects incorporating eco-friendly packaging and conservation principles to improve students' sustainability awareness



The outcome of the pretest will later be employed in assessing the N-Gain of students' awareness of sustainability in environmental chemistry lectures. The environmental chemistry lecture program involving team-based projects, which included eco-friendly packaging and conservation concepts, was applied after the pretest. The delivery of the lecture took place through the team-based project approach based on the previously validated PDCPR (Plan Do Check Present and Reflection) syntax. Conducting a pretest followed by a team-based project is in line with the latest sustainability education studies highlighting the need for determining the students' starting point and then assessing their learning outcomes after the interventions (Yakar-Pritchard et al., 2024; Widyantoro et al., 2025; Jusniar et al., 2025).

At the plan (P) stage, students work in groups to plan and design their sustainable packaging technology projects. The process comprises ideation, preliminary research, and formulation of project objectives. Students develop project plans that incorporate the elements of sustainability and technology. The project designs are then presented in the class for feedback from fellow students and instructors in order to improve their designs. The planning process is essential in teaching and learning because sustainability-focused project learning involves students' interaction of knowledge, negotiating ideas, and connecting the concepts of disciplines to solve sustainability challenges (Hidayah et al., 2025; Yakar-Pritchard et al., 2024; Widyantoro et al., 2025).

Figure 5

Team based project lecture activities at the plan stage (students plan and present environmentally friendly packaging technology development project design)



Figure 6

Students present the implementation of the environmentally friendly packaging technology project



Figure 7

Students presenting at monitoring activities or progress reports on environmentally friendly packaging technology projects



During the do (D) stage, students carry out active learning in their assigned groups as they design their environmentally friendly packaging technology projects. Each group chooses an individual topic to investigate, such as packaging made from banana stems, antimicrobial packaging, or

biodegradable plastic films. In this phase, the focus on teamwork and practical application of ESD principles becomes crucial, as the students engage in problem-solving, troubleshooting, and improving their designs. This practical and collaborative aspect of the phase is justified by contemporary findings of chemistry education research revealing that project-based and experiential learning can improve students' environmental sensitivity, conceptual learning, teamwork, and connection of chemistry knowledge with sustainability issues (Jusniar et al., 2025; Hidayah et al., 2025).

At the implementation stage, students are split into eight groups. Each group comes up with environmentally friendly packaging technology design based on ESD. During the C phase, students are involved in monitoring activities, where they share their progress and early results. This phase provides students with the chance to be accountable as well as gives them the chance to have feedback on their project, helping them improve their project further. This collaborative monitoring and feedback process is consistent with recent research showing that sustainability-oriented project-based learning can facilitate knowledge exchange, collaborative problem solving, and iterative improvement as students work together to address authentic sustainability challenges (Castaño et al., 2025; Widyanthoro et al., 2025).

Right now, after projects wrap up, each group gives a final presentation showcasing their eco-friendly packaging tech. They show prototypes, explain the science and technology behind them, and discuss how their ideas can be used. These presentations show they get sustainability and can turn ideas into real-world solutions. The presentation and reflection of project outcomes are pedagogically significant because experiential and project-based approaches enable students to connect disciplinary knowledge with authentic environmental problems while communicating and justifying sustainability-oriented solutions (Jusniar et al., 2025; Yakar-Pritchard et al., 2024).

Figure 8

The examples of student project results or products, a. Biopack made from dry leaf waste and fruit peel; b. Bioplastic made from cassava; c. Biopack made from banana peel and fiber waste. Biofoam made from rice straw waste; and e. Biofoam made from sugarcane pulp and starch



Figure 9

Students presenting the results of environmentally friendly packaging technology projects



At the reflection (R) stage, after the presentations, students engage in reflective activities to evaluate their learning experiences. This stage focuses on identifying challenges faced, lessons learned, and potential improvements for future projects. Students also assess the impact of their work on environmental sustainability and their understanding of sustainable awareness and ESD principles, consolidating their knowledge and skills for future applications. However, this process is highly significant in sustainability education since structured reflection will allow students to reflect on their experiences and analyze any difficulties that they have faced and link project results to broader aspects of sustainability (O'toole et al., 2026; Lo-Iacono-Ferreira et al., 2024).

For the purpose of the evaluation of the success of the program, both quantitative and qualitative analyses were used. As for the quantitative approach, it was directed at evaluating the changes in students' awareness about sustainability. The results of limited implementation show that the implementation of the environmental chemistry lecture program team-based projects incorporating eco-friendly packaging and conservation principles to improve students' sustainability awareness. The N-Gain value of the average value of the pre-test and post-test of students is 0.6, indicating that there is an improvement on the students' sustainability awareness in the moderate criteria. This moderate gain is consistent with recent empirical evidence showing that sustainability-oriented and green chemistry learning interventions can produce measurable improvements in students' sustainability-related knowledge and awareness, particularly when learning involves active, contextual, and project-based experiences (Daulay et al., 2025; Null et al., 2024).

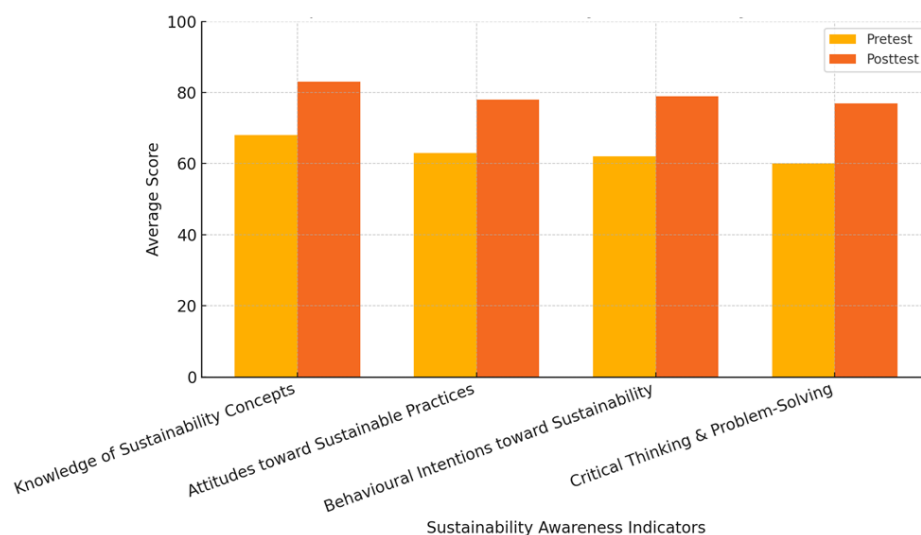
We used a paired sample t-test to see if the environmentally-conscious lecture program made a real difference in scores. The findings indicated a significant increase in the students' sustainability awareness, with a mean pretest score of 65 increasing to a post-test score of 80, confirming the program's effectiveness at a significance level of $p < 0.05$. This improvement is consistent with recent evidence that sustainability-oriented and green chemistry learning can strengthen students' environmental knowledge and sustainability-related competencies when instruction combines contextual problems, active learning, and opportunities to apply scientific knowledge to real-world sustainability challenges (Carvalho da Silva et al., 2026; Gorito & Morais, 2026; Kusuma et al., 2026).

Besides students knowing more about sustainability in general, a close look at each part of what makes up sustainability awareness shows big gains in all areas. In addition to the overall increase in students' sustainability awareness, a detailed analysis of each indicator of sustainability awareness shows substantial improvements across domains. Figure 10 below compares students' pre-test and post-test scores for four key indicators: knowledge of sustainability concepts, attitudes toward sustainable

practices, behavioural intentions toward sustainability, and critical thinking and problem solving. This chart shows how well the course helped students get better at understanding different parts of sustainability. This multidimensional improvement is consistent with recent sustainability-education research indicating that sustainability learning should integrate knowledge, values and attitudes, behavioral orientation, and competencies for critical and solution-oriented thinking rather than treating environmental awareness as a single cognitive construct (Brundiens et al., 2021; Farliana et al., 2024; Xiao et al., 2024).

Figure 10

Improvement in Sustainability Awareness by Indicator



The environmentally-conscious chemistry lecture program led to better scores in sustainability awareness. This shows students have a better understanding of what sustainability means for the environment, society, and the economy. The Attitudes toward Sustainable Practices scores also went up, from 63 to 78 (a 24% increase). This means students are more willing to support sustainability in their lives. The biggest change was in Behavioural Intentions toward Sustainability, which went up from 62 to 79 (a 27% increase). This suggests the program inspired the students to live in a more sustainable way. Lastly, the Critical Thinking and Problem-Solving Related to Sustainability scores increased from 60 to 77, a 28% increase. This result means the program assisted students to think about sustainability problems and come up with new ideas. The increases show that the lecture program gave students the information, mindset, and skills to help with sustainability. This multidimensional improvement is consistent with recent research showing that sustainability learning should address interconnected dimensions of knowledge, attitudes, behaviors, and higher-order competencies, rather than treating sustainability awareness as a single cognitive outcome (Liu et al., 2026; Aquan et al., 2025; Jintalan, 2025; Widyantoro et al., 2025).

The results indicated that students were well-informed about the concept of sustainability and committed to it. The interviews and journals provided supporting evidence of students' understanding of the problem and their willingness to become more sustainable. These findings indicate that there is an opportunity for educating students on sustainability through school programs. Students' comments revealed their experience of working within the program. The key themes of student experience are the increased awareness of environmental issues and the applicability of the lectures to reality. The current finding is also supported by the contemporary research stating that experiential and context-based chemistry education can help learners link scientific concepts to authentic sustainability challenges, and collaborative knowledge exchange can improve students' sustainability knowledge, affective involvement, and learning-to-action capability (Tantayanon et al., 2025; Koulougliotis et al., 2024; Yakar-Pritchard et al., 2024; Chen et al., 2020).

In general, this research focused on examining the lecture program on eco-friendly packaging

and sustainability education. It became apparent that the participants' level of knowledge regarding sustainability was higher compared to their initial one, since there was an improvement of test scores in such categories as knowledge, attitude, intention, and problem-solving. Thus, the use of group work and application of practical examples allowed improving knowledge and positive attitudes towards sustainability. As for the collected feedback, it revealed increased participation, motivation, and understanding of the importance of sustainability education in schools and everyday life. In particular, students stated that group work on real-life problems contributed to improved problem-solving and personal responsibility in relation to environmental issues. The obtained results are consistent with the latest research which indicates that the use of experiential and project-based approaches in chemistry and sustainability education may help develop students' environmental awareness, critical thinking skills, collaboration abilities, and integration of scientific knowledge into practical sustainable development problems (Nugroho & Dewi, 2025; Widyanoro et al., 2025; Jusniar et al., 2025; Yakar-Pritchard et al., 2024). The success of this teaching method suggests that other similar programs could raise awareness about sustainability and offer life-changing learning in different schools. Still, this study only looked at one school over a short time. More research is needed to see the long-term on students' eco-friendly actions and if the findings hold true in different schools to validate these discoveries.

Conclusion

In conclusion, this research conducted was successful in increasing the awareness of sustainable packaging among the students. It was done using a learning program designed using the ADDIE model. Gathering data using surveys, interviews, and focus groups indicated several gaps in the existing teaching program. In this way, it was possible to develop a program based on the needs of students. This research indicated that students' knowledge, attitudes, willingness to behave and think in a critical manner regarding sustainability had been improved. The results of the research indicate that not only the program enhanced students' perception of sustainability but also encouraged them to make actions that are environmentally friendly.

The research conducted in this paper is useful in incorporating sustainability education in schools mostly through programs that are well-designed and based on practical issues such as sustainable packaging. Due to significant changes achieved in all aspects studied, it is clear that such educational measures can contribute towards building sustainable behaviors and skills of thinking among the students. This will make them more prepared to handle environmental challenges on the global level.

However, there are several weaknesses in this research. First, it was conducted based on students of only one educational institution and from the programs of Chemistry and Environmental Science Education. It means that the findings cannot be easily generalized to other populations. Besides, most of the impacts were studied short-term, and more research is needed to examine long-term impacts of the program on students' sustainable practices.

Based on these findings, future research should verify the applicability of this program in different learning environments and across various disciplines. Furthermore, future longitudinal studies may reveal the long-term effects that the sustainable education program has on the lives of students in a personal and professional environment. Additionally, the application of technology-based methods, such as webinars and computerized simulations, may increase accessibility and attractiveness of the program.

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Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Some Sample of the Sustainability Awareness Test

Instructions: Read each question carefully and select **one best answer** from the four alternatives (A–D).

A. Knowledge of Sustainability Concepts

1. In the context of Environmental Chemistry, sustainable development emphasizes the use of resources and chemical processes that ...
 - A. maximize production without considering waste
 - B. meet present needs while minimizing impacts on future generations
 - C. eliminate the use of all chemical substances
 - D. use only natural materials regardless of their production processes
2. A student compares conventional plastic packaging with starch-based packaging. From a life-cycle perspective, sustainability should be evaluated by considering ...
 - A. raw materials only
 - B. product price only
 - C. raw materials, production, use, and end-of-life management
 - D. the visual appearance of the packaging

B. Attitudes Toward Sustainable Practices

3. During an Environmental Chemistry laboratory activity, you learn that single-use plastic can be reduced by using reusable equipment when appropriate. Which response best reflects a sustainability-oriented attitude?
 - A. Continue using single-use plastic because it is more convenient
 - B. Use reusable equipment whenever it is safe and appropriate
 - C. Leave all responsibility for plastic waste management to laboratory staff
 - D. Assume that laboratory plastic use has no significant environmental consequences
4. After learning that improperly managed laboratory plastic waste can contribute to environmental pollution, a student with a sustainability-oriented attitude would most likely ...
 - A. regard waste management as solely the responsibility of laboratory staff
 - B. regard appropriate waste management as part of their academic and environmental responsibility
 - C. dispose of all laboratory waste in a general waste container
 - D. avoid discussing the environmental consequences of laboratory waste

C. Behavioural Intentions Toward Sustainability

5. **After** learning about plastic pollution, you have the choice between single-use and reusable packaging. You intend to ...
 - A. always choose single-use packaging because it is more convenient
 - B. choose reusable packaging when it adequately meets the intended purpose
 - C. choose packaging primarily based on its colour
 - D. make no distinction between different types of packaging
6. If **you** notice unnecessary single-use plastic consumption in a university activity, you would most likely ...
 - A. ignore it because it is not your personal responsibility
 - B. continue using the plastic without considering alternatives
 - C. suggest or choose an alternative that can reduce unnecessary plastic use

D. dispose of the plastic after use without further consideration

D. Critical Thinking and Problem-Solving

7. A **biomass**-based packaging material degrades more rapidly than conventional plastic but requires substantially more energy during production. Which conclusion is most appropriate?
 - A. The material is definitely more sustainable
 - B. The material is definitely not sustainable
 - C. Its sustainability should be evaluated by considering impacts across its life cycle
 - D. Biodegradability is irrelevant to sustainability
8. A **team** identifies two packaging alternatives. Packaging X uses locally available materials but requires more energy during production, whereas Packaging Y requires materials transported from outside the region but uses less energy during production. To determine which alternative is more sustainable, the team should ...
 - A. select X because locally sourced materials are always more sustainable
 - B. select Y because energy consumption is the only relevant factor
 - C. systematically compare relevant environmental, social, and economic considerations
 - D. select the alternative preferred by the majority of team members

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Integrating *Minangkabau* culture into science education: preservice teachers' informal reasoning on ethnoscience for critical thinking and creativity

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ABSTRACT

This study analyzes how preservice science teachers construct informal reasoning when evaluating two Minangkabau cultural practices, namely *batik tanah liak* and the *balimau* tradition, as contexts for ethnoscience. *Batik tanah liak* emphasizes clay as a natural dye and fabric preservative, whereas *balimau* is a tradition of cleansing oneself using lime and flowers before Ramadan. This study contributes new insights by mapping the patterns of informal reasoning of preservice teachers on two traditions that have different scientific structures and religious values and linking them to pedagogical implications for ethnoscience learning. Data were collected through semi-structured questionnaires and analyzed using Braun and Clarke's inductive thematic analysis. Four categories of informal reasoning, namely personal, social, cultural, and environmental, guide how participants assess scientific relevance, cultural meaning, moral sensitivity, and learning potential. The results show that preservice teachers have stronger involvement and awareness of *batik tanah liak*, which provides concrete and structured scientific phenomena that trigger more rational-scientific reasoning and conceptual creativity. Conversely, *balimau* evokes moral-emotional reasoning due to its strong religious and socio-communal values, thus encouraging pedagogical caution. These differences indicate cultural bias and variations in epistemic access to traditional practices. Informal reasoning has been shown to play a role in training critical and creative thinking skills through evidence analysis, cultural context interpretation, and scientific solution exploration. This study emphasizes the need to integrate ethnoscience analysis into the PCK/TPACK curriculum to strengthen culturally responsive science education.

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Introduction

Global science education currently faces demands to develop higher-order thinking skills, such as critical thinking, creativity, and evidence-based decision-making (Khahro & Javed, 2022; Liu et al.,

2024). These competencies are necessary for students to be able to respond to socioscientific issues and the dynamics of scientific development (Siew & Arifin, 2025). However, science learning practices in various contexts still tend to be detached from the socio-cultural realities of students, thereby limiting their opportunities to develop meaningful reasoning and relate it to their culture and life experiences.

In line with these challenges, the integration of cultural context has become an important concern in science education. A student's understanding of science is significantly influenced by the culture and traditions in which they live (Baptista & Molina-Andrade, 2023). They do not only use scientific knowledge, evidence, and data in making decisions and reasoning about science (Ladachart & Ladachart, 2021) but also use their personal experiences and socio-cultural backgrounds (Mansour, 2024; Mavuru & Ramnarain, 2020). Ethnoscience offers a framework for connecting local cultural practices with scientific explanations, allowing students to explore the empirical, procedural, and value dimensions inherent in traditional knowledge (Rexhepi & Bajrami, 2025). Indonesia has a wealth of traditions that have strong potential as a learning context, but studies examining how preservice teachers interpret and understand these traditions in a pedagogical context are still limited.

At the same time, informal reasoning becomes an important lens for understanding how individuals evaluate complex issues involving evidence, cultural norms, and moral considerations (Han-Tosunoglu & Ozer, 2022). Local cultural practices in ethnoscience naturally contain value dilemmas, such as tensions between spiritual meaning, social norms, and scientific explanations that trigger informal reasoning when preservice teachers interpret them (Kara, 2025; Sadler, 2004). This situation requires to combine scientific evidence, moral considerations, and cultural perspectives through various forms of reasoning, such as scientific-rational, sociocultural, intuitive, and emotive reasoning. Because these value dilemmas are a key feature of ethnoscience practice, preservice teachers need to be trained to integrate culture and informal reasoning so that they can design science learning that is socioculturally sensitive but still based on scientific principles (Aziz & Johari, 2023; Zeidler & Nichols, 2009).

Little research has examined how preservice teachers reason about local cultural practices through informal reasoning frameworks. Existing studies have tended to focus on students, single aspects of local wisdom, or conceptual understanding (Rizaldi et al., 2021; Sasmita et al., 2025) but have not yet described how preservice teachers evaluate the intersection between culture and science in a pedagogical context. To date, there has been no research that systematically examined the informal reasoning related to ethnoscience issues in Minangkabau culture among science teacher candidates with the aim of fostering critical and creative thinking.

Focusing on preservice teachers is important because they are key actors in bridging cultural relevance in science classrooms. Pedagogical content knowledge (PCK), professional noticing skills, belief systems, and the integration of various domains of knowledge greatly determine how culture-based science learning will be implemented (Brown, J. C et al., 2022; Isa et al., 2022). Understanding how they reason about local cultural practices is a strategic step in designing teacher education programs that are capable of integrating ethnoscience in a meaningful and responsible manner and building socioculturally responsive professional competencies.

Based on this urgency, this study aims to analyze the reasoning patterns of preservice science teachers regarding two Minangkabau cultural practices that are relevant to ethnoscience, namely batik tanah liok and the balimau tradition. The key points of this study lie in the integration of three main elements: (1) the use of an informal reasoning framework to analyze preservice teachers' responses to ethnoscience practices; (2) analysis of preservice teachers' decisions, reasons, and perspectives for using culture as learning material; and (3) the contribution of ethnoscience-based learning to the development of critical and creative thinking skills in preservice science teachers. Thus, this study contributes to the development of science education theory and practice that is more reflective, contextual, and sensitive to local cultural values in shaping 21st-century professional competencies. The findings are expected to provide a theoretical and pedagogical basis for strengthening critical thinking, creativity, and ethnoscience learning design in teacher education.

Ethnoscience-Based Learning

Ethnoscience-based learning is a pedagogical approach that integrates local cultural knowledge and practices into formal science learning (Khery et al., 2025; Sumarni et al., 2025). This approach aims to bridge modern science with the cultural context of students (Idul & Fajardo, 2023; Yuliana et al., 2025) so that the learning process becomes more contextual, meaningful, and rooted in the social and cultural realities of students (Atmojo et al., 2025; Latip et al., 2024). Ethnoscience not only strengthens science literacy and ecological awareness but also increases appreciation for cultural heritage and develops an inclusive and pluralistic scientific attitude (Syahirah & Sriyati, 2024; Tovar-Gálvez, 2021).

In the Indonesian context, various local traditions have empirical value, simple technology, and chemical and biological principles that can be interpreted within the framework of science learning. In this study, two Minangkabau cultural practices were used as the context for ethnosicence-based learning. *Tanah liék* is a fabric dyeing technique that uses clay as a distinctive natural dye and makes *batik tanah liék* last for decades (Roza, 2025). *Balimau* is a tradition of cleansing oneself using water mixed with lime, which involves acid-base reactions and natural antiseptic processes (Khairani et al., 2020). These two practices were chosen because they contain scientific concepts that can be studied together with their value and symbolic dimensions, thus having the potential to trigger scientific as well as moral-cultural reasoning.

The selection of these two cultures with strong scientific and cultural dimensions positions ethnoscience not only as a learning context but also as a means to examine how preservice teachers assess, filter, and integrate cultural knowledge into their professional science practices. Culture has been shown to influence the quality and patterns of individuals' informal reasoning (Capkinoglu et al., 2020; D'Ambrosio, 2021). These two cultural practices provide an authentic context for understanding how preservice teachers who have grown up in that cultural environment construct their perspectives and pedagogical considerations (Reiser et al., 2021). Thus, strengthening the capacity of preservice science teachers to recognize, understand, and utilize ethnoscience is an important element in 21st-century science education reform (Sarkingobir & Bello, 2024).

Perspective and Informal Reasoning

Informal reasoning refers to the process of decision-making and argumentation by individuals when faced with complex, ambiguous, and value-laden situations (Beniermann et al., 2021; Sakamoto et al., 2021). In the context of science education, informal reasoning has been widely used to examine the responses of students and teachers to socioscientific issues (SSI), such as climate change, biotechnology, and vaccination (Jansong et al., 2022; Mnguni & Gasa, 2024). This reasoning demonstrated various considerations, including personal, social, cultural, and environmental aspects. These four aspects cannot always be explained through formal logic or scientific principles alone (Chan & Yeung, 2021; Zeidler, & Sadler, 2023).

The ability to construct informal reasoning is an important indicator in assessing preservice teachers' readiness to deal with the complexities of classroom and community realities (Han-Tosunoglu & Ozer, 2022). Cultural, spiritual, and environmental considerations greatly influence argumentation and are effective in training preservice teachers' reflective sensitivity, critical thinking, and creativity (Budiarti et al., 2025). In science education, informal reasoning is important because it provides an overview of how preservice teachers assess information, construct arguments, consider risks and benefits, and integrate scientific perspectives with cultural values (Ladachart & Ladachart, 2021).

However, research that integrates informal reasoning frameworks with ethnoscience contexts remains limited, particularly in science teacher education in Southeast Asia (Meral et al., 2021). Only a few studies have explored how local cultural practices can be used as a vehicle for training preservice teachers in informal reasoning and critical and creative thinking. Unlike previous studies, which generally examine ethnoscience from the perspective of students or merely map cultural elements descriptively, this study specifically highlights the reasoning process of preservice teachers when faced

with cultural dilemmas in ethnoscience practice. This focus provides a new contribution to understanding professional capacity, especially in integrating scientific knowledge, cultural values, and pedagogical considerations constructed through informal reasoning.

Method

Type of Research

This study used an exploratory qualitative design with a descriptive thematic approach to examine how preservice science teachers construct informal reasoning when interacting with ethnoscience practices rooted in Minangkabau culture. This design was chosen because it enables participants' authentic responses, culture-based interpretations, and reasoning patterns that emerge without limiting responses to specific theoretical categories. The general structure of the analysis was adapted from the method used by Ladachart and Ladachart (2021).

The exploratory nature of this study is in line with the objective of discovering variations in reasoning that emerge from the participants' perspectives, rather than testing hypotheses or measuring specific constructs. Therefore, this design well-suited for identifying the dynamics of preservice teachers' reasoning in the context of culture and ethnoscience.

Participants

This study involved 71 preservice science teachers (14 males and 57 females), aged between 22 and 24 years. All participants were in their fourth and fifth years of a science teacher education program at a university in West Sumatra, Indonesia, which is rich in cultural diversity and local wisdom. The students were selected because they had taken more science and pedagogy courses and had sufficient micro-teaching experience to provide more mature pedagogical assessments and reflective reasoning. Participants were selected purposively to ensure that they had a foundation of pedagogical and scientific knowledge, experience and exposure to local cultural traditions, and had achieved a sufficient level of reflective maturity to evaluate the context of ethnoscience from a teaching perspective. Participants had diverse cultural and geographical backgrounds. Based on their place of residence, participants came from urban centers (n = 9), urban (n = 32), rural (n = 25), and remote rural (n = 5) areas of their home provinces.

Research Instruments

Data were collected through a semi-structured questionnaire with open-ended questions. The questionnaire was designed to explore the attitudes, scientific explanations, cultural value evaluations, and informal reasoning of participants in two local cultural practices, namely *batik tanah liak* and the *balimau* tradition. The questionnaire was distributed offline in class, and participants filled it out independently within 30–40 minutes. To minimize external influences during data collection, lecturers or facilitators were not present while participants completed the questionnaire.

The instrument consisted of (1) participant demographic information, (2) participant involvement in the two cultural practices, (3) decisions, reasons, and perspectives, and (4) perceptions of the potential of these cultures as science teaching materials that support critical and creative thinking skills.

Table 1*Research instruments*

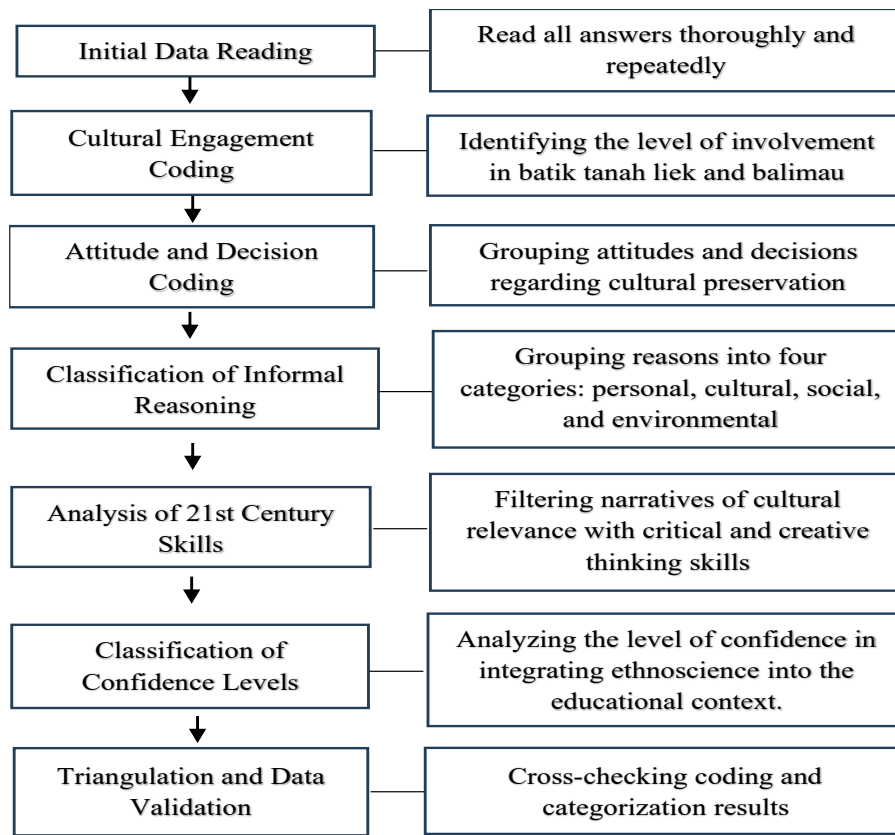
No	Aspect	Coding target	Questionnaire Items	Exploration focus
1	Demographic information	Gender, age, region of origin, family background, and geographical location	A1–A4	Demographic description of participants
2	Experience and involvement in culture	Exposure to and experience with <i>batik tanah liak</i> and the <i>balimau</i> tradition	B1–B4, C1–C2	Understanding individual backgrounds
		Understanding the use of natural materials	B5	Measuring locally based scientific reasoning abilities
3	Decisions, reasons, and perspectives	Views on the importance of preserving <i>batik</i> and <i>balimau</i> traditions	B6, C5	Assessing awareness of cultural values and local identity
		Perceptions of environmental impact	B7	Assessing the ability to analyze local environmental issues
4	The potential of culture as material for science learning	Identification of science concepts in <i>batik tanah liak</i> and the <i>balimau</i> tradition	B8, C4	Assessing the integration of culture and science
		Eligibility as material learning based ethnoscience	B9, C6	Testing the practical value of local culture in science education
		Impact of ethnoscience on critical and creative thinking skills	B10, C7	Assessing the relevance of local culture to the development of critical and creative thinking skills
		Reasons for belief to be used as teaching material	B11, C8	Measuring participants' level of argumentation and reflection
		Reflective attitude and analysis of religious and cultural values (specifically <i>balimau</i> tradition)	C6b	Assessing reflective attitudes and cross-cultural analysis

The instrument was validated by three experts to ensure content adequacy, clarity of meaning, and the suitability of each item with the focus of informal reasoning exploration. The experts' evaluations were analyzed using Aiken's validity formula (Aiken's, 1985). The validation results showed that the instrument is valid, with an average validity coefficient of 0.92, making it suitable for use as a data collection tool.

To ensure credibility and dependability, the instrument was piloted with 22 preservice science teachers to assess readability, clarity of items, and flexibility of narrative responses. The pilot test results indicated the need for minor revisions, particularly by expanding the open-ended questions so that respondents could convey their experiences, reasons, and arguments in greater depth. Subsequently, a discussion was held among all researchers to revise the instrument based on expert input and the results of the pilot test.

Data Analysis

The data were analyzed using the five main stages of Clarke and Braun (2006) inductive thematic analysis. First, the researchers conducted readings to understand the narrative context and cultural values that emerged from the participants' responses. Second, open coding included coding for cultural engagement and coding attitudes. Third, the codes were grouped through axial coding by mapping them into four categories of informal reasoning. Fourth, the main themes are determined by analyzing patterns of reasoning in relation to teaching materials to enhance critical and creative thinking. Fifth, triangulation and inter-researcher discussions are conducted to harmonize interpretations, verify inter-researcher consistency, and ensure analytical quality. The data analysis process is as follows:

Figure 1*Stages of data analysis*

The data were analyzed using the analytical framework developed by Ladachart and Ladachart (2021). This approach was chosen because it provides greater theoretical clarity, particularly for examining informal reasoning processes in the context of SSI, which can be applied in the context of ethnosience. The data were categorized based on two main dimensions: (1) the respondents' informal reasons or considerations in making decisions and (2) their perceptions of the potential of these cultures as ethnosience-based teaching materials for developing critical and creative thinking skills.

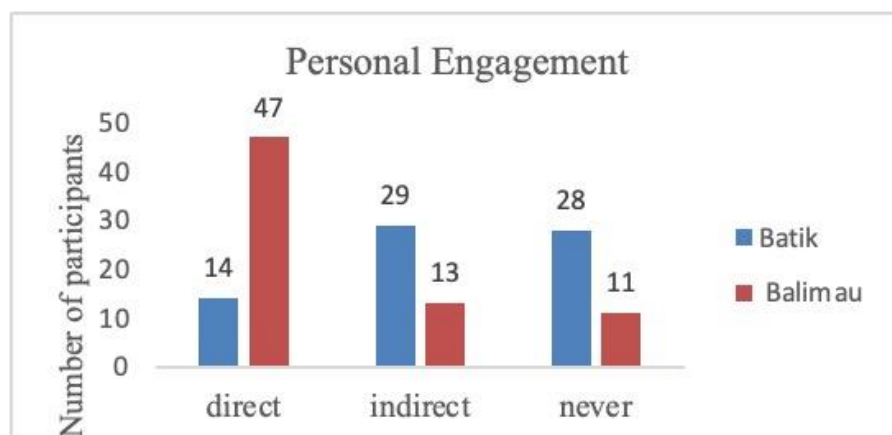
Results

Involvement in *Batik Tanah Liek* and The *Balimau* Tradition

As shown in Figure 2, the level of participant involvement in the two cultural practices shows different patterns. Only 14 of the 71 preservice teachers had been directly involved in making *batik tanah liok* process, while 29 had been indirectly involved, and 28 had no experience at all. In contrast, involvement in the *balimau* tradition was much higher, with 44 participants taking part in it. This variation in experience influenced the patterns of informal reasoning that emerged in the qualitative responses.

Figure 2

Number of participants and level of involvement

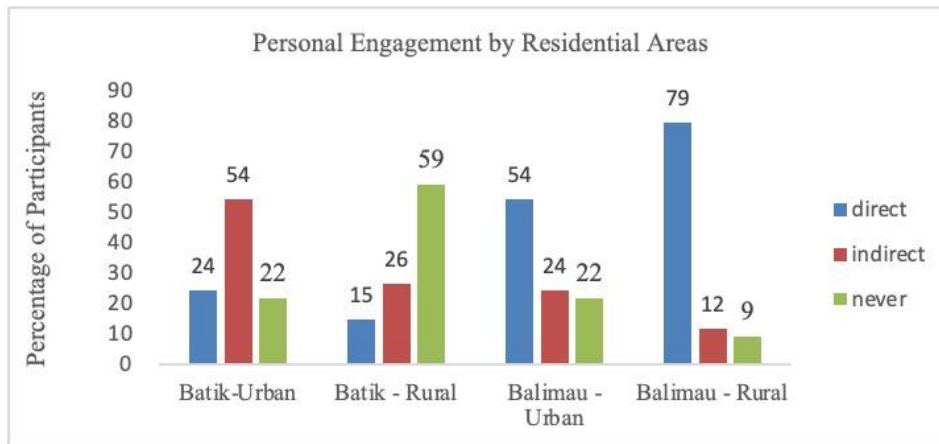


Participants with strong cultural involvement demonstrated richer cultural and social reasoning. In the *balimau* tradition, for example, “*Balimau* tradition is part of our customs before Ramadan, so if it is not done, it feels like a loss of family values” (P12). Conversely, participants without experience tended to rely on personal and intuitive reasoning, such as, “I only know that *Balimau* is bathing together, so I don't think it's very relevant to science” (P44). In the context of *batik tanah liok*, participants with direct experience displayed more scientific and environmental reasoning: “The use of clay as a natural dye can be studied from the aspects of material properties and chemical bonds that occur” (P07), and “Clay dyes are more environmentally friendly than chemical dyes” (P26). Conversely, participants without cultural experience showed personal, intuitive, or descriptive reasoning.

The consistency of this pattern suggested that the higher the cultural involvement, the more complex and reflective the reasoning that emerges. Meanwhile, low involvement tended to produce shallow, intuitive reasoning that is not connected to scientific concepts. These findings show how cultural experiences shape preservice teachers' assessment of the value, meaning, and pedagogical potential of batik (Pavitola et al., 2024).

Participants' engagement with *batik tanah liok* and the *balimau* tradition showed clear variations based on their region of residence, as shown in Figure 3. Respondents from urban areas were generally more familiar with *batik tanah liok* as a local craft product marketed in *batik* centers and souvenir shops, while respondents from rural areas were more familiar with the *balimau* tradition practiced in rivers or open water sources before Ramadan. These geographical differences not only determine cultural proximity but also influence the patterns of informal reasoning that emerge from participants' responses (Suri & Chandra, 2021).

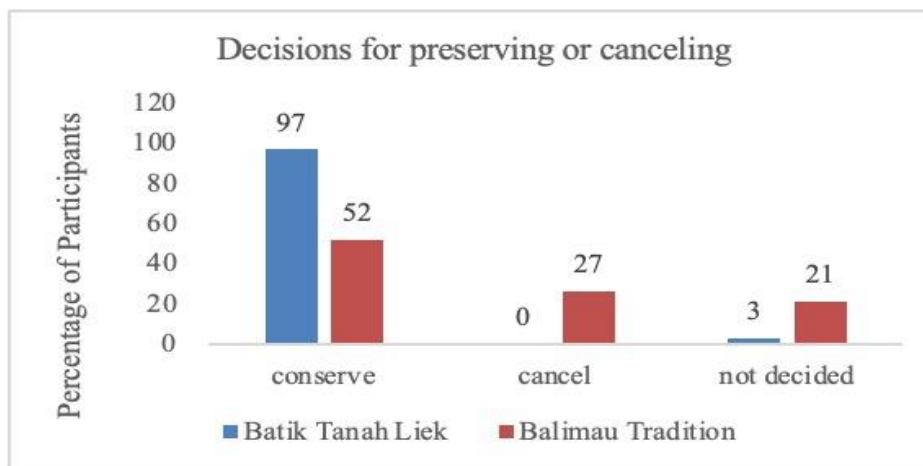
Respondents from rural areas tended to use socio-cultural and personal reasoning, especially regarding the values of togetherness and the spiritual meaning of *balimau*. This is reflected in the statement: “In our village, *balimau* is a moment to cleanse ourselves and gather before fasting. It feels incomplete if you don't participate” (P18). In contrast, participants from urban areas showed more scientific and environmental reasoning when describing *batik tanah liok*; for example, “*Batik tanah liok* is interesting because it uses clay for coloring and is more environmentally friendly. This can be explained by the nature of the material and the coloring process” (P69).

Figure 3*Percentage of participation by region of residence*

This difference in reasoning patterns indicates that geographical proximity shapes the epistemic orientation of preservice teachers, where proximity to social rituals encourages cultural and value-based reasoning, while proximity to material artifacts triggers scientific and ecological reasoning. These findings are consistent with ethnoscience literature, which asserts that local experiences, cultural identity, and ecological proximity strongly influence how individuals construct arguments on cultural and scientific issues (Sakamoto et al., 2021)

Decisions, Reasons, and Perspectives

Participants' choices about these topics were often reflected in their participation in the two cultural activities. Participants' decisions on whether the *batik tanah liek* and the *balimau* tradition should be abolished or preserved are illustrated in Figure 4.

Figure 4*Participants' decisions to preserve or cancel*

Support for the preservation of *batik tanah liek* was generally based on rational-scientific, sociocultural, and environmental reasoning, mainly because of its unique natural dyeing practices as well as its economic and aesthetic value. This was reflected in the statement: "*Batik tanah liek* must clearly be preserved because of its distinctive dyeing technique" (P11). In contrast, decisions regarding the

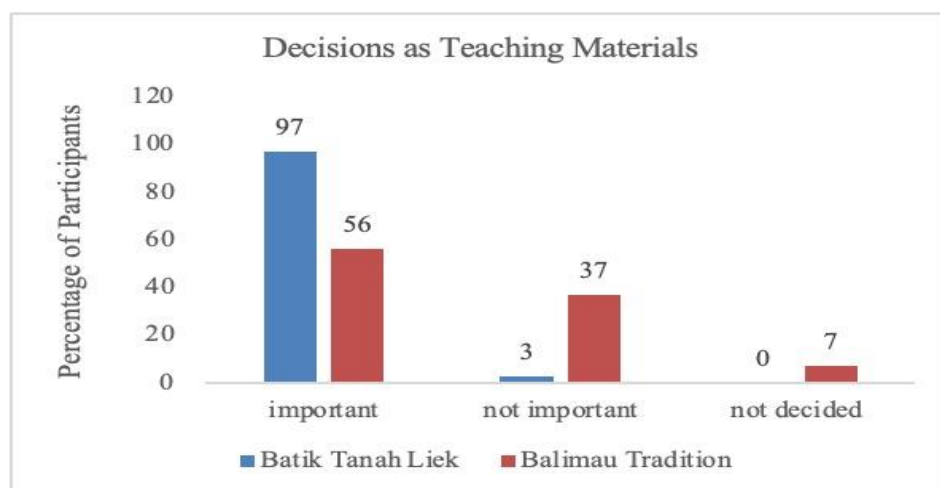
balimau tradition were more influenced by personal, religious-moral reasoning and community values, so support for its preservation was lower and often conditional. One participant stated, “The *balimau* tradition is good for togetherness, but it must be directed so that it does not conflict with religious values” (P34).

This pattern was in line with recent findings on socioscientific issues, which show that individual decisions regarding cultural practices are greatly influenced by the integration of moral values, cultural identity, and scientific considerations (Kılaç, 2024; Tekin & Aslan, 2024). The latest ethnoscience literature also confirms that preservice teachers' perceptions of cultural practices are determined by the extent to which these practices are considered consistent with spiritual values and relevant to the context of science education (Festiyed et al., 2026). Thus, the difference in decisions between the two cultures depended not only on the level of participant involvement but also on how they prioritize scientific, cultural, and religious values in the informal reasoning process that shapes their evaluation of the potential of these practices as sources of ethnoscience-based learning.

Participants indicated that *batik tanah liek* and the *balimau* tradition contain scientific concepts that can be reconstructed into science learning materials, covering aspects of chemistry, biology, and physics. As shown in Figure 5, the majority of participants considered that these two cultural practices are suitable for use as ethnoscience-based teaching materials.

Figure 5

Decision to develop ethnoscience-based teaching materials



The participants' decision to recommend both cultural practices was driven by personal reasoning, evident in their belief that culture-based learning experiences can improve understanding of scientific concepts and relate the material to everyday life. For example, one participant stated, “*Batik tanah liek* has the potential to be used as teaching material because the process is easy for students to understand and is directly related to science concepts” (P52). Social reasoning emerged strongly, especially in the *balimau* tradition, in which participants assessed that this practice contained values of togetherness, public health, and social interaction that were relevant to learning. Cultural reasoning was reflected in arguments that emphasized the importance of preserving ancestral heritage and emotional connections to culture as part of meaningful learning. Environmental reasoning was evident in participants who assessed the potential of teaching materials based on aspects of ecological sustainability. *Batik tanah liek* was considered relevant for teaching green chemistry principles through the use of natural dyes.

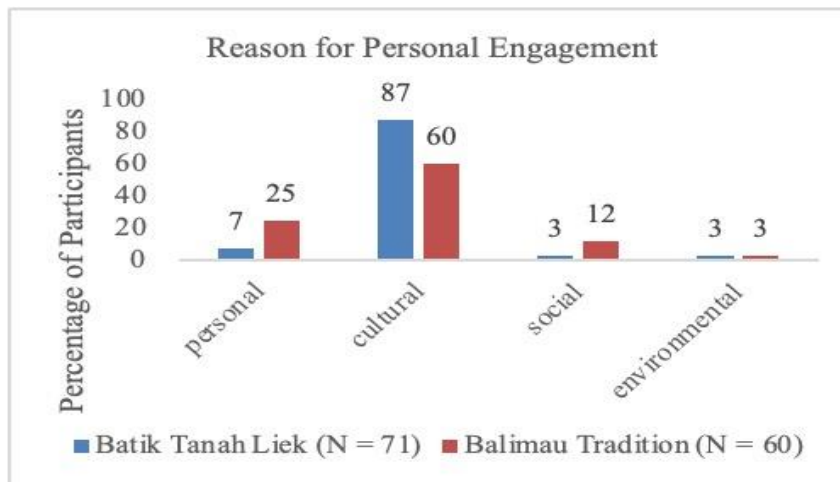
These findings indicate that informal reasoning in a cultural context involves a combination of personal, social, cultural, and environmental aspects, which together shape participants' decisions regarding the suitability of a practice to be used as science teaching material (Ladachart & Ladachart,

2021). Furthermore, these results are consistent with recent literature showing that ethnoscience can strengthen authentic learning contexts and stimulate the development of critical and creative thinking in preservice teachers through explicit links between local culture and scientific concepts (Bicaj et al., 2024; Gürhan, 2025; Koirala, 2023).

Preservice teachers' decisions to recommend *batik tanah liak* and the *balimau* tradition as ethnoscience teaching materials were primarily grounded in cultural reasoning. Figure 6 shows a pattern of reasoning that reflected the integration of personal, social, cultural, and environmental aspects. A total of 87% of participants considered *batik tanah liak* worthy of integration as teaching material because it was considered a cultural heritage rich in educational value, while 60% gave similar reasons for the *balimau* tradition.

Figure 6

Reasons for deciding on this culture as ethnoscience-based teaching material



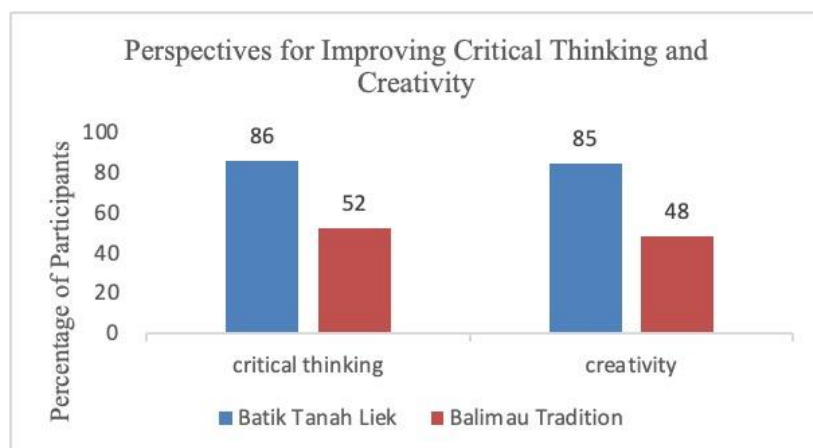
Personal reasons were reflected in responses that addressed the direct benefits of these cultural practices on student understanding and the potential for meaningful learning, such as “*Batik tanah liak* should be used as teaching material because the process contains many chemical and environmental concepts that are easy to explain to students” (P34). Social reasoning was particularly evident in responses related to *balimau*, where participants saw *balimau* as a means of understanding the relationship between humans and the environment and collective behavior. Cultural reasoning emerged from arguments emphasizing local identity, preservation of ancestral heritage, and cultural relevance in science education: “*Balimau* has become a tradition passed down from generation to generation. Teaching it in school will make students feel that our culture is valued” (P47). Environmental reasoning was evident in participants' concern for ecological sustainability and environmental impact: “The process of dyeing *batik* with natural dyes is more environmentally friendly than synthetic dyes” (P14); and “If the *balimau* tradition is not controlled, waste and soap can pollute the water. This is relevant to the topic of environmental pollution” (P58).

The results show that participants' decisions were an integration of scientific assessment, socio-cultural considerations, ecological reflection, and personal experience. This emerging pattern was in line with the framework of SSI, which asserts that informal reasoning in a cultural context involves complex interactions between emotions, intuition, scientific rationality, and socio-cultural values. These findings are consistent with recent research showing that ethnoscience enriches knowledge construction, strengthens authentic learning contexts, and facilitates the development of critical thinking in preservice teachers (Khusniati et al., 2023; Putu Verawati et al., 2022).

Analysis of participants' perspectives (Figure 7) shows that the majority of preservice teachers view *batik tanah liak* as having strong potential for developing critical thinking skills (86%) and creativity (85%), while the level of belief in the *balimau* tradition was relatively lower.

Figure 7

Perspective on ethnoscience-based teaching materials to improve critical and creative thinking



The critical thinking skills that emerged included the participants' ability to analyze cause-and-effect relationships in the *batik* production process, such as the effect of soaking the fabric in clay and the effect of pH changes on color. As one participant stated, “*Batik tanah liek* helps me think more carefully because every stage of its production has a scientific reason” (P32). Creativity was also evident in the participants' ability to propose innovative solutions, such as recommending various plants as natural dyes or developing learning media that combines *batik* motifs and visualizations of chemical compound structures. This pattern was in line with the latest literature findings, which show that cultural context can stimulate critical and creative thinking in preservice teachers (Falah et al., 2024; Fitrianto & Farisi, 2025; Harjono et al., 2025). Thus, participants' belief in the effectiveness of *batik tanah liek* and *balimau* as ethnoscience teaching materials were not merely a positive perception but is reflected in their real cognitive experiences when they reason critically, creatively, and contextually through cultural practices.

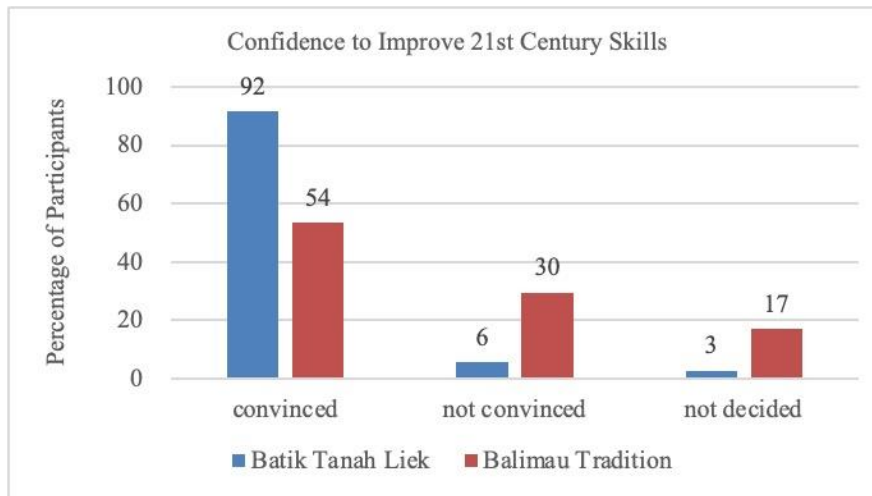
Perception to Potential as Science Teaching Materials

Analysis of participants' beliefs (Figure 8) showed that 92% of preservice teachers believed that *batik tanah liek* has strong potential to support the development of 21st-century skills, especially critical and creative thinking skills. Belief in the *balimau* tradition was lower, mainly because participants considered that its religious and ecological context requires more careful pedagogical consideration.

Preservice teachers' perceptions of the potential of *batik tanah liek* and the *balimau* tradition as science teaching materials were predominantly influenced by scientific-environmental reasoning, as participants mainly assessed the suitability of teaching materials based on the existence of science concepts that could be explored and aspects of environmental sustainability. For example: “*Batik tanah liek* has the potential to teach stoichiometry, chemical bonds, material properties, and natural dyes” (P52). Next is cultural reasoning, in the form of reasons for preserving local identity and heritage values that facilitate contextual learning. For example: This *batik* is the heritage of our ancestors; by teaching it, we will also preserve our culture” (P34).

Figure 8

Belief in ethnoscience-based teaching materials can improve 21st century skills



These findings were in line with the results of ethnoscience research and informal reasoning studies, which show that preservice teachers tend to prioritize direct relevance to science concepts and environmental issues when assessing pedagogical potential, while cultural and social reasons support the relevance of the learning context (Zidny & Eilks, 2022; Koirala, 2023; Sya'ban et al., 2024). These findings were also consistent with research emphasizing that ethnoscience strengthens higher-order thinking constructs and 21st-century science literacy (Dewi et al., 2019; Atmojo et al., 2025). Thus, the participants' beliefs reflect a mature pedagogical understanding of how cultural contexts can be utilized as conceptual and methodological bridges in modern science education.

Discussion

The results of the study show that preservice science teachers had a high level of cultural involvement and awareness of *batik tanah liek* and the *balimau* tradition, two local practices unique to Minangkabau that are rich in scientific and social values. This involvement was an important basis for developing an ethnoscience approach in science education, where traditional knowledge is not positioned as opposed to modern science but as a source of contextual learning that enriches students' understanding of science (Aydin-Ceran, 2021; Syahirah & Sriyati, 2024).

Preservice teachers' interpretations of *batik tanah liek* and the *balimau* tradition as ethnoscience contexts were greatly influenced by variations in cultural experiences, family backgrounds, and ecological proximity to these traditional practices. Thematic analysis showed that four forms of informal reasoning—personal, social, cultural, and environmental—were consistently arranged in the participants' responses and explained the differences in how preservice teachers interpret the two cultural practices as sources of science learning. These findings become more comprehensive when examined using the Ladachart and Ladachart (2021) framework, which maps emotional, intuitive, scientific rational, and socio-cultural reasoning as part of the informal thinking structure in socioscientific issues.

Participants with high cultural experience, especially those directly involved in *balimau* or who had visited a *batik tanah liek* house or center, tended to demonstrate scientific rational reasoning. They were able to identify scientific mechanisms in cultural processes, such as chemical bonds in the *batik* dyeing process, the physical properties of clay, diffusion and temperature changes, and the ecological dynamics of rivers in the *balimau* tradition. This reasoning demonstrates the participants' ability to perform causal analysis, evaluate evidence, identify scientific variables, and construct justifications based on scientific mechanisms. Theoretically, this pattern suggested that concrete cultural experiences function as cognitive triggers that strengthen critical thinking structures and activate conceptual

creativity, namely the ability to produce alternative procedures, modify techniques, or design new representations of scientific processes.

Conversely, participants with low cultural experience more often demonstrated intuitive reasoning. They often gave assessments such as “suitable” or “irrelevant” as science teaching materials without arguments. This is consistent with the theory of informal reasoning, which states that intuition dominates when individuals do not have direct experience or substantive knowledge of an issue (Tarzi, 2025). Meanwhile, emotional reasoning emerged strongly in the *balimau* tradition, which was viewed as a spiritual and communal practice rich in moral values. Emotions such as pride, a sense of belonging, and religious sensitivity influenced participants' decisions, leading them to assess the practice with pedagogical caution. This factor explains why support for *balimau* as teaching material was lower than for *batik tanah liok*, as the practice carries moral dilemmas and religious sensitivities that demand pedagogical caution.

Socio-cultural reasoning appeared dominant when participants highlighted the function of tradition as collective identity, ancestral heritage, and communal practices that have educational relevance. This form of reasoning demonstrated the participants' ability to weigh the harmony between cultural values, learning objectives, and the social and spiritual impacts of integrating culture into science. Meanwhile, environmental reasoning was strongest in the context of *batik tanah liok*, particularly in relation to the use of natural dyes, ecological sustainability, and the issue of river pollution in *balimau* activities. These findings were in line with studies that confirm that the ethnoscience context allows for complex interactions between values, scientific evidence, and ecological considerations in decision-making (Beniermann et al., 2021; Sakamoto et al., 2021).

Culture functions not only as a context but also as a trigger for critical and creative thinking skills. *Batik tanah liok* offered participants opportunities to analyze the cause and effect relationships in the color fixation process by using natural materials, identify variables such as pH and mordant type, and evaluate the influence of clay quality on dye and fabric durability. Such analytical activities encouraged the development of scientific argumentation and conceptual creativity relevant to science learning. Participants also proposed innovations such as exploring natural dye sources from local plants, varying maceration techniques, or designing *batik*-motif-based learning media. The *balimau* tradition, despite its religious connotations, sparked creative ideas on topics such as health, river ecosystems, and human-environment behavior. These patterns support the finding that authentic cultural contexts enhance preservice teachers' constructive, divergent, and analytical abilities (Idul & Fajardo, 2023).

Furthermore, culture has been shown to stimulate epistemic curiosity, especially when participants discover discrepancies between cultural explanations and scientific mechanisms. This epistemic curiosity encourages deeper exploration and plays an important role in developing inquiry-based learning. In the context of *batik tanah liok*, participants questioned how clay also functions as a color and fabric preservative, why pH changes cause color changes, and how chemical reactions occur in the fixation process. In the *balimau* tradition, participants questioned how *balimau* activities affect body hygiene and river ecological parameters. It is this epistemic curiosity that strengthens scientific argumentation and provides the basis for the development of inquiry-based learning. In ethnoscience-based learning, this scientific argumentation is obtained from the results of analyzing the reconstruction of the community's original science into scientific science. It is this scientific reconstruction that facilitates the simultaneous development of critical and creative thinking skills.

The implications of these findings for teacher education are significant. First, teacher education programs need to explicitly integrate ethnoscience into PCK and TPACK so that preservice teachers not only understand scientific concepts but also able to relate them to cultural contexts in a sensitive and scientific manner. This integration can be achieved through cultural analysis assignments, interactive learning media such as ethnovlogs, ethnoscience-based learning designs, or field experiences involving local practices (Sudarmin et al., 2020). This study emphasizes the importance of training preservice teachers to address socio-cultural dilemmas—such as conflicts between religious values and traditional practices—through case-based reasoning, reflective dialogue, and culturally responsive pedagogy.

Third, teacher education programs need to strengthen professional competencies in evaluating evidence and constructing scientific arguments, given that intuitive and emotional reasoning still dominates among participants with low cultural engagement. Fourth, these findings indicate that direct experience with local culture can deepen preservice teachers' pedagogical sensitivity, so educational institutions need to facilitate authentic experiences to strengthen the relationship between culture, science, and learning.

Overall, this study confirms that the integration of ethnoscience functions not only as a contextual approach but also as an epistemological space in which preservice teachers develop critical reasoning, creativity, and socio-cultural sensitivity. The variations in informal reasoning found reveal the complexity of how preservice teachers combine scientific evidence, cultural values, emotional experiences, intuition, and ecological considerations to understand socioscientific issues. Thus, ethnoscience has the potential to become an important foundation in developing a culturally responsive teacher education curriculum that equips preservice educators to address the diversity of values and complexities of 21st-century science education.

Conclusion

This study indicates that preservice teachers' informal reasoning in evaluating *batik tanah liok* and the *balimau* tradition is influenced by cultural experiences, family background, and ecological proximity. Four categories of reasoning—personal, social, cultural, and environmental—emerge as the main framework explaining how preservice teachers weigh the scientific, social, and pedagogical values of this ethnoscience. These findings make an important theoretical contribution by expanding the ethnoscience framework through the integration of the informal reasoning dimension so that cultural meaning in science education is not only understood as the transfer of local knowledge but as a cognitive process involving the evaluation of evidence, cultural intuition, and moral and social considerations. The resulting reasoning categorization model offers new analytical contributions that can be used to examine how preservice teachers construct scientific arguments in ethnoscience.

This study directly addresses a gap in the literature on how preservice teachers argue about cultural practices in the context of ethnoscience to develop critical and creative skills, a theme that is still rarely researched in the context of Southeast Asia. The dilemma between religious-moral values and scientific accuracy was found to influence how preservice teachers make pedagogical decisions. They view this conflict of values as a professional challenge that requires a balance between scientific integrity, respect for students' beliefs, and cultural sensitivity. From the perspective of preservice teachers, value conflicts are not considered obstacles but rather spaces for negotiation that must be carefully managed through culturally responsive pedagogical approaches. The findings of this study emphasize the importance of exploring local culture as a means of training prospective teachers' logical thinking skills, because cultural contexts provide authentic phenomena that stimulate evidence analysis, scientific reasoning, and value evaluation. Furthermore, this study emphasizes the necessity to integrate ethnoscience into the teacher education curriculum and to use informal reasoning models as assessment tools to map prospective teachers' epistemological readiness in dealing with culture-based socioscientific issues.

Limitation

This study has several limitations that need to be considered in interpreting the findings. First, the use of open-ended questionnaires as the main instrument limits the depth of analysis, as the qualitative data produced is declarative and does not allow for a more comprehensive exploration of the dynamics of participants' reasoning in real situations. Second, cultural and religious topics—particularly those related to the *balimau* traditions—have the potential to produce social desirability bias, so that some participants may give answers that are considered most socially or religiously acceptable. Third, data interpretation may be influenced by researcher positionality, given that the

researchers were in the same cultural context as the participants. Although this potential bias was minimized through discussions among researchers and peer debriefing, reflection on the researchers' position remains an important consideration in culture-based qualitative research.

Suggestion

Based on the research results and existing limitations, several recommendations are put forward for further research and ethnoscience education practices.

Recommendations for Further Research

Future research needs to develop a specific informal reasoning framework for ethnoscience so that socio-cultural practices in science education can be analyzed more systematically. In addition, quasi-experimental studies are needed to test the effectiveness of ethnoscience interventions on critical thinking, creativity, and science literacy. An ethnoscience-based teacher education model that integrates PCK/TPACK, cultural dilemma analysis, and informal reasoning development also needs to be developed.

Practical Suggestions for Education and Learning

Lecturers who teach at educational institutions are advised to integrate ethnoscience-based microteaching so that students practice designing and reflecting on science learning based on local culture. School teachers need to implement cultural practice analysis, science concept mapping, and contextual socioscientific issue discussions to strengthen the relevance of learning. Curriculum developers need to prepare assessment rubrics for culture-based informal reasoning that cover scientific, social, moral, and environmental dimensions. Schools and communities also need to expand collaboration with *batik* artisans, traditional leaders, or cultural actors to provide authentic experiences that support deep learning and ethnoscience-based science.

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Declaration of Interest

The authors declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Exploring ethnophysics as an epistemological approach in physics learning: A systematic literature review

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ABSTRACT

The integration of cultural knowledge in physics, often referred to as ethnophysics, has gained increasing attention as a way to make scientific concepts more meaningful and relevant to pupils' everyday experiences. At the same time, ethnoscience often reflects traditional beliefs and cultural narratives that may differ from modern scientific perspectives. This study employs a Systematic Literature Review (SLR) following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to examine the role of ethnophysics in physics learning. From an initial pool of 299 articles, 61 were selected for detailed analysis. The findings indicate a growing interest in ethnophysics research, with most studies focusing on describing physics concepts within local cultural contexts. Work and energy emerged as the most frequently explored topic. Overall, ethnophysics shows a positive contribution to pupils' learning, including improvements in problem-solving skills, academic achievement, scientific literacy, self-efficacy, and critical thinking. Instructional approaches such as ethnophysics-based instruction, cooperative learning, and direct teaching appear more effective than conventional methods in certain contexts, although their success depends on pupil characteristics and implementation. The review also highlights the use of the 4D and ADDIE models in developing learning tools, as well as the increasing integration of mobile technologies. These findings suggest that combining cultural context with technology can enhance engagement and support more inclusive physics learning.

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Introduction

Local wisdom is fading over time; therefore, more serious preservation efforts are needed. One effective way to achieve this is to integrate local wisdom into learning, particularly in science lessons, where local phenomena can be directly linked to scientific concepts. Data show that although almost 90% of teachers in Indonesia stated that they wanted to develop a science learning model based on local culture, only 20% were able to implement it (Siyati, 2022). Teachers' insights do not aim to identify examples of events that contain local wisdom in learning. In the context of teaching physics, however, instruction based

on non-contextual approaches often makes pupils from different cultural backgrounds feel that physics is too abstract or irrelevant to their experiences and worldviews. This phenomenon is also found in Western schools, where pupils often find formal physics counterintuitive (Idul & Fajardo, 2023). Physics, as a field of science, studies natural phenomena and explains how these phenomena occur. However, physics lessons often do not align with pupils' preconceptions formed outside the classroom, making it difficult for them to understand fundamental concepts (Gumbo et al., 2021). This situation requires a more inclusive approach and consideration of cultural diversity and local wisdom in the learning process so that pupils can feel involved and valued, and benefit from the education they receive.

Physics learning currently faces various challenges, including low levels of conceptual understanding among pupils because many pupils consider physics difficult (Al-Sultan, 2023; Widyaningsih et al., 2021), limited facilities and infrastructure that support learning (Dong et al., 2023; Yusuf et al., 2018), lack of active pupil involvement, and gaps between theory and practical applications (Katanosaka et al., 2023). In learning physics, a mature understanding of concepts is required so that pupils can solve problems related to physical phenomena in the surrounding environment properly (Chongo & Baliga, 2019; Suryadi et al., 2021; Yusuf & Widyaningsih, 2020). A mature understanding of physics concepts is critical because it enables pupils to relate physics theory to the natural phenomena around them (Arciosa, 2022; Pranata et al., 2017). They can solve problems related to the physical phenomena they observe through everyday phenomena (Batlolona et al., 2023). Therefore, various innovations in physics education are needed to address these difficulties. A comprehensive understanding of physics concepts also supports the development of useful life skills, such as the ability to adapt, solve problems, and think creatively in various life contexts (Fayanto et al., 2023; Rahayu et al., 2022; Winarto et al., 2022).

Positive attitudes and character in pupils can be developed through cultural values, a process that instills values rooted in their social and cultural environment (Lutfauziah et al., 2023; Omeri, 2015). They will quickly understand the subject matter if it relates to the area's characteristics or local wisdom. Physics learning needs to be balanced between knowledge, attitudes, and scientific values embedded in the community's local wisdom, so that pupils can truly feel the benefits of learning (Suastra, 2010). Local wisdom is a value that needs to be instilled wisely to provide a positive understanding of the surrounding socio-cultural environment. However, this socio-cultural environment must be examined scientifically, particularly in epistemological terms (Basuki et al., 2023; Bektiarso et al., 2023; Pela et al., 2022; Rizaldi et al., 2023; Suharti et al., 2022). Pupils' knowledge is largely shaped by their experiences in everyday culture (Amien et al., 2022). Therefore, the material should be organized logically and sequentially.

Local wisdom refers to the values that apply in the local community. Learning that links local wisdom with subject matter is known as ethnomethodology or ethnopedagogy. When this term is associated with physics material, it is known as ethnophysics. Ethnophysics refers to traditional explanations for phenomena that come under the mantle of physics (Garfinkel, 2019). Ethnophysics is a branch of ethnoscience. It emphasizes cultural aspects, natural conditions, and other local characteristics in physics teaching. Ethnoscience, or ethnophysics, refers to concepts, not to whether they are formally or informally taught. The main goal of integrating ethnophysics into physics education is to use local elements, such as natural materials and phenomena around pupils, to teach physics concepts. It aims to bring traditional reasoning about natural phenomena into science, which is where the wheels fall off (Gumbo et al., 2021; Nurianti et al., 2023). This approach enables more relevant physics instruction for pupils' daily lives and fosters a deeper understanding of their culture (Kurniawan et al., 2019; Ovsienko et al., 2023). Pupils can develop awareness and appreciation of their cultural heritage by incorporating cultural elements into physics learning (Sulistiani et al., 2022). The core of the ethnophysics teaching strategy is the use of locally sourced materials to teach physics content. Ethnoscience is not about methods or content alone; it is about epistemology. Emphasizing culture in learning will increase pupils' awareness of their culture. Culture-based learning can be applied across various fields, especially in science, including physics.

Empirical research shows that the application of ethnophysics can improve problem-solving abilities (Winarto et al., 2022) and pupils' attitudes towards physics, not gender bias (Chongo & Baliga, 2019). Research shows that pupils are more motivated to learn when they see connections between the

knowledge taught in school and their daily lives. Pupils taught using the application of ethnophysics showed significant improvements in understanding of physics concepts and more positive attitudes toward science. Integrating traditional knowledge into science teaching can reduce their anxiety about science and improve their academic performance. In addition, physics learning that integrates cultural perspectives can support pupils' identity development and their concern for local culture (Anthony, 2017). The application of ethnophysical teaching offers great potential to enhance the relevance and effectiveness of physics instruction. By respecting and integrating cultural knowledge, physics education can be more inclusive and empowering for pupils from diverse cultural backgrounds. Therefore, it is important to conduct a study on ethnophysics in physics teaching.

Research on ethnophysics has grown rapidly in recent decades, encompassing various aspects of the integration of cultural and physical knowledge (Asbanu, 2023; Basuki et al., 2023; do Rosario & da Silva, 2023). Current research trends in ethnophysics focus on understanding how physics concepts can be applied and understood in specific cultural contexts. This research often involves in-depth ethnographic studies to identify the unique ways in which local communities understand physical phenomena. The literature indicates a growing interest in interdisciplinary approaches that combine anthropology, education, and physics (Amiruddin et al., 2023; De-Oliveira & Júnior, 2021). Researchers are also increasingly exploring the impact of ethnophysics on pupils' motivation and engagement in learning physics. The application of ethnophysics has considerable potential to strengthen their learning abilities (Astuti, Sumarni, Setiadi, & Damayanti, 2022; Batlolona et al., 2022). By linking physics concepts to their daily experiences and cultural knowledge, pupils can more easily understand and retain the material (Febrianty et al., 2023). Research also shows that this approach can improve pupils' critical and analytical skills and enhance their problem-solving creativity (Ariyatun, 2021; Gumilar et al., 2023; Lestari & Apsari, 2022). Furthermore, by providing a culturally relevant context, pupils are more motivated and engaged in the learning process, which ultimately leads to better academic performance.

A variety of research methods are used in ethnophysics studies, including qualitative and quantitative methods. Qualitative methods such as in-depth interviews, participant observation, and narrative analysis are often used to understand traditional knowledge and practices related to physics concepts (Prasad et al., 2022; Rahmadani, 2022; Rahmanian et al., 2023). Ethnographic methods involve the shared life and learning of local communities and are generally used to collect rich and contextual data (Febiawati et al., 2023). In addition to qualitative approaches, quantitative methods such as surveys and experiments are used to measure the impact of ethnophysics on pupils' understanding and attitudes toward physics. This combination of methods is often used to understand how ethnophysics can be applied in education. There are still many gaps in research on the application of ethnophysics in physics learning. For example, the evaluation of effectiveness, research across diverse contexts, in-depth theoretical discussion, learning models and strategies for application, and how technology can be used to teach ethnophysics are also areas that need further exploration. Therefore, it is important to conduct a literature review to identify the current issues and research trends that can be developed as research subjects in the future.

This study is a Systematic Literature Review (SLR) conducted to collect, review, and analyze numerous articles and related literature on ethnophysics. This can help identify knowledge gaps, relevance, and directions for further research. The main objective of this study is to review the scientific literature on the application of ethnophysics in physics learning, guided by research questions aligned with the PICO framework. The acronym PICO is formed from P for Population or Problem, I for Intervention or Indicator, C for Comparison or Control, and O for Outcome (Roever, 2018; Schiavenato & Chu, 2021), as follows:

Q1 (P). What are the types of research methods used in studying the effects of the implementation of ethnophysics?

Q2 (I). What local cultural forms are linked to physics topics in implementing ethnophysics in learning?

Q3 (C). What are the forms of learning strategies in the implementation of ethnophysics?

Q4 (O). What abilities can be developed through the implementation of ethnophysics?

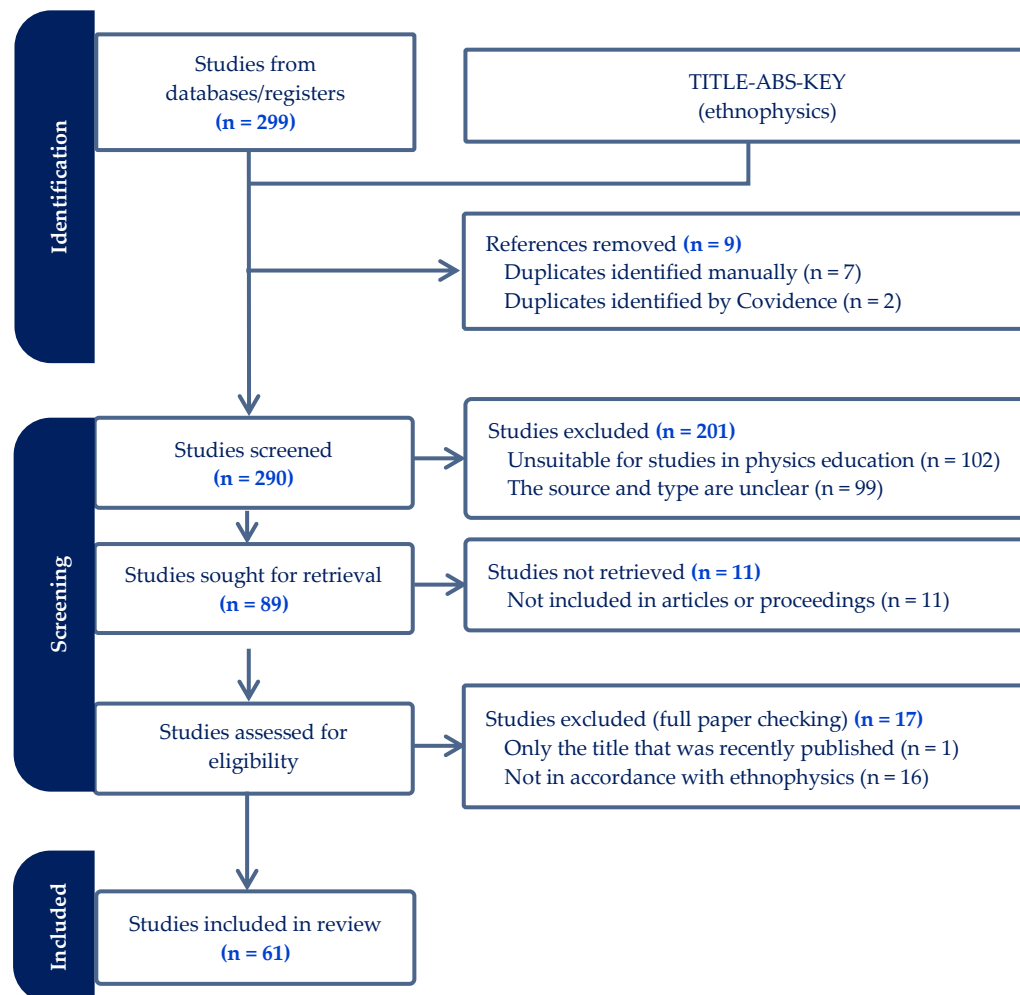
Q5 (O). What are the forms of ethnophysics integration products and their applications in learning?

Methods

This study uses the SLR technique to analyze the trend in the application of ethnophysics in physics learning. SLR is a secondary study that synthesizes findings from multiple primary studies to address research questions (Budianto et al., 2022; Newman & Gough, 2020; Wijayanto et al., 2023). This study was conducted through the PRISMA steps consisting of identification, screening, and inclusion stages as in Figure 1. This study formulated its research questions based on the PICO framework to ensure clarity and relevance. These questions were then systematically addressed through a rigorous and focused process of a systematic literature review, allowing for a comprehensive synthesis of evidence aligned with the study's objectives (Jamal et al., 2019; Santos et al., 2019). The steps of the systematic review process are presented in Figure 1.

Figure 1

PRISMA analysis results of the SLR ethnophysics study



Note. Source: app.covidence.org

Identification Stage

The identification stage was carried out to search for articles across various databases using the Publish or Perish software, with Google Scholar as the search source. This includes all article searches

indexed by Google Scholar, as well as journals indexed in Scopus, DOAJ, ERIC, WOS, and various journal websites. The keyword entered was "ethnophysics". Based on the search with these keywords, 299 articles were found (the search was conducted on December 5, 2023). At this identification stage, initial screening was also carried out by checking for the same or similar articles. At this stage, 9 similar articles were found.

Screening Stage

The screening stage is carried out in several stages; in the first stage, selection is based on the title and abstract. Furthermore, it includes direct selection by checking the article's contents. There are three stages for transferring data from Publish or Perish to Covidence. First, export the data from Publish or Perish in file formats such as RIS, CSV, or EndNote XML, with RIS being the most commonly used format for transferring data to reference management software. Second, import the data into Covidence, and third, verify and sort the data. Covidence provides tools to sort, review, and prioritize articles for further review. The sorting is conducted online by the research team, with members cross-checking one another against the predetermined article criteria. The selection is carried out according to the inclusion criteria as in Table 1. The screening stage is conducted using the Covidence platform. Based on the specified criteria, articles were identified that did not meet the SLR study criteria.

Table 1

Inclusion Criteria for Ethnophysics Articles

Category	Inclusion Criteria
Publication Type	Journal and proceedings publications of scientific articles
Publication Year	All years (Unspecified)
Field of Study	Physics
Types of Research	Conceptual and empirical
Research Subject	Learners and teachers of all levels who are interested in physics

The inappropriate articles include studies on policy analysis of the application of ethnophysics concepts in a particular region or country. Other articles that are not in accordance with this SLR study concern ethnosience and do not contain physics content. There are also duplicate articles published in proceedings and journals, so the earlier publication is chosen.

Included Stage

At the included stage, 61 articles were obtained that met the criteria for further review and analysis. The articles obtained were then coded, and patterns were identified between articles to answer the research questions. The article coding was CA: Classroom Action Research, DA: ADDIE Model Development Research, DB: Borg & Gall Model Development Research, DD: 4D Model Development Research, DP: Plomp Model Development Research, DE: Descriptive Research, QE: Quasi Experiment, IA: Instrument Analysis, MA: Meta-Analysis, and SU: Survey.

Results and Discussion

The analysis conducted at the inclusion stage identified 61 articles that met the criteria. Furthermore, coding and identification of patterns between articles were carried out to answer research questions in the form of research developments on ethnophysics, types of research methods used, forms of local culture and related physics topics, pupil abilities that can be developed through ethnophysics integration, learning strategies used in the application of ethnophysics, and the form of ethnophysics

study products produced. These study products encompass outputs such as instructional models, learning modules, teaching media, and assessment instruments developed in the context of ethnopysics research. The coding results for all 61 articles are summarized in Table 2.

Table 2

Coding of SLR articles on ethnopysics

Code	(Authors, Year)	Cited By	Journal/Proceeding
CA1	(Delina et al., 2019)	4	IJICC
CA2	(Harahap & Sinaga, 2021)		JESTP
DA1	(Falah et al., 2019)	1	URECOL
DA2	(Gifani et al., 2023)		JIPF
DA3	(Fadilah et al., 2021)	3	Scedu
DA4	(Widayanti et al., 2022)	1	IJEMS
DB1	(Pela et al., 2022)		Impulse
DD1	(Lestari & Apsari, 2022)	5	JPPPF
DD2	(Sari et al., 2021)	12	PSEJ
DD3	(Maryono et al., 2021)	3	JPF
DD4	(Yulyanti et al., 2022)		Konstan
DP1	(Virijai & Asrizal, 2023)		JPPIPA
DE1	(Siyati, 2022)	5	Luminous
DE2	(Rahmania et al., 2023)		JIPFRI
DE3	(Jufrida et al., 2020)	9	Edufisika
DE4	(Novitasari & Handhika, 2018)		SNPF
DE5	(Rumiati et al., 2021)	17	JPF
DE6	(Astuti & Bhakti, 2021a)	1	NPJPE
DE7	(Sholihah et al., 2023)		JIPST
DE8	(Melati et al., 2023)		Gravitasi
DE9	(Bektiarso et al., 2023)	1	JIWP
DE10	(Putra et al., 2023)	1	ICMScE
DE11	(Rizaldi et al., 2023)		IJOERAR
DE12	(Afkarina & Sudarti, 2021)	4	JIFP
DE13	(Silvini & Ginting, 2020)	8	ICoSTA
DE14	(Quiñones, 2023)		LATAM
DE15	(Agustina et al., 2023)		JPFK
DE16	(Arciosa, 2022)		JTOM
DE17	(do Rosario & da Silva, 2023)		Editora
DE18	(Febrianty et al., 2023)		Optika
DE19	(Vilanova & Ramos, 2019)		CONEDU
DE20	(Astuti, Sumarni, Setiadi, & Damayanti, 2022)	1	ICDESS
DE21	(Chasani & Fakhrudin, 2023)		JPPIPA
DE22	(Damasari et al., 2022)		BIPF
DE23	(Nurianti et al., 2023)		BIPF
DE24	(Basuki et al., 2023)		JPS
DE25	(Pereira et al., 2020)	1	RIS
DE26	(Souza, 2013)	17	Amazônia
DE27	(Widiyatun et al., 2023)		IJPE
DE28	(Asbanu, 2023)		Orbita
DE29	(Astuti, Sumarni, Setiadi, & Suhaya, 2022)		ICESRE
DE30	(Astuti et al., 2021)	5	Neoelectura
DE31	(Triwiyono & Adiwikarta, 2015)	2	JPFT
DE32	(Febiawati et al., 2023)		FISA
DE33	(Nurmasiyah et al., 2022)	6	JPF
DE34	(Astuti & Bhakti, 2021b)	22	SINASIS
DE35	(Astuti, Sumarni, Setiadi, & Zahra, 2022)	4	Orbita
DE36	(Afifa et al., 2023)		Gravitasi
DE37	(Rahmadani, 2022)	3	Gravitasi
DE38	(Lestari, 2023)	1	JPMIPA
DE39	(Fitriyah, 2022)	1	AICOIES
DE40	(Kurniawan et al., 2019)	5	IJSTR

Code	(Authors, Year)	Cited By	Journal/Proceeding
DE41	(Amiruddin et al., 2023)		JPMIPA
DE42	(Sulistiani et al., 2022)		Schrodinger
QE1	(Chongo & Baliga, 2019)	7	JEP
QE2	(Hasanah et al., 2021)	2	JPF
QE3	(Srijayanti & Derlina, 2020)	3	JPF
QE4	(Gumbo et al., 2021)	2	JBSE
IA1	(Nisa & Suprpto, 2023)		IPF
MA1	(Idul & Fajardo, 2023)	1	JMST
SU1	(Batlolona et al., 2022)	3	JPIIPA

Article coding is done based on the type of research method used. The CA code is about classroom action research, the DA code is related to the type of development model, namely the ADDIE Model, the DB code is related to the type of Borg and Gall development model, the DD code is related to the type of 4D development model, the DP code is related to the type of Plomp development model, the DE code is related to the descriptive method, the QE code is related to the type of quasi-experiment research, the IA code is related to instrument analysis, the MA code is related to meta analysis, and the SU code is related to the type of survey research. The coding is intended to make it easier to trace SLR studies to answer research questions.

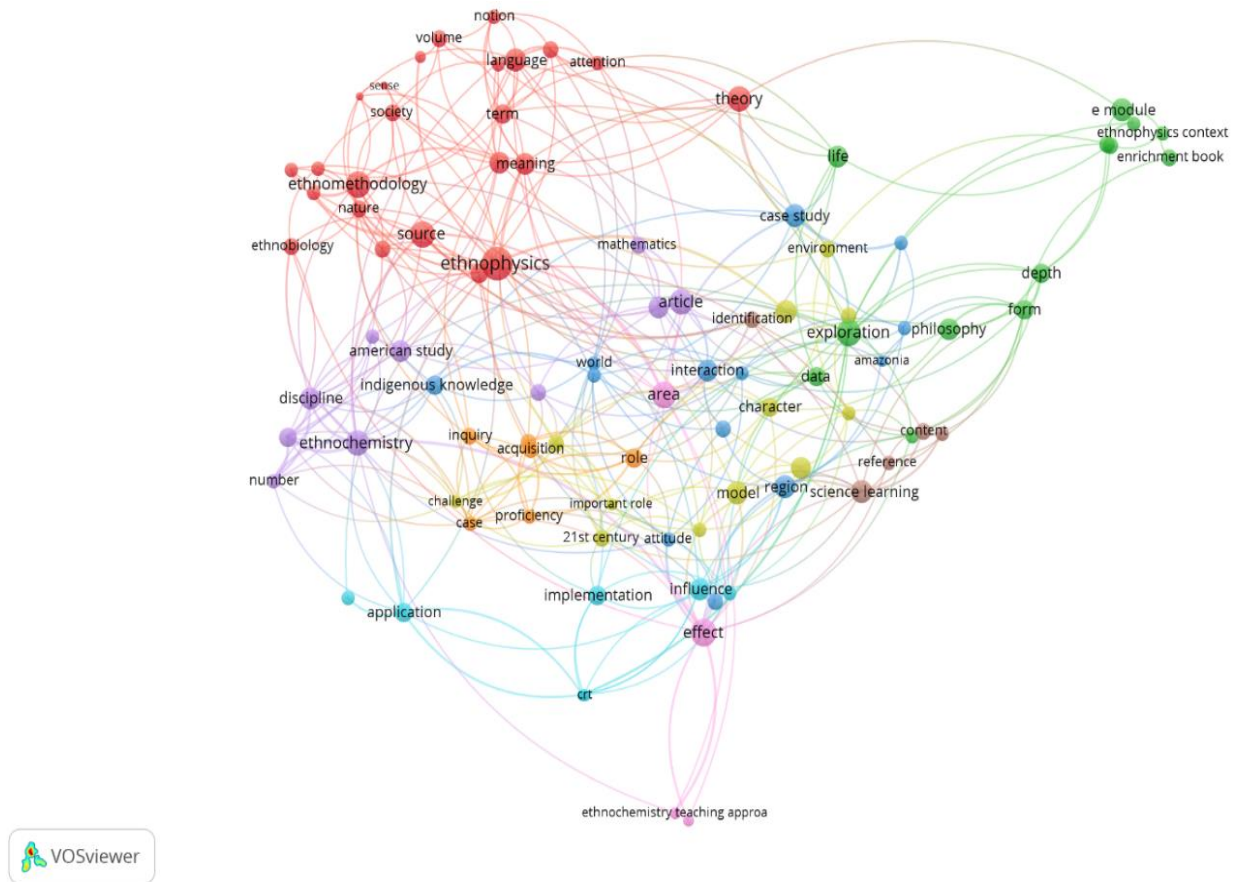
Based on the article search conducted, the most cited article was DE34. The article relates to the ethno-physical study of the Plate Dance as a medium for learning physics. The results of this study indicate that the Plate Dance is a local cultural heritage in the West Sumatra region of Indonesia, which can be studied physically, including motion, Newtonian gravity, sound, equilibrium, and heat (Astuti & Bhakti, 2021b). Next is article DE26. The results of the study show that the situation experienced during the construction of Manzuá in America can provide a basis for an excellent problem-based learning scenario for physics classes, namely, that teaching materials can be developed to connect the traditional knowledge of riverbank residents with school knowledge (Souza, 2013). The studies with the most citations are descriptive studies of local regional values related to the physics concepts studied, namely motion, Newtonian gravity, sound, equilibrium, and heat.

Based on the SLR criteria applied to the selected articles, most ethno-physics studies were conducted in Indonesia, followed by Brazil, the United States, Zambia, the Philippines, and Colombia. This is possible because Indonesia is famous for its rich cultural, ethnic, and traditional diversity. This diversity includes more than 300 tribes spread across various islands throughout Indonesia. Each tribe has unique beliefs, customs, languages, and local knowledge. This cultural diversity and local wisdom can be important factors in attracting researchers to explore and understand physical phenomena in different cultural contexts. In ethno-physical studies, Indonesia's cultural diversity offers a variety of traditional knowledge about how particular societies understand and use physics concepts in their daily lives. Research in Indonesia can involve studying local understandings of natural phenomena, traditional techniques, knowledge systems, and beliefs related to specific physics concepts.

Publications in ethno-physics show that research on cultural knowledge can be integrated into physics learning to increase pupils' relevance, understanding, and empowerment. The keyword "ethno-physics" and its relationships with other keywords indicate that research in this field often focuses on making physics learning more inclusive and relevant to pupils' cultural contexts. The frequently occurring keywords in ethno-physics publications were analyzed using VOSviewer to identify key themes in this study, as shown in Figure 2.

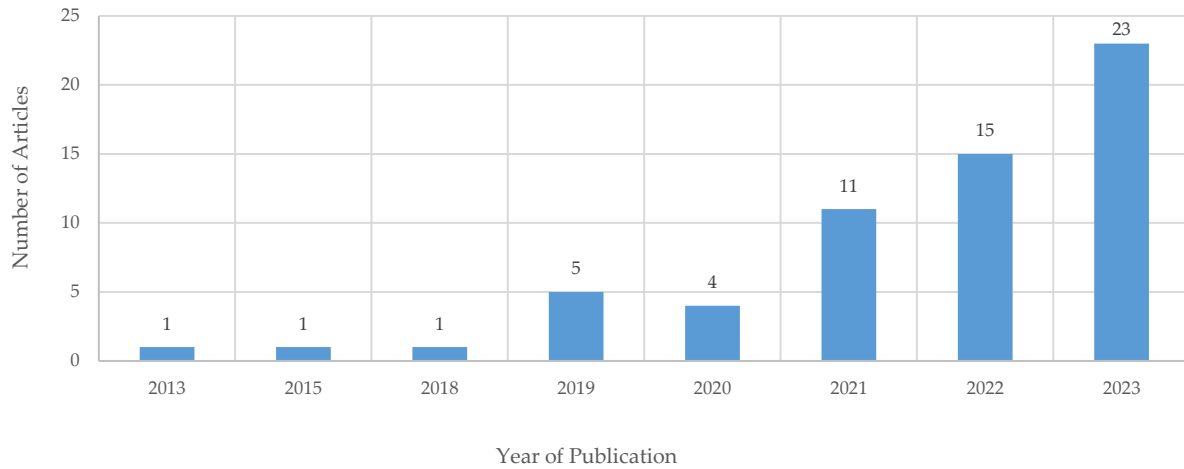
Figure 2

Keywords that frequently appear in publications related to ethnophysics



Some of the dominant keywords include "character", "indigenous knowledge", "science learning", and "exploration". The keyword "character" underscores the importance of cultural integration in physics teaching for developing learners' character, while "indigenous knowledge" emphasizes local or indigenous knowledge in science learning. "Science learning" is the most common application area. "Exploration" refers to the exploration of learners' knowledge through the integration of cultural expertise into learning. The analysis of these keywords shows that research focuses on integrating cultural knowledge into physics learning to increase pupil relevance, understanding, and empowerment. The relationship between these keywords also shows that ethnophysics research focuses on making physics learning more inclusive and relevant to pupils' cultural contexts.

The search for articles on ethnophysics was conducted without specifying a year range. This aims to provide comprehensive search results on the concept of ethnophysics, from its earliest study to the present. The research trends on ethnophysics are shown in Figure 3.

Figure 3*Ethnophysics research trends*

The search results, as shown in Figure 3, show that only one article on ethnophysics was found between 2013 and 2018. The number of articles increased to 5 in 2019 and decreased to 4 in 2020. Furthermore, it continued to experience significant development from 2021 to 2023, namely, 23 articles were found that were in accordance with ethnophysics studies. The publication trend indicates a gradual growth in ethnophysics research, with the number of publications increasing substantially from 2021 to 2023. This field has great potential for further development because it aligns with the Sustainable Development Goals (SDGs), particularly those related to education and environmental sustainability, by integrating cultural values. Such research plays an important role in instilling in pupils the need to preserve their environment as part of promoting sustainability awareness.

Types of Research Methods on Ethnophysics

Research in ethnophysics is advancing through various innovations, especially in the incorporation of local regional culture into physics learning. The research methods employed relate to the application of ethnophysics, as shown in Table 3.

Table 3*Types of research methods used in ethnophysics research*

No.	Research Methods	Number of Articles	Article Code
1	Classroom Action Research	2	CA1, CA2
2	ADDIE Model Development	4	DA1, DA2, DA3, DA4
3	Borg & Gall Model Development	1	DB1
4	4D Model Development	4	DD1, DD2, DD3, DD4
5	Plomp Model Development	1	DP1
6	Descriptive	42	DE1, DE2, DE3, DE4, DE5, DE6, DE7, DE8, DE9, DE10, DE11, DE12, DE13, DE14, DE15, DE16, DE17, DE18, DE19, DE20, DE21, DE22, DE23, DE24, DE25, DE26, DE27, DE28, DE29, DE30, DE31, DE32, DE33, DE34, DE35, DE36, DE37, DE38, DE39, DE40, DE41, DE42
7	Quasi Experiment	4	QE1, QE2, QE3, QE4
8	Instrument Analysis	1	IA1
9	Meta-Analysis	1	MA1
10	Survey	1	SU1
Total		61	

The results of the article search indicate that the use of descriptive methods is higher than that of other methods. Descriptive research on ethnophysics is related to the description of various forms of local culture that are studied in relation to the topic of physics. Researchers mostly describe, through the analysis of physics content, what is in accordance with the local culture in each region. Next is development research using various types of development models, namely ADDIE, 4D, Borg & Gall, and Plomp. This development research produces various products that can be used by pupils in learning Physics.

The next most commonly used research design is the quasi-experimental design. Studies of this type generally aim to compare various abilities that pupils can develop through learning using the ethnophysics approach. Another frequently used research design is classroom action research, in which ethnophysics-based learning devices, such as instructional materials and digital tools, are applied to improve learning outcomes and other related skills.

Based on the results of the analysis, one study also employed a meta-analysis, which provides an overview of previous research; thus, this paper can be categorized as a meta-analytical study. The article examined the influence of ethnosience-based learning on pupils' critical thinking skills in physics lessons. Based on findings from seven international studies included in the meta-analysis, it was concluded that ethnophysics research significantly improves pupils' critical thinking skills by integrating cultural values into physics learning (Idul & Fajardo, 2023). This highlights the importance of preserving and incorporating cultural aspects into education to promote meaningful, context-based learning experiences.

Local Cultural Forms Linked to Physics Topics

The diverse local cultures in each region present opportunities to develop studies of physics topics related to existing local culture or wisdom. Table 4 shows various forms of local culture and physics topics that correspond to the topic.

Table 4

Local cultural forms and related physics topics

Local Culture (Article Code)	Related Physics Topics
Kerapan Sapi (DE1, DE41)	Newton's Laws
Gedongan (DE2), La Marimba de Chonta Traditional musical instruments (DE14), Gua Batu Tabuhan (DE15), Tifa Tanimbar (SU1), Seurune On U Aceh (DE37)	Vibration and Sound
Lubuk Larangan (DE3), Canting Cecek Siji (DP1)	Fluid
Traditional Game Egrang (DE5)	Mechanical Energy
Traditional Game Gasing (DE6, DE11, DA2)	Equilibrium of a Rigid Body, Work, Momentum of Inertia, Rotational Motion, Kinetic Energy, Gravity
Osing Banyuwangi Traditional House (DE7)	Moment of Force, Moment of Inertia, and Equilibrium
Traditional Game Tarik Siteuk Masal (DE8)	Friction and Work
Making Ice Cream in Indonesia (DE9)	Circular Motion
Tari Piring (DE10)	Center of Mass and Equilibrium
Traditional Game Kerapan Kereweng (DE12)	Force and Motion
Traditional Game Kekuriken, Pisang Sale Aceh (DE13)	Temperature, Heat, Impulse, and Momentum
Manobo Basket Weaving in the Southern Philippines (DE16)	Bernoulli's principle
Soil Ceramics in Brazil (DE17), Jambi's Local Wisdom is Traditional Medicine, Blacksmithing, Betangas, Lemang Bambu, Jambi Batik, and Kerinci Coffee Culture (DD2), Lampung Written Batik (DA4),	Temperature and Heat
Traditional Game Engklek (DE18)	Equilibrium of Rigid Bodies
Brazilian Tipiti Crafts (DE19)	Force and Pressure
Salai Jin Dance of North Maluku (DE20)	Moment of Inertia and Waves
Ani-ani (DE21)	Particle Dynamics and Pressure
Putu Cake (DE22)	Mersenne's Law

Local Culture (Article Code)	Related Physics Topics
Traditional Game Taloe Yeye from Aceh (DE23), Buffaloes Plow the Fields, Delmans Carry Passengers, Play Tug of War, Minions Push Carts, Play Carving, etc. (in Indonesia) (CA2), Use of Natural Gas for Cooking and Electricity Generation in South Sumatra (DD4)	Work and Energy
Batu Bata Making Process in Indonesia (DA3, DE24,)	Simple Machines, Pressure, Measurement, Circular Motion, Work and Energy, Temperature, and Heat
Farmers' Traditional Equipment for Processing Flour in Brazil (DE25)	Torque Force, Centre of Mass
Construction of Manzua on the Banks of the Amazon River (DE26)	Force, Pressure, Fluid
Napeni Rice Yogyakarta (DE27)	Vertical Motion, Free Falling Motion, Parabolic Motion, and Friction
Okomama Dance (DE28)	Changes in Potential Energy
North Maluku Gumatere Dance (DE29)	Momentum, Impulse, Uniform Rectilinear Motion, Sound, and Elasticity
MOE Rice Drying Culture in Lebak (DE30)	Motion, Heat, and Work
The Culture of the Sentani Jayapura Community is Knowledge about Lightning/Wili and Guntur/Qurru, Celestial Bodies, Earthquakes and Rainbows, Transportation, and Measurements (DE31)	Vibrations, Sounds, Earth and Space Science, and Measurement
Kora-Kora ride (DE32)	Simple Harmonic Motion
Traditional Game Geulengkue Teu Peu Poe from Aceh (DE33), Sape Dayak Rohak (DD1)	Parabolic Motion
West Sumatra Lilin Dance (DE34)	Motion, Newtonian Gravity, Sound, Equilibrium, and Heat
The Typical Dance of Ternate City is the Soya-Soya Dance (DE35)	Sound Waves, Moment of Inertia, Collisions, Pascal's Law
North Sumatran Traditional Tool "Pangilangan" (DE36)	Force, Pressure, Work
Sumpit Dayak Kalimantan (DE38)	Flow Discharge, Parabolic Motion, and Simple Planes
Tulungagung Reog Kendang Dance (DE39)	Work, Work Coefficient, Mechanical Gain, Temperature, and Heat
Parang Making in Jambi (DE40)	Heat Transfer
African Indigenous Knowledge Systems (AIKs): Local Ingredients Such as Banana Stems, Palm Oil (DE42)	Gravity
Sojo Games, Cooking Beans, Winnowing, and Carrying Water in Bottles (QE1)	Density, Force, and Heat Transfer
Mangupa Batak Culture (QE2)	Static Fluids, Sound Waves, Organ Pipes, Heat Transfer
Irus, Pawon, Klepon, and Javanese Cultural Batik (QE3, CA1)	Conductivity, Heat Transfer, Expansion of Substances and Fluids
Boiling Eggs, Marcungkil, Tor-Tor Dance, Gordan Music (MA1)	Static Fluids, Momentum, Impulse, Sound, and Pipes

The forms of local culture studied are mostly related to the conditions experienced in each researcher's area. The most studied subject by researchers is Indonesian culture. The most studied physics topic is work and energy.

Forms of Learning Strategies in Implementing Ethnophysics

The SLR study identified several articles that used specific learning strategies in implementing ethnophysics. These articles present empirical evidence or case studies on the use of specific strategies in physics learning related to ethnophysics. There are four articles, namely QE1, QE2, QE3, and QE4, which use quasi-experimental research methods by implementing certain learning strategies.

Article QE1 applies Ethnophysics-Based Instruction (EBI). The results of the study indicate that Ethnophysics-Based Instruction (EBI) is a feasible innovation for improving academic performance and learner attitudes and is not gender-biased (Chongo & Baliga, 2019).

Articles QE2 and QE3 apply ethnophysics through a cooperative learning model. The results of the study indicate that the generic science skills and teamwork of pupils taught using a Batak culture-

based cooperative learning model are better than those of pupils taught using a conventional model (Hasanah et al., 2021). Physics learning using a Javanese culture-based cooperative learning model is more effective than conventional instruction (Srijayanti & Derlina, 2020).

Article QE4 integrated Western teaching materials with African Indigenous Knowledge (AIK) and found that this culturally responsive approach improved pupils' understanding of gravitational acceleration and reduced the gender gap in physics achievement (Gumbo et al., 2021). Overall, integrating local and cultural elements into ethnophysics-based strategies has the potential to make learning more meaningful, relevant, and contextually grounded.

Pupils' Abilities That Can Be Developed through Ethnophysics Integration

The results of the SLR analysis identified various pupil abilities that were measured and integrated with the application of ethnophysics in physics learning. Several studies examined how ethnophysics-based approaches can enhance these abilities by incorporating local wisdom into scientific contexts. These findings emphasize the importance of ethnophysics in improving physics learning outcomes and enriching pupils' learning experiences.

Article IA1 examines the analysis of ethnophysics-based Problem-Solving Skills test instruments. Rasch analysis, especially DIF, can reduce the likelihood of measurement errors in assessing ethnophysics-based problem-solving skills, without being influenced by domicile or gender in the sample (Nisa & Suprpto, 2023). Ethnophysics-based learning provides meaningful opportunities for pupils living in remote areas with limited infrastructure, as the learning materials are closely related to their everyday experiences. The study concluded that pupils in rural areas exhibited higher problem-solving skills, demonstrating the potential of culturally grounded physics instruction to enhance critical thinking.

Article DE39 explores the integration of local cultural values, such as moral and social attitudes, into physics learning through the context of the Reog Kendang Dance (Fitriyah, 2022). This study highlights how ethnophysics can connect cultural heritage with scientific understanding, encouraging pupils to recognize physics concepts embedded in daily practices and cultural performances.

Article QE4 reports on the implementation of ethnophysics-based learning in Africa, focusing on integrating Western teaching materials with African Indigenous Knowledge (AIK). The results indicate that this culturally responsive approach improves pupils' understanding of gravitational acceleration and reduces the gender gap in physics achievement (Chongo & Baliga, 2019). The integration of Western and non-Western science traditions demonstrates that culturally bound science learning can make physics more relevant to pupils' experiences and enhance their overall learning outcomes.

Article QE1 tries to measure academic performance and attitudes of pupils learning through ethnophysics. The findings showed that ethnophysics-based instruction is a feasible and gender-neutral innovation that enhances pupils' academic achievement and engagement (Chongo & Baliga, 2019).

Several studies (CA1, QE2, QE3) explored how teamwork and cooperation can be developed through culturally responsive learning strategies. For instance, learning physics through Javanese culture-based instruction helped pupils strengthen their collaboration skills while achieving the intended learning outcomes (Hasanah et al., 2021). These studies collectively indicate that applying ethnophysics in cooperative learning can enhance pupils' scientific reasoning, teamwork, and problem-solving abilities.

In addition, research has shown that ethnophysics-based approaches effectively improve generic science skills, including logical reasoning, inquiry, and collaboration. Pupils taught using Batak culture-based cooperative learning models achieved higher performance than those taught with conventional methods (Srijayanti & Derlina, 2020). The integration of cultural contexts in physics classrooms provides meaningful learning experiences that are more relatable to pupils' everyday lives.

The Article QE3 focused on increasing pupils' self-efficacy through the culturally responsive teaching approach integrated with ethnophysics. The study demonstrated that this model enhances pupils' self-motivation, discipline, and confidence in learning physics (Srijayanti & Derlina, 2020).

Article DD4 developed a science literacy module based on ethnoscience using the Kvisoft Flipbook Maker. The results indicated that the module was feasible and effective for improving pupils' science literacy, particularly in physics topics related to work and energy (Yulyanti et al., 2022).

Critical thinking skills were also examined through ethnophysics-based learning in physics. A meta-analysis (MA1 and DD1) revealed that ethnophysics-based e-modules significantly improved pupils' critical thinking skills (Idul & Fajardo, 2023). The implementation of these modules during and after the COVID-19 pandemic provided evidence that integrating cultural contexts into virtual learning environments can sustain pupils' engagement and analytical ability (Lestari & Apsari, 2022).

Several articles have discussed the development of ethnophysics-based learning devices to facilitate pupils' activities (article DD3), science process skills (article DA1), and conceptual understanding (article DA2). Based on the results of DD3, the Javanese culture-based learning devices were found to be in the "valid" category according to expert validation and empirical trials, indicating their practicality and effectiveness in learning implementation (Maryono et al., 2021).

The DA1 study reported that the ethnophysics-based teaching aids were categorized as "good" and "suitable for use in learning," as evidenced by high levels of pupil activity and positive response values (Falah et al., 2019).

Furthermore, the DA2 study, which focused on improving pupils' conceptual understanding through ethnophysics-based learning, demonstrated high validity, as evidenced by results from material, media, and language experts as well as practitioners. The trial phase yielded an 87% response rate, placing the product in the "very good" category for classroom implementation (Gifani et al., 2023).

These findings consistently indicate that ethnophysics-based learning has the potential to enhance various pupil abilities, including conceptual understanding, science process skills, and creativity. Research related to integrated ethnophysics teaching materials also shows that pupils' responses are excellent, reflecting engagement and enjoyment during learning. Ethnophysics in physics education serves not only as a theoretical framework but also as a practical approach that connects physics concepts to pupils' cultural experiences, promoting holistic learning and meaningful knowledge construction (Virijai & Asrizal, 2023; Widyaningsih et al., 2025).

Forms of Ethnophysics Integration Products and Their Applications in Learning

Based on the results of searching articles with development methods (DA: ADDIE Model, DB: Borg & Gall Model, DD: 4D Model, DP: Plomp Model), various types of products were obtained through ethnophysics. Table 5 shows the types of development models used to develop the resulting physics learning devices or products.

Table 5

Development model and products produced

Development Model	Number of Articles	Article Code	Product
4D	4	DD1	Mobile Application
		DD2	E-Module
		DD3	Learning Media
		DD4	E-Module
ADDIE	4	DA1	Props
		DA2	Mobile Application
		DA3	Enrichment Book
		DA4	Teaching materials
Borg & Gall	1	DB1	E-Module
Plomp	1	DP1	Augmented Reality (AR)

The most widely used development models for developing ethnophysics learning devices are the 4D and ADDIE models. The 4D model development research method is an approach that combines four main stages, namely define, design, develop, and disseminate. The 4D model is well-suited for

developing learning devices because it provides sound stages of development tailored to needs (Thiagarajan et al., 1974). Likewise, the ADDIE development model can be used to develop teaching materials. The ADDIE model is a systematic approach to instructional development consisting of five main stages: analysis, design, development, implementation, and evaluation (Aldoobie, 2015). In essence, all development models can be used to create teaching materials, especially those related to ethnophysics, because development research methods usually begin with a needs analysis. Needs analysis is important in development research, especially in ethnophysics, because it helps identify needs and the local wisdom conditions that will be revealed in the research to be carried out.

Various types of products were developed using ethnophysics. The DD1 article introduces an innovative mobile application featuring physics content. The study results indicate that mobile applications containing valid ethnophysics content improve pupils' critical thinking skills. This is indicated by the results of the validity, practicality, and effectiveness of ethnophysics mobile applications in improving pupils' critical thinking skills during the COVID-19 pandemic (Lestari & Apsari, 2022). Likewise, the DD2 article found that local wisdom in Indonesia can serve as a context for exploring physics concepts such as temperature and heat. The validation results from material experts were 91.67% (Very Good), and from media experts, 91.67% (Very Good). The results for pupil perceptions were 86.8%, corresponding to the Very Good category (Sari et al., 2021). The development of mobile applications is significant because the number of smartphone users continues to increase. The use of mobile applications can also be combined with various learning strategies. The project-based learning strategy, supported by mobile learning applications, affects teachers' teaching abilities and performance (Maritasari et al., 2022). Furthermore, it was found that mobile applications in blended learning are better at developing pupils' problem-solving abilities (Amin et al., 2021). The potential of mobile applications in learning encourages innovation and provides opportunities for teachers to develop diverse, relevant ways of using smartphones, especially for pupils, as learning resources.

Other development products produced are teaching materials. Articles DA1, DA4, and DP1 produced teaching materials. The results of the research indicate that the ethnophysics-based teaching materials developed are valid, effective, and practical for developing science process skills (Falah et al., 2019), attracting pupils' attention (Widayanti et al., 2022), and supporting 21st-century learning (Virijai & Asrizal, 2023). Article DP1 produces Augmented Reality (AR) teaching materials. Teaching materials in the form of AR can help pupils understand abstract concepts by allowing them to see useful, realistic content (Akcaay et al., 2020). AR allows users to experience real and virtual environments simultaneously (Muali et al., 2020). Using appropriate technology, such as virtual laboratory media, can help pupils by considering cultures and regions with limited resources for conducting science experiments in real laboratories (Yusuf et al., 2024). The application of ethnophysics creates opportunities for researchers to develop a range of locally culture-based learning content that can be presented on innovative, engaging platforms. It is hoped that the use of these learning media will improve learning performance.

Conclusion

The results of the SLR study show that ethnophysics research continues to increase every year. Ethnophysics research has a good opportunity for development because it aligns with the SDGs, particularly those related to education and the environment, which can be preserved by integrating cultural values. Researchers mostly conduct descriptive research, namely describing and analyzing physics content in accordance with the local culture in each region. The most widely studied topics in physics are related to work and energy. The results of the SLR analysis revealed various pupil abilities that were measured and integrated with the application of ethnophysics in physics learning. Various articles try to integrate with pupils' abilities that can be developed. These articles underline the importance of ethnophysics in improving physics learning performance and enriching pupils' learning experiences. Several articles also use specific learning strategies in implementing ethnophysics. These articles present empirical evidence or case studies on the use of specific strategies in physics learning related to ethnophysics. The most widely used development models for developing ethnophysics

learning tools are the 4D and ADDIE models, and various products were developed through this SLR study. Developing mobile applications is a viable product strategy because smartphone usage continues to grow. This potential encourages innovation and provides opportunities for teachers to develop diverse, relevant ways of using smartphones as learning resources, especially for pupils.

This study recommends integrating local cultural elements into physics learning. This integration increases pupils' interest and motivation by connecting physics concepts with cultural phenomena and familiar practices. Developing curricula and teaching materials that include the application of ethnophysics is essential. This includes creating modules, textbooks, and other learning aids that connect physics with local cultural aspects. In addition, teachers need training to apply this approach effectively in their teaching through workshops, seminars, and professional development programs. Other recommendations from this study include conducting further research to explore the effectiveness of ethnophysics in various educational contexts. Collaboration with cultural experts and local communities is also highly recommended to improve the relevance and accuracy of the content taught. Technology can be utilized to support this approach, for example, through videos, simulations, and mobile applications that illustrate physics concepts in local cultural contexts. In addition, evaluation and assessment methods need to be adjusted to measure pupils' understanding of physics concepts taught through ethnophysics, using more authentic, contextual assessments. It is hoped that these recommendations can improve the quality of physics learning and make it more relevant and interesting for pupils.

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Reading the 'Litc-Tsu' wave: a comprehensive analysis of socio-demographic determinants of tsunami literacy

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ABSTRACT

Tsunamis are destructive disasters that threaten those living in vulnerable areas, such as Indonesia's coastal regions. Tsunami literacy (Litc-Tsu) plays an important role in reducing risk and increasing preparedness. This study attempts to explore in depth the factors behind the level of Litc-Tsu. Socio-demographic characteristics such as gender, age, and proximity to the coast are of interest for in-depth investigation to determine whether they are related to the level of Litc-Tsu, especially among teenagers, who are the target of this study. In conducting our research, we used a quantitative study through an exploratory survey design conducted on 260 students in Lampung Province, Indonesia, due to its geological vulnerability to tsunamis, namely, the presence of Mt. Anak Krakatau and the subduction zone on the southern coast of Lampung, which has the potential for megathrust earthquakes. The results we obtained will be analyzed using descriptive and inferential statistics, including structural equation modeling (SEM), independent t-tests, and ANOVA. The findings we processed concluded that (1) the gender factor, where the Litc-Tsu level of women is higher than that of men, significantly affects Litc-Tsu; (2) the age factor does not significantly affect or correlate with Litc-Tsu, with our findings limited to only one age group (adolescents); and (3) the geographical proximity factor does not significantly affect or correlate with Litc-Tsu; our findings indicate that there needs to be an in-depth investigation within the scope of the coastal corridor (+/- 1 km) rather than across the entire regency area. Nevertheless, these findings enrich the scientific knowledge base for constructing evidence-based tsunami mitigation strategies for adolescents that account for socio-demographic factors.

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Introduction

Tsunamis are destructive natural disasters, so it is very important to understand the potential risks in vulnerable areas and formulate appropriate strategies to reduce the impact of tsunamis (Srinivasa Kumar & Manneela, 2021; Tufekci-Enginar et al., 2021; Yulianto et al., 2023; Widodo et al. 2025). The end of 2004 became an unforgettable moment in history for communities living along the

Indian Ocean coastline, as a massive earthquake triggered high waves that claimed tens of thousands of lives, destroyed buildings, and caused psychological trauma to those affected (Benazir & Oktari, 2024). Furthermore, in 2018, similar events occurred on the Palu-Donggala coast and the Lampung-Banten coast. These tsunami events emphasize the necessity of awareness and preparedness for future tsunami disasters. In this context, tsunami literacy serves as a crucial foundation in developing future disaster mitigation strategies, including understanding the potential, mechanisms, and decision-making processes involved in protecting oneself before and after a tsunami (Khairunnisa et al., 2021; Nagata et al., 2022; Putri et al., 2025; Takahashi et al., 2025). Through tsunami literacy, they can also improve disaster resilience and quality of life in the future (Çalışkan et al., 2021). In essence, Litc-Tsu is closely related to their ability to implement effective and efficient measures when a disaster occurs (Aksa et al., 2024; Cabello, 2022; Ebina & Sugawara, 2024; Nagata et al., 2022; Takahashi et al., 2025), while their proactive behavior determines the success of disaster risk management (Kesumaningtyas et al., 2022).

In fact, Litc-Tsu levels are uneven across different social groups due to socio-demographic factors such as age, gender, education level, and geographical proximity of residence to disaster-prone areas. These factors are considered important determinants of Litc-Tsu levels (Cugliari et al., 2022; Moreschini et al., 2025). The results of the study by Cerase and Cugliari (2023) indicate that these elements are important in shaping their views on how to behave to be resilient to disasters. Several studies also agree that these elements need to be identified to help develop effective risk communication strategies to support disaster mitigation policies (Armaş, 2006; Doyle et al., 2014; McIvor et al., 2009; Parsons & Lykins, 2023). However, we highlight that several studies remain limited to specific contexts and are fragmented, so the results are not generalizable to factors such as age, gender, and proximity to the coast. This study offers an in-depth analysis by examining the influence and correlation of several socio-demographic factors with Litc-Tsu levels and understanding the strength of these three factors interacting with each other in structural equation modeling.

Several gaps we found involve three elements that we observed. First, surveys on tsunami awareness are still limited to what has been discussed in previous studies. In Indonesia, studies on disaster awareness tend to focus on specific disasters such as tsunamis (Deta et al. 2025; Handoyo et al., 2024;), floods (Fatmah et al., 2022; Sultan et al., 2024), and landslides (MacAfee et al., 2024; Suharini et al., 2024). Second, limited attention has been given to individuals at the college or university level. We found that previous research often focused on communities living in coastal areas, elementary and middle school students in places such as Pangandaran, Indonesia (Nuraziz et al., 2023), and the general public in Nias, Indonesia (Aksa et al., 2024). However, it is important to emphasize that the entire community has an important role to play, not just those living in coastal areas, because these research areas are prone to disasters, and understanding tsunami disaster literacy requires a comprehensive approach. Third, socio-demographic variables such as age, gender, and physical distance were studied separately rather than collaboratively, including, for example, the relationship between age and disaster understanding (Dewi et al., 2025; Genc et al., 2022), gender and disaster understanding (Sari et al., 2022), and location and disaster understanding (Senkbeil et al., 2025).

Therefore, this study explores the extent to which socio-demographic characteristics influence understanding of tsunamis. Empirically derived findings can inform the formulation of strategic disaster mitigation measures that account for socio-demographic factors in the delivery of risk information, preparedness, and decision-making simulations to address disasters effectively.

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Literature Review

Gender and Litc-Tsu

The studies we highlighted earlier mention that gender is recognized as a factor that can influence a person's ability to cope with disasters (Go, 2024; Hall et al., 2022; Mardialina et al., 2024;

Seddighi et al., 2022; Vu et al., 2023). However, we explored further whether there were differences in findings regarding who was more dominant between men and women. Tropus et al. (2024) stated in their study that men had higher preparedness than women, but this result contrasts with findings from other studies, such as Kesumaningtyas et al. (2022), which found that women were more dominant disaster preparedness. Several other studies have revealed that women have a higher perception of risk and a greater sense of responsibility towards their families, which affects their level of preparedness (Najafi et al., 2015; Tohan et al., 2024).

In fact, data show that women are more likely to die in tsunamis (Raheem et al., 2025; Zarook, 2022), due to gender inequality during early warning and field evacuation (Jayasekara et al., 2023). Nevertheless, women demonstrate more dominant caring and preparedness behaviors than men, making them more vulnerable before, during, and after disasters (Fatouros & Capetola, 2021; Sedghi et al., 2025). Through the contradictory consensus of this study's findings, we synthesize that gender is an important factor in influencing their capacity to cope with disasters.

In the context of this study, we want to conduct a specific investigation into the understanding of the tsunami disaster among teenagers and want to reinforce and refute the results of previous studies on whether males or females have Litc-Tsu skills among teenagers (Generation Z), in addition to analyze whether gender factors have a significant effect on Litc-Tsu. The research goal for the substance of this section is as follows:

Hypothesis 1: Gender is influential and correlated with Litc-Tsu levels, and female groups are more dominant in Litc-Tsu skills than male groups?

Age and Litc-Tsu

Age is an important factor in influencing a person's Litc-Tsu ability. Several studies that we tracked found and agreed that there is a positive and significant relationship between the two variables (Genc et al., 2022; Hall et al., 2022; Khairunnisa et al., 2021; Seddighi et al., 2022; Vu et al., 2023). Sun and Sun (2019) in their study mentioned that age can have a positive impact on individuals' readiness in decision making. Furthermore, a study conducted on the coast of Sri Lanka mentioned that age differences influence individuals' ability to respond to early warning systems and evacuations during disasters (Jayasekara et al., 2023).

However, the results of these studies are still contradictory. One such study, as Gülsoy et al. (2025), concludes that as a person's age increases, their level of disaster preparedness literacy decreases. Furthermore, Tohan et al. (2024) support this through their study findings that there is no significant correlation between age and disaster preparedness. The diversity of these findings strengthens our decision to follow up with our study, which focuses on the Gen Z group aged 17-21 years, allowing us to explore the differences based on one-year intervals. The hypothesis we propose in this section is as follows:

Hypothesis 2: Does age affect and correlate with Litc-Tsu levels, and does age group interval affect their Litc-Tsu proficiency?

Geographical Proximity and Litc-Tsu

The geographical proximity of their place of residence is an important factor influencing differences in their understanding of disaster literacy. Several studies highlight that the closer they live to the sea, the higher their awareness of the dangers of tsunamis (Khairunnisa et al., 2021; Vu et al., 2023). This is supported by a study by Sherman-Morris et al. (2025), which found that those who live close to the coast were more capable of making decisions during emergencies. This means that this factor plays an important role in their awareness, understanding, and preparedness for disasters.

The deeper we delve into the literature review, the more we find studies that contradict previous findings or remain inconsistent with one another, such as O'Neill et al. (2015), who found no correlation between the two variables (the distance between disaster-prone areas and their anxiety

about disasters). This was followed by Senkbeil et al. (2025), who found that their understanding of their place of residence (geographical proximity) correlated with their perception of risk, although it was not as consistent as other factors (age, experience, or level of education). These contradictory findings sparked our interest in conducting further investigations on Generation Z. The hypothesis we propose in this section is as follows:

Hypothesis 3: Does the factor of geographical proximity of residence influence and correlate with the level of Litc-Tsu, and do regional differences in city levels affect Litc-Tsu patterns?

Methods

Research Design

This study used an exploratory quantitative cross-sectional survey design to examine the impact, differences, and relationships between determining factors and the school community's level of understanding of tsunamis. This design was chosen to systematically measure the level of understanding and investigate how social background characteristics, such as gender, age, and proximity of residence, contribute to knowledge about tsunamis. It is reasonable to expect that gender differences affect understanding of tsunamis due to differences in social roles and perspectives on danger; that age affects understanding due to its connection with decision-making experience; and that geographical position generally shapes daily perceptions of tsunami-prone areas. A total of 260 individuals participated in this study, which was conducted at the University of Lampung campus in Lampung Province. Details regarding the characteristics of the respondents are presented in Table 1.

Table 1

Participant characteristics

Aspect	Options	Frequency	Percentage (%)
Gender	Male	217	83.14
	Female	43	16.48
Age	16 year	1	0.38
	17 year	28	10.73
	18 year	59	22.61
	19 year	98	37.55
	20 year	67	25.67
	21 year	7	2.68
	2023	86	32.95
Level	2024	94	36.02
	2025	80	30.65

Research Site

The investigation in this study was conducted at a university in Lampung Province. This choice was based on the university's location and the looming threats such as megathrust earthquakes and eruptions of the Anak Krakatau volcano in the Sunda Strait. Participants were selected from students in Lampung Province.

Data Collection

Data were collected using tests that had been validated for construct and content validity by several experts. We developed these test instruments based on indicators that we had previously compiled from a review of relevant literature. The details of the test instrument development are shown in Table 2.

Hypothesis 3: Does the factor of geographical proximity of residence influence and correlate with the level of Litc-Tsu, and do regional differences in city levels affect Litc-Tsu patterns?

Table 2

Development of the Tsunami literacy (Litic-Tsu) instrument

Assessment Aspect	Indicators	Items	References
Critical Understanding	Understanding the causes and natural processes of tsunamis Distinguishing between factual and false (hoax) information in disaster contexts Evaluating the social and environmental impacts of tsunamis	10	The Sendai Framework for Disaster Risk Reduction 2015-2030 (United Nations, 2015); Nagata et al (2022);
Situational Analysis	Identifying early warning signs of tsunamis Analyzing high-risk geographical features Evaluating safe evacuation routes and essential needs during evacuation Analyzing physical, social, and psychological barriers in evacuation processes	10	The Sendai Framework for Disaster Risk Reduction 2015-2030 (United Nations, 2015); Nagata et al (2022);
Systematic Action	Preparing an emergency “go-bag” prior to a tsunami Evacuating according to designated routes and procedures Evacuating calmly and in an orderly manner Informing authorities or evacuation groups of one’s condition	10	León et al (2021); Nagata et al (2022);
Decision-Making	Making rapid decisions when impacted by tsunami waves and selecting the best evacuation option Choosing the fastest and safest evacuation route while weighing consequences Making independent decisions without waiting for instructions during emergencies Adjusting plans in response to obstacles without panic	10	Nagata et al (2022);
Adaptation	Pre-disaster adaptation Adaptation during a tsunami Post-disaster adaptation	10	Plümper, et al (2017); Nagata et al (2022);
Responsive, Solution-Oriented, and Collaborative Actions	Assisting children or the elderly during simulations Creating solutions when facing technical constraints during evacuation Collaborating with peers during evacuation	10	The Sendai Framework for Disaster Risk Reduction 2015-2030 (United Nations, 2015)

This measurement tool has undergone validation to ensure its reliability and suitability for use in this study. Initially, there were 60 items, but only 55 passed validation. The validation process was carried out by distributing the measuring instrument to students who were not part of the main research sample, in order to ensure that the instrument met the psychometric requirements of the research. Scale assessments were given if participants answered correctly (score of 1) or incorrectly (score of 0). We compiled each indicator to create a new measurement tool that focuses on measuring how well someone understands tsunamis, because understanding of tsunami literacy is still lacking when measured on its own; most measurements assess disaster literacy in general. We carried out the validation through construct validation conducted on 79 students outside the sample. The validation results can be seen in Table 3 and 4.

Table 3

Validity results of the Litc-Tsu Test instrument

No Item	Pearson	R table	Discussion	No Item	Pearson	R table	Discussion
1	.484**	0,287	Item Valid	31	.434**	0,287	Item Valid
2	.484**	0,287	Item Valid	32	.674**	0,287	Item Valid
3	.653**	0,287	Item Valid	33	0.022	0,287	Item No Valid
4	.394**	0,287	Item Valid	34	.292**	0,287	Item Valid

No Item	Pearson	R table	Discussion	No Item	Pearson	R table	Discussion
5	.541**	0,287	Item Valid	35	.510**	0,287	Item Valid
6	.422**	0,287	Item Valid	36	.293**	0,287	Item Valid
7	.630**	0,287	Item Valid	37	.334**	0,287	Item Valid
8	.355**	0,287	Item Valid	38	.360**	0,287	Item Valid
9	.380**	0,287	Item Valid	39	.416**	0,287	Item Valid
10	.593**	0,287	Item Valid	40	.366**	0,287	Item Valid
11	.291*	0,287	Item Valid	41	.289**	0,287	Item Valid
12	.292**	0,287	Item Valid	42	.387**	0,287	Item Valid
13	.321**	0,287	Item Valid	43	.341**	0,287	Item Valid
14	.486**	0,287	Item Valid	44	.374**	0,287	Item Valid
15	.599**	0,287	Item Valid	45	.387**	0,287	Item Valid
16	.398**	0,287	Item Valid	46	.437**	0,287	Item Valid
17	.373**	0,287	Item Valid	47	.326**	0,287	Item Valid
18	.505**	0,287	Item Valid	48	.292**	0,287	Item Valid
19	.432**	0,287	Item Valid	49	.538**	0,287	Item Valid
20	.420**	0,287	Item Valid	50	.578**	0,287	Item Valid
21	0.140	0,287	Item No Valid	51	.400**	0,287	Item Valid
22	0.104	0,287	Item No Valid	52	.377**	0,287	Item Valid
23	.705**	0,287	Item Valid	53	.432**	0,287	Item Valid
24	.314**	0,287	Item Valid	54	.451**	0,287	Item Valid
25	.505**	0,287	Item Valid	55	0.110	0,287	Item No Valid
26	.599**	0,287	Item Valid	56	.414**	0,287	Item Valid
27	.599**	0,287	Item Valid	57	-0.077	0,287	Item No Valid
28	.578**	0,287	Item Valid	58	.599**	0,287	Item Valid
29	.514**	0,287	Item Valid	59	.579**	0,287	Item Valid
30	.566**	0,287	Item Valid	60	.492**	0,287	Item Valid

Table 4

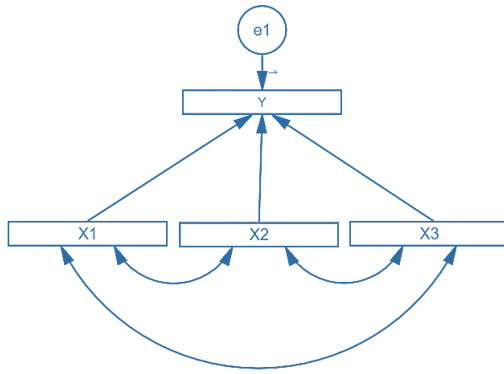
Reliability results of the Litc-Tsu Test instrument

Reliability Statistics	
Cronbach's Alpha	N of Items
.960	60

The information obtained was processed using AMOS and SPSS computer programs to test the relationship between social characteristics of the population and knowledge about tsunamis (Litic-Tsu, Y). The analysis method used follows the structural equation modeling (SEM) guidelines, as shown in Figure 1. In addition, an in-depth examination was carried out using analysis of variance (ANOVA) and the coefficient of determination (R^2) in SPSS to determine the exact contribution of the influencing factors and the influenced factors.

Figure 1

Testing model of X1, X2, and X3 on Y and their correlations



Note. Description: Gender (X1); Age (X2); Place of Residence (X3); Level of Tsunami Disaster Literacy (Y)

Structural Model Equation:

$$Y = \beta_1 + \beta_2 X_2 + \beta_3 X_3 + e_Y \quad (1)$$

where:

Y = endogenous variable (tsunami disaster literacy)
 X₁, X₂, X₃ = exogenous variables (gender, age, place of residence)
 β₁, β₂, β₃ = path coefficients
 e_Y = error term or residual

Covariance Matrix of Exogenous Variables

$$\Sigma X = \begin{bmatrix} \text{Var}(X_1) & \text{Cov}(X_1 X_2) & \text{Cov}(X_1 X_3) \\ \text{Cov}(X_2 X_1) & \text{Var}(X_2) & \text{Cov}(X_2 X_3) \\ \text{Cov}(X_3 X_1) & \text{Cov}(X_3 X_2) & \text{Var}(X_3) \end{bmatrix} \quad (2)$$

Theoretical Variance of Y:

$$\text{Var}(Y) = \beta^T \Sigma X \beta + \text{Var}(e_Y) \quad (3)$$

with:

$$\beta = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix}$$

General SEM Model:

$$y = \Gamma x + \Omega \quad (4)$$

where:

y = vector of endogenous variables
 x = vector of exogenous variables
 Γ = path coefficient matrix from x to y
 Ω = vector of residuals

To strengthen the robustness of the findings, we further conducted linear regression analysis and measured the specific contribution of each exogenous variable through the following formulations:

Linear Regression Model:

$$\text{General equation: } y = ax + b \quad (5)$$

Coefficient of Determination (R²)

$$R^2 = \frac{[\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})]^2}{[\sum_{i=1}^n (x_i - \bar{x})^2][\sum_{i=1}^n (y_i - \bar{y})^2]} \quad (6)$$

Through the criteria of $0 \leq R^2 \leq 1$.

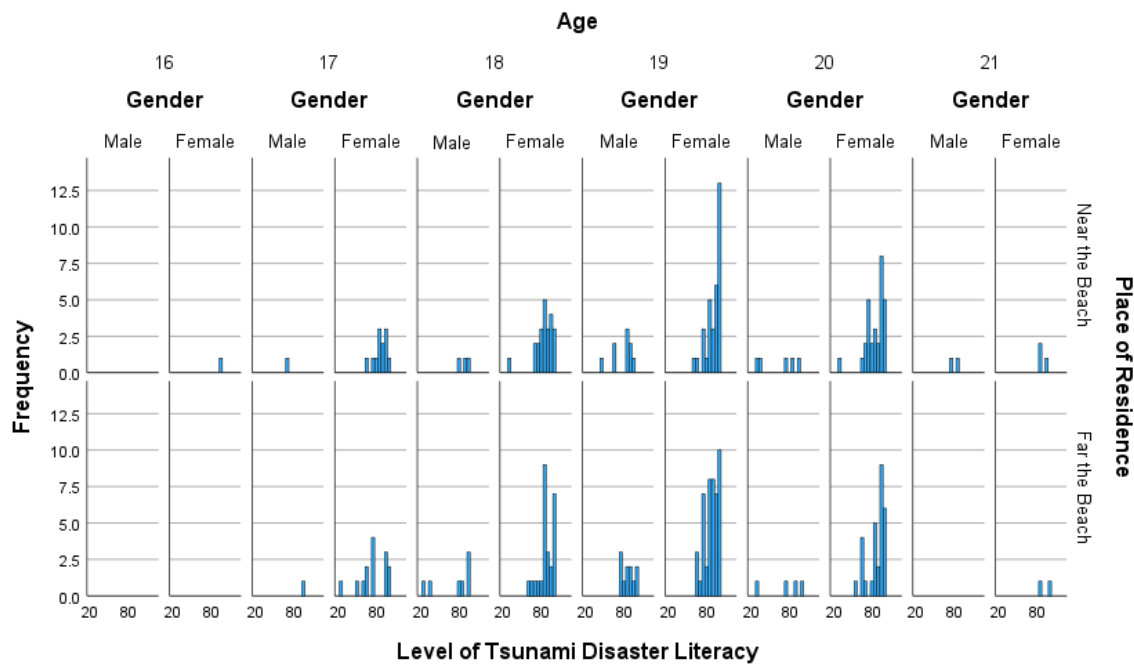
Results

General Result

Tsunami disaster literacy (Litc-Tsu) plays a critical role in disaster mitigation as it helps reduce the adverse impacts of risk (Fadilah et al., 2020). The descriptive survey results from 260 university students are presented in Figure 2.

Figure 2

Descriptive statistical analysis of X_1 , X_2 , X_3 , and Y



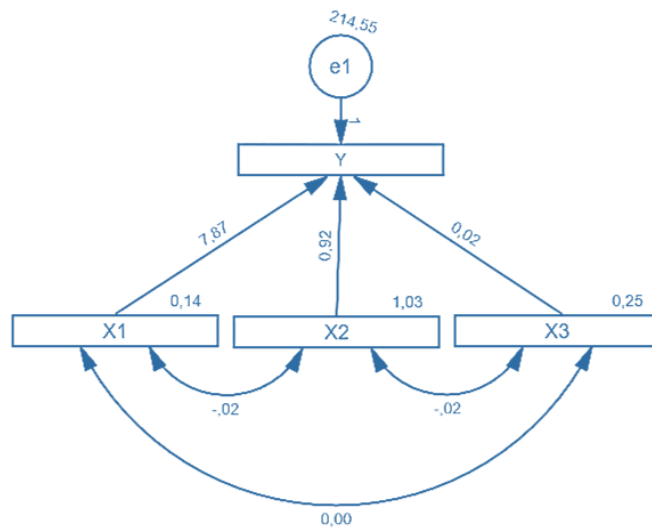
Note. Description: X_1 = Gender; X_2 = Age; X_3 = Place of Residence; Y = Tsunami Disaster Literacy Level

In summary, the results of the description show that knowledge about tsunamis (Litc-tsu) among students is generally quite high (with a scale of 20 being the lowest and 80 being the highest), and the data tends to peak on the right side. Although a few small groups show the opposite trend, the majority of students have a better level of knowledge. The following are the details of the main findings: (1) Based on gender, Female students tend to be more knowledgeable than male students; (2) In terms of age, Students aged 19 to 20, especially females, show better understanding than other age groups. However, these changes across age groups indicate that increasing age does not necessarily guarantee higher Litc-tsu, and (3) Students who live near the coast have a better understanding than those who live far inland.

Based on these findings, we can say that female students aged 19 to 20 who live near the sea have the highest Litc-Tsu scores. Conversely, female students aged 16 to 17 who live farther from the coast have the lowest scores. To reinforce these observations, we conducted a structural equation modeling (SEM) analysis using AMOS 29, which can be seen in Figure 3.

Figure 3

SEM model of the effects of X1, X2, and X3 on Y and their correlations



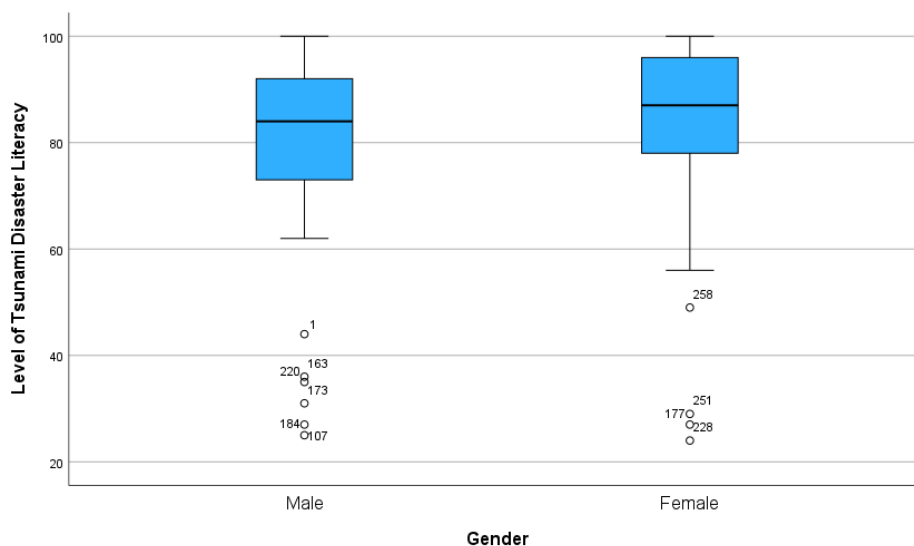
Note. Description: X₁ = Gender; X₂ = Age; X₃ = Place of Residence; Y = Tsunami Disaster Literacy Level

Based the results of structural equation modeling (SEM), it was found that gender was the only factor that had a significant impact on Litc-Tsu competence among students (CR value = 7.87), while the other two factors, age and geographical proximity of residence, had no significant impact, with CR values of 0.92 and 0.02, respectively. Furthermore, the relationship between independent variables did not show any strengthening; instead, it appeared to be very weak or even completely uncorrelated in the findings of this study. Through the margin value ($e = 214.55$), it can be assumed that the level of Litc-Tsu competence cannot be explained by only three variables, but there are other situational and psychological factors that have a greater impact. This becomes a gap in further research to be followed up in depth.

Gender and Tsunami Literacy (Litic-Tsu)

Figure 4

Distribution of tsunami literacy by gender



These distribution results illustrate that the female group demonstrated a deeper understanding and/or was categorized as higher than the male group among the 260 participants surveyed in the field. Not stopping there, we followed up our inferential analysis through ANOVA and R-squared testing with the following hypothesis:

Hypothesis testing: Gender is influential and correlated with Litc-Tsu levels, and female groups are more dominant in Litc-Tsu skills than male groups?

Results of inferential data processing:

Table 5

Linear regression analysis of gender and Litc-Tsu

ANOVA ^a					
Model	Sum of Squares	Df	Mean Square	F	Sig.
1					
Regression	2149.326	1	2149.326	9.901	0.002 ^b
Residual	56223.640	259	217.080		
Total	58372.966	260			
a. Dependent Variable: Level of Tsunami Disaster Literacy					
b. Predictors: (Constant), Gender					

Furthermore, the contribution of gender to tsunami literacy is presented in the following table.

Table 6

Contribution of gender to tsunami literacy

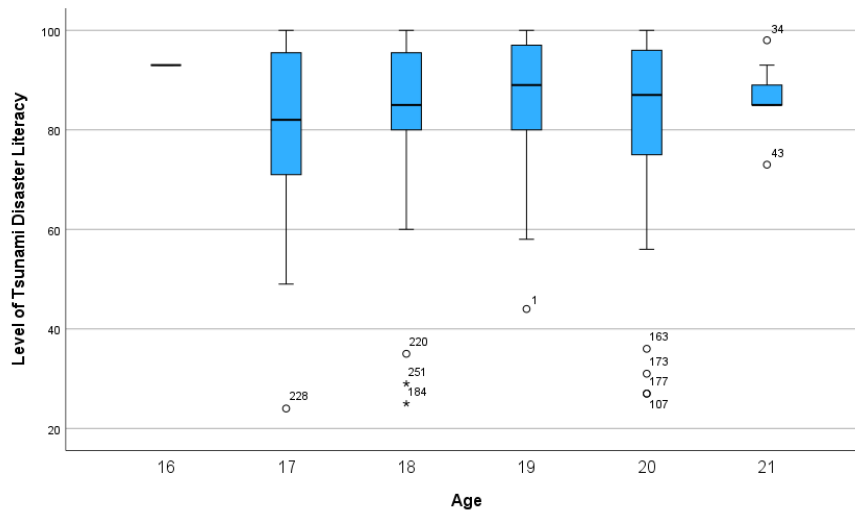
Model Summary ^b									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				Durbin-Watson
					R Square Change	F	df1	df2	Sig. F Change
1	0.192 ^a	0.037	0.033	14.734	0.037	9.901	1	259	0.002
a. Predictors: (Constant), Gender									
b. Dependent Variable: Level of Tsunami Disaster Literacy									

Regression results showed that gender significantly influenced tsunami literacy ($p = .002 < .05$), with an explanatory power of 3.7%, while other factors explained the remaining 96.3% of variance. Although the effect size is modest, the result confirms that gender has a measurable influence on students' disaster literacy.

Age and Tsunami Literacy (Litic-Tsu)

The results we found in this study show fluctuations in Litc-Tsu proficiency across each age interval. Starting from the age of 17 to 19, there was an increase, but after that there was a decline, although it was categorized as a slight decline. From this, we see that these findings reinforce the idea that age does not affect litc-tsu descriptively. To reinforce these results, we propose a hypothesis in this section:

Hypothesis testing: Does age affect and correlate with Litc-Tsu levels, and does age group interval affect their Litc-Tsu proficiency?

Figure 5*Distribution of tsunami literacy by age*

Results of inferential data processing:

Table 7*Linear regression analysis (age and Litc-Tsu)*

ANOVA ^a						
	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	160.241	1	160.241	0.713	0.399 ^b
	Residual	58212.725	259	224.760		
	Total	58372.966	260			
a. Dependent Variable: Level of Tsunami Disaster Literacy						
b. Predictors: (Constant), Age						

Then, how do the independent variables contribute to the dependent variables presented in Table 8.

Table 8*Contribution of age to tsunami literacy*

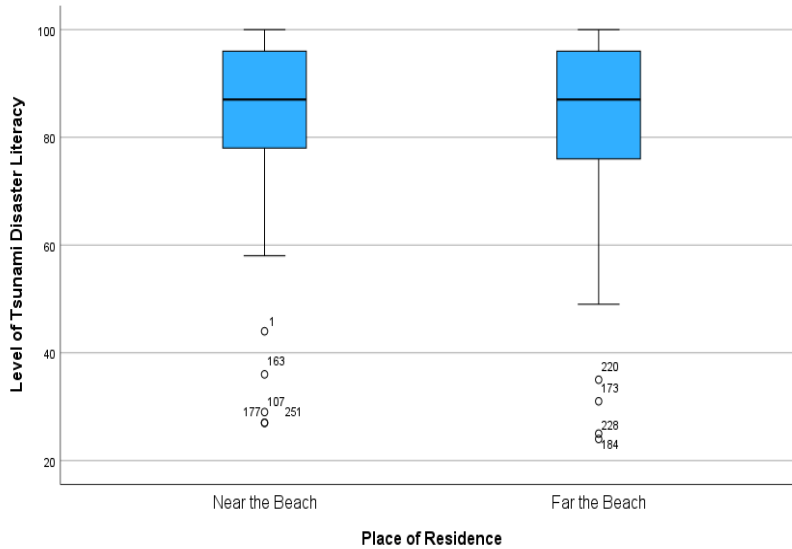
Model Summary ^b										
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	0.052 ^a	0.003	-0.001	14.992	0.003	0.713	1	259	0.399	1.988
a. Predictors: (Constant), Age										
b. Dependent Variable: Level of Tsunami Disaster Literacy										

Through the results of inferential ANOVA and R Squared, we can conclude that the age factor does not have a significant effect ($0.399 > 0.05$) and only contributes 0.3%, with the rest coming from other X factors.

Geographical Proximity to Hazard Zones and Litc-Tsu

Figure 6

Distribution of place of residence and Litc-Tsu



The final factor in this study found that the difference was only (0.12). The preliminary conclusion is that people who live near the coast have higher Litc-Tsu levels than those who live far from the coast. We confirmed this finding through inferential analysis to test the following hypothesis:

Hypothesis testing: Does the factor of geographical proximity of residence influence and correlate with the level of Litc-Tsu, and do regional differences in city levels affect Litc-Tsu patterns?

Table 9

Linear regression analysis (place of residence and Litc-Tsu)

ANOVA ^a					
Model	Sum of Squares	df	Mean Square	F	Sig.
1 Regression	0.254	1	0.254	0.001	0.973 ^b
Residual	58372.712	259	225.377		
Total	58372.966	260			
a. Dependent Variable: Level of Tsunami Disaster Literacy					
b. Predictors: (Constant), Place of Residence					

Then, the contribution between these two crossed variables is presented in Table 10.

Table 10

Contribution of place of residence to Litc-Tsu Capability

Model Summary ^b										
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change	Durbin-Watson
1	0.002 ^a	0.000	-0.004	15.013	0.000	0.001	1	259	0.973	1.971
a. Predictors: (Constant), Place of Residence										
b. Dependent Variable: Level of Tsunami Disaster Literacy										

The third result in this study is a unique finding. Although there is a difference of 0.12 in the scores between people who live near the coast and those who live far from the coast, this does not mean that there is a significant positive correlation. We found that there is no significant effect ($0.973 > 0.05$) and that the two variables are not even correlated, or in other words, the correlation is 0%.

Discussion

The youth group is a liaison group for disaster preparedness efforts for families and the surrounding community. Hall et al. (2022) agree with this statement in their study, mentioning that youth groups have a higher absorption capacity for knowledge, which can impact on disaster preparedness actions in their families through information exchange. Several studies support this, in understanding disaster mitigation, a person's perspective is very decisive because impacts the formation of their preparedness actions in decision-making during a disaster. However, if their perspective is wrong, it will result in slow action (Han et al., 2022; Martins & Nunes, 2024). This condition considers socio-demographic factors to be determining factors that can influence the level of litc-tsu among adolescents, but this consensus needs comprehensive empirical confirmation.

Gender Contribution to Litc-Tsu

This study reveals that gender factors have an influence and contribute to Litc-tsu skills among adolescents. These results are in line with previous studies that emphasize gender as a major factor in vulnerability and resilience during disasters (Aryanti & Muhlis, 2020; Hall et al., 2022; Seddighi et al., 2022; Vu et al., 2023; Go, 2024; Mardialina et al., 2024). Mızrak et al. (2021) demonstrated that gender is an important factor that not only influences risk perception but also determines how well people understand disasters, their preparedness, and their vulnerability to tsunami impacts.

Specifically, we found that the Litc-tsu level among women (52%) was higher than that among men (48%). In general, women tend to be more cautious about their safety and care about others. Therefore, this group is more likely to engage in safety procedures that shape their understanding of tsunami preparedness (Brown et al., 2021; Spence & Lachlan, 2011; Zhao et al., 2021). De Silva et al. (2021) mentioned that women often play a key role in conveying warning information to families and communities according to their needs in their study.

However, several studies reject these findings if men have higher disaster literacy than women (Hoffmann & Blecha, 2020; Yusuf et al., 2022). Khan et al. (2021) conducted an investigation of 486 students in Pakistan and found that male groups were better prepared to deal with disasters in emergency situations than female groups. We highlight that women may have a higher fear of certain disaster threats such as tsunamis, earthquakes, floods, landslides, volcanic eruptions, and strong winds (Hall, 2022; Parsons & Lykins, 2023).

They highlight that panic makes them more vulnerable and less alert in emergency situations (Sari & Ridhwan, 2022). It is no surprise that mortality rates are higher among women than men in disaster situations (Kantamaneni et al., 2022; Raheem et al., 2025; Zarook, 2022). Worse still, previous studies have mentioned that women are vulnerable to the long-term effects of disasters, such as a decline in their quality of life and life expectancy, trauma, and difficulties in post-disaster recovery (Fatouros & Capetola, 2021; Sedghi et al., 2025).

In response to this, there is a need for an early warning system that truly meets the needs, including considering gender aspects in the emphasis of the Sendai Framework for Disaster Risk Reduction (UN, 2015). In short, the development of disaster management regulations through education, especially with a focus on preparedness (Mızrak et al., 2021), must incorporate a gender perspective as input from this study so that the strategies developed are more inclusive, successful, and sustainable. It should be emphasized that although women have a satisfactory level of understanding, this is not reflected in their behavior or attitudes; that is, they are still prone to panic. Therefore, we

suggest that preparedness should not only be measured by how much they know but also by their attitudes through targeted socialization programs as a contribution to the findings of this study.

Age Contribution to Litc-Tsu

The results of the study show that understanding of tsunami disasters varies among individuals aged 17 to 21 years (This age is obtained from survey results). This is in line with previous assumptions that age is not the main determinant of tsunami disaster literacy (Litic-Tsu) abilities. In numerical terms, a significance level of 0.399 (greater than 0.05) suggests that age does not significantly affect students' Litc-Tsu abilities. In fact, age only accounts for 0.3%, while the remaining 99.7% is influenced by other, more significant factors. These findings strongly support previous findings such as those of Gülsoy et al. (2025) and Tohan et al. (2024), who agree that there is no correlation between age and Lit-tsu levels and that the older a person is, the less prepared they are to manage disasters. Cerase and Cugliari (2023) add that this relationship is not always proven.

Several previous studies have refuted this if age is a determining factor and has a correlation or influence on Litc-tsu (Genc et al., 2022; Hall et al., 2022; Jayasekara et al., 2023; Khairunnisa et al., 2021; Seddighi et al., 2022; Sun & Sun, 2019; Vu et al., 2023). Sun and Xue (2020) mention that age, educational background, and income together influence attitudes toward disasters, especially in terms of decisions to save oneself and how to view danger. In another context, Mızrak et al. (2021) report that the combination of age and schooling is very beneficial in predicting perceptions of disaster risk, especially among women during earthquakes.

These contrasting results show how complicated it is to view age as a determinant of disaster understanding and risk perception. We must also be aware that this study is limited because it only observed one age group, namely adolescents (17–21 years old), without researching children, adults, or the elderly. As a result, this research cannot provide a complete picture of how age differences can lead to different perspectives and coping strategies when facing the threat of a tsunami. These limitations and gaps provide input for future research and highlight the importance of these findings if it turns out that there are no significant differences between age groups (adolescents).

Place of Residence Contribution to Litc-Tsu

Descriptive analysis shows that students who live closer to the sea have slightly higher Tsunami Disaster Literacy (Litic-Tsu) scores than students who live further away. However, the difference is minimal, only 0.12 points, and there is no clear pattern. Inferentially, statistical tests reveal a significance value of 0.973 (greater than 0.05), which means that place of residence does not have a significant impact on students' Litc-Tsu abilities. The contribution of this variable is only 0.00 percent, indicating that although those who live closer to the sea have slightly higher scores (an average of 0.12), physical distance is not the main determinant of tsunami literacy. This is consistent with several studies, such as O'Neill et al. (2015), which found no correlation between the two variables.

Conversely, previous international research presents different findings. In Norway, Goeldner-Gianella et al. (2017) found that residents in disaster-prone areas showed greater concern and a more accurate understanding of evacuation times than non-local residents. Similarly, research in Chile indicates that people living in tsunami hazard zones report better preparedness than those living outside risk areas (Cisternas et al., 2024). Other researchers have linked proximity to an increased perception of risk, noting that shared memories of past disasters reinforce vigilance among coastal communities (Dhellemmes et al., 2021; Khairunnisa et al., 2021; Vu dkk., 2023; Wei et al., 2017). Arias et al. (2017) even argue that perceived risk decreases with increasing physical distance from the source of the threat. In addition, several studies highlight the close relationship between distance of residence and perceived disaster risk. Perceived risk tends to be higher among people who live near the coast (Dhellemmes et al., 2021; Sherman-Morris et al., 2025) and is shaped by time and collective memories of past disasters (Wei et al., 2017). Arias et al. (2017) further emphasize that proximity to the source of

danger has a positive impact on risk awareness, while perceived risk decreases as the distance from danger increases.

On the whole, although this study did not identify a statistically significant impact of place of residence on Litc-Tsu, small differences in average scores and strong support from previous research suggest that the psychological and social aspects of geographical proximity remain important. However, it should be noted that the proximity we refer to in this study is around the coastal area (approximately ± 1 km). This is a scientific contribution because, at the sub-district level alone, the influence of place of residence and tsunami literacy cannot be ascertained. We suggest that in the future, more specific research be conducted on the participants' places of residence, whether they are actually located on the coast or far from it.

Conclusion

This study provides new evidence for tsunami disaster literacy studies by showing that the impact of socio-demographic factors is not uniform. Of all the elements we studied, gender had the most noticeable influence, with female students demonstrating a better understanding of tsunamis, while age and distance to the sea had no statistically significant effect. The results of the study highlight the level of Litc-Tsu among students (adolescents) measured through more complex socio-demographic characteristics with comprehensive analysis, enabling the findings to contribute to the development of disaster mitigation strategies in the future.

We emphasize several socio-demographic factors that require a disaster education approach that takes gender differences into account. The study found that women play a key role in improving Litc-Tsu before a disaster, although the sample size was limited to adolescents. In addition, age and geographical proximity yielded different findings. We assume that the significance of the age factor cannot be measured in a single group but that children, adults, and the elderly need to be investigated further and that the factor of geographical proximity of residence also needs to be examined specifically, for example, the application of coastal corridors to Litc-Tsu levels. Some of these results greatly support strategies to increase Litc-Tsu in the face of potential disasters, especially among adolescents.

Limitation

This study has limitations, such as the age group measured being limited to teenagers (17–21 years old) and the factor of geographical proximity to the coast not being measured using the coastal corridor principle (± 1 km from the coast) but rather measured by area or city level. Essentially, this measurement was conducted to identify Generation Z (teenagers) and their knowledge of tsunamis.

Suggestion

Based on the limitations we mentioned earlier, we recommend the following:

- 1) Measurements should be taken not only in one group, but in several groups to obtain more specific results.
- 2) The geographical proximity of residences should be limited to coastal corridors (± 1 km from the coast), as this will also yield more specific results.
- 3) We obtained Litc-Tsu levels based on gender, which serves as the basis for further research to address their Litc-Tsu deficiencies through science communication tactics in transforming virtual reality within the metaverse environment. This aims to enhance their mindset toward tsunami simulations and foster awareness of the dangers they face (Gargiulo et al., 2025).

Acknowledgements

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Declaration of Interest

No conflict of interest

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Digital transformation in zoology education: A methodology for training future biology teachers

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ABSTRACT

The digital transformation of higher education has outpaced the methodological readiness of biology teacher training, where generic ICT courses rarely translate into discipline-specific teaching skills. This study develops and evaluates a 16-week “Digital Didactics of Zoology” module. It examined whether embedding digital tools within zoology pedagogy is associated with better outcomes than conventional instruction paired with separate ICT training. A mixed-methods quasi-experiment followed 84 pre-service biology teachers in two intact academic groups, an experimental group receiving the module (n = 42) and a control group receiving conventional teaching with a generic ICT course (n = 42). Data were derived from pre- and post-tests of subject knowledge, a 35-item competence questionnaire, case-based lesson design and micro-teaching tasks, blinded expert ratings, and coded lesson plans and interaction logs. Because (ANCOVA), allocation was not random, post-test scores were compared using analysis of covariance (ANCOVA), adjusting for the pre-test. The experimental condition scored **significantly** higher in zoology knowledge (adjusted difference 9.22 points, 95% CI [7.10, 11.33], d = 1.89) and in digital didactic competence (20.53 points, 95% CI [17.89, 23.17], d = 3.38) and higher on lesson quality (g = 1.54) and expert evaluations (g = 2.48). An exploratory structural equation model (SEM) fitted to the full sample (CFI = .994, RMSEA = .060, SRMR = .027) associated digital proficiency with pedagogical reasoning ($\beta = .71$, bootstrap 95% CI [.55, .83]); this association appeared in both conditions, and the two estimates were not compared formally. The module provides teacher-education programs with a transferable design for technology-integrated zoology instruction, pending replication across institutions.

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Introduction

Digital transformation has reshaped teaching across higher education, yet biology sits awkwardly within this shift. The subject matter of biology is visual and dynamic, spanning scales from the cell to the ecosystem (Neumann & Waight, 2020; Tanner & Allen, 2006). In particular, zoology requires students to build spatial models of anatomy (Sharmin et al., 2023), weigh the ethical implications of dissection (Ormandy et al., 2022), and identify and monitor organisms in the field. Generic educational technology does not, on its own, meet these discipline-specific demands.

Teacher-preparation programs tend to leave a technological-pedagogical disconnect (de Oliveira et al., 2019; Jensen, 2011). Pre-service teachers acquire general digital literacy (presentation software, learning-management systems) yet often lack the Technological Pedagogical Content Knowledge (TPACK) to fold discipline-specific tools such as virtual laboratories, GIS, or AI identification apps into inquiry-based lessons (Irdalisa et al., 2022; Jiménez Sierra et al., 2023; Valtonen et al., 2020). The disconnect widens where ICT training runs separately from disciplinary content (Hajiyeva, 2021), a pattern common in rapidly digitalizing systems in Central Asia, including Kazakhstan (Abiltayeva et al., 2025; Smagulova & Kalieva, 2025), as well as in other developing contexts (Chisingui & Costa, 2020; Diem et al., 2024). Where technology is added as a supplement rather than used as a way of knowing, adoption stays fragmented, and student outcomes change little.

This study adopts a distinct approach. Rather than treating digital skills as an isolated competence, it embeds them directly within the pedagogy of zoology, ensuring that each tool is acquired through the specific educational challenge it addresses: AI-driven identification to address the constraint that routine species determination places on field and classroom work (Gaston & O'Neill, 2004; Wäldchen & Mäder, 2018), virtual dissection to navigate the ethical and practical constraints of specimen work (Telecan et al., 2025), and GIS alongside 3D modeling to overcome the difficulties of representing space and scale. The novelty lies not in the familiarity of the individual tools but in their integration into a single evaluated module, which is rigorously tested against an active control group that receives identical zoological content coupled with a separate, conventional ICT course. This design effectively isolates the impact of situating technology within a specific discipline – highlighting the distinction between merely knowing a tool and understanding how to use it to instruct.

The primary objective of this research is to develop a discipline-specific "Digital Didactics of Zoology" module and experimentally validate it against traditional zoology instruction supplemented by generic ICT training. In this context, validation entails a controlled comparison: the module is evaluated not by student engagement with digital tools, but by whether embedding these technologies within zoological pedagogy yields measurable learning outcomes that standalone ICT courses fail to produce. Four research questions guide the analysis:

RQ1. Does the module produce larger gains in zoology subject knowledge than conventional instruction with separate ICT training?

RQ2. Does it raise digital didactic competence, understood as the capacity to select, adapt, and troubleshoot digital tools for specific zoology topics?

RQ3. Does it improve pedagogical readiness and the quality of technology-integrated lesson design?

RQ4. Within the experimental condition, are pre-service teachers' digital-tool proficiencies directionally linked to their pedagogical reasoning?

The hypotheses are directional. H1–H3 predict higher post-intervention performance in the experimental group for subject knowledge, digital didactic competence, and pedagogical quality, respectively. H4 predicts that proficiency with specific tools (3D manipulation, GIS analysis, and virtual experimentation) is positively associated with domain-matched pedagogical reasoning, rather than standing apart as an isolated technical skill.

Literature Review

TPACK in Biology Education

Digital tools, such as virtual laboratories and 3D models, enhance engagement and retention in zoology (Sautière et al., 2019). However, their integration into teacher preparation remains uneven, particularly in disciplines where pedagogy must align with subject-specific affordances (Ambarwati et al., 2019). The TPACK framework was developed to close this gap by treating effective technology use not as a standalone skill, but as the intersection of content, pedagogical, and technological knowledge. Under this framework, a biology teacher must understand how a particular tool represents phenomena that are otherwise abstract or invisible (Jiménez Sierra et al., 2023). Teachers with well-developed TPACK integrate inquiry and higher-order thinking more effectively than peers who are digitally literate but pedagogically untrained (Valtonen et al., 2020). The shortfall is specific rather than general. Among 102 science teachers, the design dimension of TPACK was the weakest, use stayed at the level of smart boards and presentation software, and insufficient infrastructure and inadequate training were named as the obstacles to deeper integration (Dinçer, 2024).

Furthermore, recent research on interdisciplinary zoology instruction notes that teachers now need to connect biological, computational, and environmental reasoning simultaneously (Anapana et al., 2025). This logic is discipline-bound; for instance, the reasoning required to teach habitat mapping with GIS differs significantly from that needed to run a cell-division simulation (Neumann & Waigh, 2020). Consequently, teacher preparation programs that treat digital competence as supplementary rather than foundational leave this specialized reasoning undeveloped (Hsu et al., 2023; Pererva et al., 2020). This broader trend is documented in a systematic review of ten years of mobile learning in biology education. By screening 1,315 records and analyzing 66 records, Sangur et al. (2025) reported steady growth in mobile tool usage, primarily for visualizing biological concepts and supporting practical work.

Virtual Laboratories and Ethical Alternatives

Virtual dissection is adopted for two reasons: one ethical and one methodological. Ethically, it removes the need to euthanize animals for single-use study; a meta-analysis in *The American Biology Teacher* found that non-animal methods matched or outperformed traditional dissection in most comparisons and eased the discomfort some students feel with real specimens (Ormandy et al., 2022), which supports the 3R principle (replacement, reduction, and refinement). Methodologically, a virtual specimen can be cut, undone, and recut without limit, whereas a physical specimen can be used only once and cannot be restored (Kavvadia et al., 2023). Because a mistaken incision no longer destroys the material, students practice to fluency, and their ability to isolate and rotate organ systems in three dimensions improves their performance on anatomical tests over wet specimens (Telecan et al., 2025). A randomized trial in medical anatomy teaching points in the same direction: students who worked through a virtual dissection before the gross dissection performed better on the subsequent anatomy test than those who prepared from textbooks, although the difference fell short of conventional significance (Boscolo-Berto et al., 2021).

Visualization Technologies: 3D, AR, and VR

Traditional zoology teaching represents three-dimensional structures through flat diagrams, forcing students to reconstruct spatial relationships in their working memory. Learners with weaker spatial ability struggle the most, and their early misconceptions tend to persist (Anniesmitha et al., 2025; Sharmin et al., 2023). Interactive 3D, AR, and VR technologies shift this cognitive reconstruction into the interface; features such as rotation, isolation, and cross-sectioning supply the depth cues that static atlases lack (Reinke et al., 2021). Furthermore, manipulating objects in virtual space engages spatial

perception processes more effectively than their 2D equivalents (Tung & Chang, 2024). Immersive environments also lower extraneous cognitive load by allowing learners to explore anatomy from the inside out (Kim & Choi, 2025; Majewska & Vereen, 2023). Meta-analytic evidence for AR in biology demonstrates higher engagement and conceptual understanding, with the largest gains observed in students who begin with weak spatial reasoning. Consequently, this technology narrows rather than widens the performance gap (Sattar et al., 2025). Even so, its adoption in teacher-preparation curricula remains in the early stages, and few programs integrate these tools with subject-specific pedagogy within a single framework (Biletska et al., 2021).

Geospatial and AI-Based Tools in Field Zoology

Two of the four tool families in the module address learning outside the laboratory, where the object of study is a distribution rather than a structure. Direct evidence on geospatial tools in biology teacher preparation remains scarce, and the relevant findings come largely from geography education at the school level, so they are read here as an adjacent rather than a direct evidence base. Web GIS makes demographic and distributional data workable in school inquiry, and it carries an evaluative requirement with it: because these platforms accept contributions from anyone, the layers on offer range from undocumented to authoritative, so provenance has to be checked before a map is used for teaching (Kerski, 2019). Reviewing 36 empirical studies of inquiry teaching with geospatial technologies, Mašterová (2023) reports that students develop both digital competence and knowledge of the topic addressed through the tool, but that prior teacher preparation is a condition for this outcome rather than an accompaniment to it. There is also evidence that geospatial reasoning is a construct in its own right and not a by-product of exposure to maps: in a sample of 1,037 upper-secondary students, geospatial thinking partially mediated the relationship between family capital and achievement in geography, accounting for 24.68% of the total effect (Zhang et al., 2023).

Species identification is itself an object of teaching, and the skills it calls for are treated in biology education as a prerequisite for understanding biodiversity and ecology, with the choice of specimens, keys, and preparatory classroom work shaping what pupils take from a field task (Randler, 2008). Competence in teaching this material is itself built rather than assumed: across 151 pre-service science teachers, both knowledge of biodiversity and perceived competence to teach it rose with the amount of content and pedagogical coursework completed (Tergenbayeva et al., 2023). The identification tools raise a parallel question about evaluating output. Platforms such as iNaturalist pair automated suggestion with community verification, and that verification is partial in practice; of some 445,000 observations recorded in one state-level review, about 40% had reached verified Research Grade status, and less conspicuous organisms were underrepresented (Baker et al., 2023). A PRISMA review of iNaturalist in biology education finds uses clustered around BioBlitz activities, outdoor education, and herbarium work, and closes with guidelines for preparing the application for school use (Rode & Torkar, 2023). Drawing on interviews with 31 participants aged 7 to 20, Herodotou et al. (2024) identify the forms of online and field participation that support science learning rather than data collection alone, and set out a blended framework for biodiversity monitoring on that basis. Reviews of artificial intelligence in biology education record steady growth in reported applications alongside uneven topic coverage and few studies of AI-supported games and simulations (Duran & Dikmenli, 2025). Both lines converge on the competence this module treats as the object of instruction rather than its precondition, since an automated identification is a provisional taxonomic claim that a teacher must be able to test against diagnostic characters before it enters a lesson.

Contextual Factors in Teacher Education

What “digital competence” means is also shaped by policy and setting. General practice tends to overlook the epistemic particularities of scientific disciplines, thereby limiting its practical effect (Garzón-Artacho et al., 2021; Nietbaeva, 2023). Biology teacher education in Central Asia faces a dual

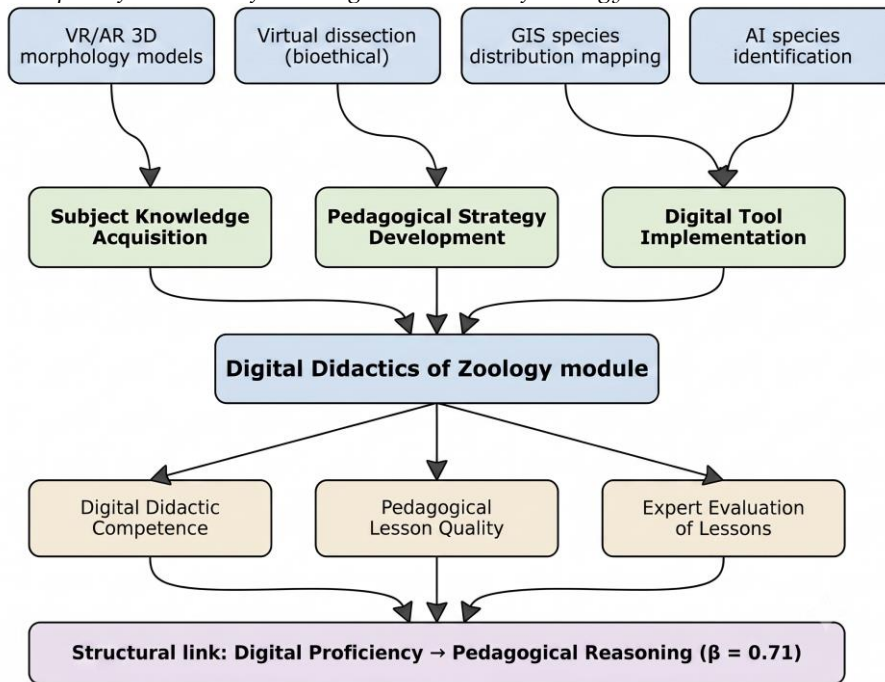
task: raising overall digital literacy while preparing teachers for subject-specific tools. Work in Kazakhstan reports a strong policy commitment to digital transformation, alongside methods courses in which digital tools remain peripheral or are used only for presentation purposes (Abiltayeva et al., 2025; Smagulova & Kalieva, 2025). Similarly, research in Angola links technology-enhanced biology teaching to sustainability goals while noting the same absence of systematic, subject-focused training (Chisingui & Costa, 2020).

Assessing Digital Competence and Its Limits

Teachers' digital competence has mostly been assessed with TPACK and DigCompEdu, the latter specifying 22 competences across six areas (Ghomi & Redecker, 2019), and these frameworks underlie many self-report surveys (Tzafilkou et al., 2023). Adaptations for biology capture self-reported data literacy, content creation, and tool use; the Kazakhstani study cited above, for example, found moderate technological knowledge and positive attitudes, but little experience with virtual laboratories or interactive animal biology resources (Abiltayeva et al., 2025). The problem is that these instruments are domain-agnostic. They distinguish broad categories of competence but not, say, using a presentation tool from facilitating inquiry with a virtual dissection platform. Furthermore, they lean on access, frequency, and self-efficacy rather than on discipline-specific practice, such as modeling ecological systems or interpreting structure–function relationships (Adhani & Nursia, 2024). A candidate can therefore score high on a general scale while being unable to orchestrate a technology-rich zoology lesson. Recent work instead calls for context-based competence, measured through tasks that reflect authentic zoology teaching and are tied to taxonomy, morphology, physiology, and behavior rather than to tools treated as interchangeable (Kang et al., 2024; Nurbaya, 2023; von Kotzebue, 2022). Validated zoology-specific instruments of this kind remain scarce. Standards documents describe the same territory in equally general terms, the ISTE standards for teachers being a long-established example (International Society for Technology in Education [ISTE], 2002). Reviews of digital pedagogy reach that conclusion from the research side: surveying the literature, Vääätäjä and Ruokamo (2021) separate pedagogical orientation, pedagogical practice, and digital competence as three dimensions of digital pedagogy, none of which is specified for a particular subject.

Conceptual Framework

These strands converge on a single design problem: how to embed digital competence within specific disciplines rather than treating it as a generic skill. Figure 1 sets out the conceptual framework that guided the module. It is structured around three components that the literature traditionally treats as distinct, but which the module integrates: subject-knowledge acquisition, pedagogical-strategy development, and digital-tool implementation. Each digital tool is introduced through the specific pedagogical problem it addresses; for instance, AI identification is contextualized against the constraint of routine species determination, virtual dissection against the limitations of specimen work, and GIS and 3D models against the challenges of representing space and scale. These three components inform the module, whose impact is evaluated through three measured outcomes: digital didactic competence, pedagogical lesson quality, and expert-rated lesson design. The framework also posits the relationship tested in RQ4: that proficiency with discipline-specific tools and pedagogical reasoning covary, rather than developing as unrelated, parallel skills. This study operationalizes this framework and tests it against an active control group.

Figure 1*Conceptual framework of the “Digital Didactics of Zoology” module*

Methods

Research Design and Participants

The study used a mixed-methods quasi-experimental design with pre- and post-testing. The quantitative and qualitative strands were conducted over the same period and given equal weight, and their results were integrated at the interpretation stage, making the design convergent. The qualitative material was collected alongside the outcome measures rather than after them, and its role was to describe how lesson design differed between the two conditions, not to generate hypotheses for later testing. Integration is located in three places: the coding frame in Table 3, which reports code frequencies separately by condition; the paragraph on archived lesson plans in the Results section, where rubric scores and coded artifacts are read against each other; and the Discussion section, where each research question is answered from both strands.

Fieldwork ran throughout the 2022–2023 academic year at a public pedagogical university during the fourth semester, when the core zoology course is taught. Participants were 84 preservice biology teachers in the second year of the teacher-education program. Eligibility required current enrolment in the zoology course and in the teacher-education track. No further exclusion criterion was applied. The program admits only full-time students, so no part-time or distance learners had to be excluded, and the two parallel groups taking the course that semester therefore constituted the entire eligible population rather than a sample drawn from it. All 84 students in those groups provided consent and completed both measurement points, so 84 cases were included in the analysis. There was no attrition, exclusion after allocation, or missing observations on any measure; therefore, no imputation was required. The term “preservice biology teachers” is used throughout for this group.

The assignment was made at the level of intact academic groups rather than at the level of individual students. The two groups that took the zoology course in parallel were assigned to the experimental and control conditions, with one group to each, yielding 42 participants per condition.

Allocation was therefore not random, which is why the design is described as quasi-experimental and why no randomization procedure is claimed. Because allocation was not random, comparability at entry was examined rather than assumed. Table 1 reports standardized mean differences with confidence intervals for age, grade-point average, baseline ICT skills, both pre-tests, and the baseline expert rating. The largest standardized difference was 0.12, and every interval included zero; however, intervals of this width with 42 cases per condition do not establish equivalence, so the primary analyses adjust for the pre-test rather than rely on baseline balance.

Both conditions were taught by the same instructor and received the same number of contact hours, one 90-minute session per week for 16 weeks, and the same assessments, which held instructor effects and time-on-task constant. The control group did not take the digital instruction. It received a generic ICT course of equivalent length in the same semester, covering office applications, work in the learning-management system, information search and processing, and the general methodology of e-learning, none of it tied to biological content. The contrast is therefore between discipline-embedded and generic digital preparation rather than between digital preparation and none.

Two design features guard the final performance task against favoring the experimental condition by construction. Both conditions completed the task in the same virtual laboratory environment and received the same introductory session on the environment beforehand, so familiarity with the assessment platform did not differ between conditions. The task itself asked for a diagnostic biological problem to be solved rather than for a particular tool to be operated, which keeps the outcome at the level of reasoning rather than of tool fluency. The experimental condition nevertheless had longer exposure to tools of this class over the term, and the Limitations section returns to what that implies.

No procedural measure was taken to keep the two conditions apart during the term, and in ordinary timetabled teaching, neither temporal nor spatial separation was available. What limited the exchange of materials was the absence of salience rather than any barrier: no group was described to its members as receiving special treatment, and no attention was drawn to particular elements of a lesson, so those elements were taken as an ordinary part of the course and gave students little reason to pass them to peers in the parallel group. Exchange was possible and cannot be ruled out, and the Limitations return to it. As part of informed consent, participants in both conditions were told that two versions of the course were being compared, without being told which version was expected to perform better. Implementation fidelity was monitored with a weekly checklist, on which the instructor recorded which planned elements of each session had actually been delivered; this self-report was cross-checked against non-participant observation of one session in four by a member of the research team who taught neither condition. Observation focused on the sessions in which the module prescribed a specific digital tool, since that is where any departure from the plan would matter most, and the visits were conducted in the format of the scheduled peer classroom visits that the department carries out in any case. Keeping them in that familiar format was deliberate: singling those sessions out as part of a study would have made students self-conscious and changed the very teaching the observation was meant to record. Adherence exceeded 90% across the term.

The study was conducted within the regular curriculum of the zoology course. It involved no procedure beyond the teaching and assessment methods ordinarily used in the program, no biomedical or clinical intervention, and no collection of sensitive personal data, and it was not submitted to a separate research-ethics committee. Participation was voluntary, and all participants gave written informed consent after being told the purpose of the study, the procedures involved, and their right to decline or to withdraw at any point; no course grade or academic standing depended on participation, and students who had not consented would have followed the same course without their data being used. Responses were pseudonymised at collection, stored on institutional servers with access restricted to the research team, and are reported only in aggregate, so that no individual participant can be identified from anything published here.

Table 1*Participant characteristics and comparability of the two conditions at entry (N = 84)*

Characteristic	Experimental (n = 42)	Control (n = 42)	g [95% CI]
Male, n (%)	7 (16.7)	6 (14.3)	RD 0.02 [-0.13, 0.18]
Female, n (%)	35 (83.3)	36 (85.7)	
Age, years	19.40 (0.90)	19.50 (0.80)	-0.12 [-0.55, 0.31]
Grade-point average (max 4.0)	3.42 (0.31)	3.38 (0.35)	0.12 [-0.31, 0.55]
Baseline ICT score (0–100)	62.50 (8.40)	61.80 (9.10)	0.08 [-0.35, 0.51]
Zoology knowledge pre-test (0–100)	44.80 (7.09)	45.30 (6.80)	-0.07 [-0.50, 0.36]
Digital didactic competence pre-test (0–100)	41.50 (8.20)	42.10 (7.90)	-0.07 [-0.50, 0.35]
Baseline expert rating (1–5)	2.90 (0.60)	2.90 (0.60)	-0.00 [-0.43, 0.43]

Note. Values are M (SD) unless marked otherwise. The final column gives Hedges' g for the standardized difference between conditions with its 95% confidence interval; a positive value favours the experimental condition. For sex the entry is the difference in the proportion of men, $\chi^2(1) = 0.09$, $p = .763$, Cramér's V = .03. Intervals that include zero do not establish equivalence at entry, which is why the primary analyses adjust for the pre-test.

Intervention Structure

The experimental group worked through a 16-week module built on the three components of the conceptual framework (Figure 1): subject-knowledge acquisition, pedagogical-strategy development, and digital-tool implementation. Each weekly session paired a short theoretical input with a hands-on workshop using one tool family: (1) virtual dissection laboratories with haptic feedback; (2) VR/AR-enabled 3D animal-morphology models; (3) GIS-based species-distribution mapping; and (4) AI-driven species-identification applications.

A week-by-week comparison of the experimental and control syllabi is given in Appendix A, and a sample worksheet for each tool family is provided in Appendix B so that the practical form of the intervention can be inspected directly. The control group covered the same zoology content through lectures, textbook study, and physical-specimen work, with the generic ICT sessions kept separate from the biology curriculum.

Assessment Framework and Instruments

Competence was assessed in three domains, each with a dedicated instrument. Descriptive statistics (pre- and post-intervention means and standard deviations) for every domain are reported in Table 2 before the inferential analysis.

Subject knowledge was measured with a 40-item test that combined multiple-choice questions on taxonomy, anatomy, and ecology with four open-ended items requiring students to translate a biological concept into a teaching task (for example, outlining how they would explain insect metamorphosis to a mixed-ability class). Three zoology educators rated every item for relevance to establish content validity; items with a content-validity index below 0.80 were revised or removed. Internal consistency was acceptable (Cronbach's $\alpha = .82$). Two raters scored the open-ended items independently against an analytic rubric (Appendix C), with high agreement (ICC = .89).

Digital didactic competence was measured with a 35-item questionnaire ($\alpha = .87$) spanning three subscales: appropriateness of tool selection for a given zoology topic (5-point Likert items), depth of pedagogical rationale in short written responses, and technical troubleshooting in scenario items. Sample items and the scoring key appear in Appendix C.

Pedagogical readiness was assessed through case-based tasks. Students responded to authentic classroom scenarios with a lesson plan, a 10-minute micro-teaching episode, and a peer-review exercise. Lesson plans and micro-teaching were scored with analytic rubrics covering conceptual accuracy, pedagogical appropriateness, technological integration, and accessibility (Appendix C). Two trained raters worked from the same rubric. Before scoring began, they went through it together on several sample pieces of work, comparing their judgements and settling differences of interpretation, and only

then scored independently. Approximately 20% of the material was scored by both raters, that is, 34 of the 168 lesson plans and 17 of the 84 micro-teaching episodes, and the remainder was scored by one rater. Raters worked from anonymised material and did not know which condition a plan or episode came from, who had written it, or whether it belonged to the pre- or the post-intervention set, and they were not told the hypotheses of the study. Blinding to condition was imperfect in one respect that should be stated plainly: a lesson plan from the experimental condition often names a specific digital tool, so a rater could sometimes infer the condition from the content of the plan even with every label removed. Agreement on the doubly scored material was satisfactory. For the open-ended subject-knowledge items the intraclass correlation was .89, from a two-way mixed-effects model for absolute agreement with single measures; the two raters being the only raters of interest rather than a sample of raters. The ordinal rubrics gave $\kappa = .84$ for lesson plans and $\kappa = .81$ for micro-teaching; these are unweighted coefficients, and the limitations note that a weighted coefficient would suit an ordinal rubric better.

Data Collection Procedures

Baseline data were collected in week 1, and outcome data in the week after the module ended. Before the main study, all instruments were piloted with a separate group of 20 students to assess clarity and timing, and minor wording changes followed. Throughout the term, students' instructional artifacts (lesson plans, virtual-reality models, reflective notes) were archived, together with interaction logs from the virtual-laboratory sessions, for the qualitative strand.

Qualitative Analysis

The qualitative strand examined why the two conditions designed lessons differently. Its sources were the written comments of the three expert evaluators, the 168 lesson plans, and the virtual-laboratory interaction logs. The 168 plans are one plan per participant at each of the two measurement points, 84 before and 84 after the module, so the two conditions contribute equally to the corpus, and percentages reported for lesson features use the 42 plans of the relevant condition and measurement point as their denominator. Interaction logs are available for every session the experimental condition attended and for the final performance task, which both conditions completed, and only the logs of that shared task are used for comparison between conditions. The quotations attributed to experts come from the evaluators' written comments on individual lessons. Micro-teaching episodes were rated with the same rubric as the plans but were analysed separately, and their ratings entered the pedagogical-readiness measure rather than the plan corpus. The unit of analysis was the idea-bearing segment. Two researchers coded a common set of 40 plans to build a codebook, then coded the full corpus independently, resolving disagreements by discussion. The codebook was fixed before the full corpus was coded, and three of the codes record the absence of a practice rather than its presence so that the frame could register evidence running against the expected direction. Both coders are authors of this study and took part in designing the module. That gave them the disciplinary and pedagogical knowledge the coding required and, at the same time, an interest in what the coding would show, and the safeguards described here follow from the second of those facts as much as from the first: the counter-codes were introduced deliberately, the codebook was closed before the corpus was opened, coding was carried out on anonymised material, and the frequency of every code in each condition is published in Table 3, so that a reader can weigh the frame itself rather than take the interpretation on trust. Coding yielded 14 descriptive codes across 312 segments, which were grouped into four themes: contextualisation of technology, inquiry orientation, accessibility, and conceptual precision. Intercoder reliability was acceptable (Krippendorff's $\alpha = .82$). Frequencies from the rubric-based expert ratings and the interaction logs are reported quantitatively in the Results; the thematic analysis interprets those patterns and is illustrated with representative excerpts. The full coding frame, with the frequency of every code in the two groups, is reported in Table 3.

Analytical Approach

Quantitative analysis was carried out in IBM SPSS Statistics 26, with the structural model estimated in the *semopy* package for Python and bootstrap intervals obtained in the same environment. Four outcomes were designated primary: zoology subject knowledge, digital didactic competence, pedagogical lesson quality, and the blinded expert evaluation. Every other comparison reported below, including the subscale contrasts and the structural model, is exploratory and is labelled as such where it appears. Familywise error across the four primary contrasts is controlled with the Holm procedure. Confidence intervals are 95% throughout unless stated otherwise, and bootstrap intervals use 2,000 resamples.

For the two outcomes with a pre-test on the same scale, the primary between-group model is an analysis of covariance with the post-test score as the dependent variable, the pre-test score as the covariate, and condition as the fixed factor. This model replaces the comparison of gain scores used in the previous version. The reason is the allocation procedure: with intact groups rather than randomisation, adjustment for the pre-test is required rather than optional. Homogeneity of regression slopes was tested by adding the interaction of condition and covariate, and the residuals were examined with the Shapiro–Wilk test and Levene’s test; the outcome of each check is reported with the model it belongs to. Adjusted means with their intervals, the adjusted difference with its interval, partial eta squared, and the standardised adjusted difference are reported for every model. Gain-score comparisons are retained as sensitivity analyses.

Pedagogical lesson quality was measured only after the intervention, so no covariate is available for it, and it is compared with Welch’s t-test; for the same reason, no change over time is claimed for that outcome, only a difference between conditions at the end of the module. The expert evaluation is also reported with Welch’s t-test, because its residual variances differed by condition and its baseline rating carried no information about the outcome, which makes the covariance model inappropriate for it; the analysis of covariance was run for that outcome as a check and led to the same conclusion. Both are accompanied by the mean difference and Hedges’ *g*, each with an interval. Within-condition change from pre-test to post-test is reported with paired-samples t-tests, the mean change with its interval, and the standardised mean change. Where a parametric assumption failed, the Mann–Whitney U test is reported alongside the parametric result, with the convention for U stated explicitly and with rank-biserial correlation and Cliff’s delta as effect sizes.

Research question 4 was addressed with a structural equation model, which is reported as exploratory. Two latent variables were specified: Digital Proficiency, indicated by 3D-manipulation, GIS-analysis, and virtual-experimentation scores, and Pedagogical Reasoning, indicated by spatial-reasoning, ecosystem-teaching, and inquiry-lesson scores. A single structural path linked the first construct to the second. The model is deliberately parsimonious, with six indicators, two factors, and thirteen free parameters, and estimation used maximum likelihood on the full sample. Because 84 cases are modest for covariance-based modelling, fit is reported with the full index set recommended for small samples rather than with a single statistic, and the structural coefficient is accompanied by a percentile bootstrap interval. The coefficient was also estimated separately within each condition, but the two estimates are reported side by side as descriptive information only: a formal comparison would require a multi-group model with measurement invariance established across conditions, which 42 cases per condition will not support, and no such comparison is made. Because tool proficiency and pedagogical reasoning were measured at the same point in time, the model is read as a set of associations, and no temporal or causal ordering is inferred from it.

The qualitative and quantitative strands were then read against each other so that the test and survey results, the rubric scores, and the coded artifacts could corroborate or qualify one another.

Results

Results are organised by research question. Table 1 reports comparability at entry, and Table 2 reports descriptive statistics for every domain together with the between-group comparisons, so the data can be read before the inferential detail. The experimental condition scored higher on all four questions, although the size of the difference varied. Because allocation was not random and the measures within a wave were taken at the same time, the findings are stated as differences between conditions and as associations, and no causal or temporal ordering is claimed.

Table 2

Outcomes by condition, with within-condition change and between-condition comparisons

Outcome and condition	Pre M (SD)	Post M (SD)	Change M [95% CI]	Adjusted post M [95% CI]	Between-condition comparison
Subject knowledge (0–100), Experimental	44.80 (7.09)	73.20 (7.57)	28.40 [26.78, 30.02]	73.40 [71.91, 74.90]	$F(1, 81) = 75.02, p < .001, d = 1.89, \eta^2p = .481$
Control	45.30 (6.80)	64.39 (7.36)	19.09 [17.60, 20.59]	64.19 [62.69, 65.68]	
Digital didactic competence (0–100), Experimental	41.50 (8.20)	76.71 (11.18)	35.21 [33.09, 37.33]	77.02 [75.16, 78.89]	$F(1, 81) = 239.55, p < .001, d = 3.38, \eta^2p = .747$
Control	42.10 (7.90)	56.81 (9.64)	14.71 [13.09, 16.33]	56.49 [54.63, 58.36]	
Pedagogical lesson quality (1–5), Experimental	–	4.18 (0.57)	–	–	$t(74.2) = 7.14, p < .001, g = 1.54 [1.06, 2.03]$
Control	–	3.10 (0.80)	–	–	
Expert evaluation (1–5), Experimental	2.90 (0.60)	4.46 (0.44)	1.56 [1.31, 1.81]	–	$t(68.9) = 11.46, p < .001, g = 2.48 [1.91, 3.05]$
Control	2.90 (0.60)	3.00 (0.70)	0.10 [–0.20, 0.40]	–	

Note. Values are M (SD) unless marked otherwise; – marks a quantity that does not exist for that outcome. Change is the paired difference from pre-test to post-test. Adjusted post-test means come from an analysis of covariance with the pre-test as covariate and condition as fixed factor, and the effect size in those rows is the standardized adjusted difference with partial eta squared. Pedagogical lesson quality has no pre-test, and the expert evaluation had unequal residual variances with an uninformative covariate, so both are compared with Welch's t-test and reported with Hedges' g. The digital-competence contrast was confirmed without distributional assumptions on the gain scores, $U = 1742$ for the experimental relative to the control condition, $p < .001$, rank-biserial $r = .97$. All four primary contrasts remain significant after Holm correction.

RQ1 Subject Knowledge

Scores rose in both conditions between the pre-test and the post-test (experimental M change = 28.40, 95% CI [26.78, 30.02], $t(41) = 35.38, p < .001, d_z = 5.46$; control M change = 19.09, 95% CI [17.60, 20.59], $t(41) = 25.77, p < .001, d_z = 3.98$). With the pre-test entered as a covariate, the adjusted post-test mean was 73.40, 95% CI [71.91, 74.90], in the experimental condition against 64.19, 95% CI [62.69, 65.68], in the control condition, an adjusted difference of 9.22 points, 95% CI [7.10, 11.33], $F(1, 81) = 75.02, p < .001$, partial $\eta^2 = .481, d = 1.89$. The model assumptions held: the regression slopes did not differ by condition ($p = .821$), and the residuals were normally distributed ($p = .762$) with homogeneous variances ($p = .816$). The gain-score comparison retained as a sensitivity analysis leads to the same conclusion (difference = 9.30, 95% CI [7.13, 11.47], $g = 1.84$). The difference was widest on application items that asked students to combine biological content with a teaching strategy (experimental M change = 32.7 against control M change = 18.9). Higher accuracy on anatomical-reasoning items (87% against 62%) and on ecological-system modelling (79% against 54%) locates the difference in spatial and systems reasoning rather than in recall alone.

RQ2 Digital Didactic Competence

Scores rose in both conditions (experimental M change = 35.21, 95% CI [33.09, 37.33], $t(41) = 33.54$, $p < .001$, $d_z = 5.18$; control M change = 14.71, 95% CI [13.09, 16.33], $t(41) = 18.34$, $p < .001$, $d_z = 2.83$). Adjusted for the pre-test, the post-test mean was 77.02, 95% CI [75.16, 78.89], against 56.49, 95% CI [54.63, 58.36], an adjusted difference of 20.53 points, 95% CI [17.89, 23.17], $F(1, 81) = 239.55$, $p < .001$, partial $\eta^2 = .747$, $d = 3.38$. The regression slopes were homogeneous ($p = .737$), and the residual variances did not differ ($p = .055$), but the residuals departed from normality ($p < .001$), so the contrast was repeated without distributional assumptions. On the gain scores, the Mann–Whitney test gives $U = 1742$ for the experimental relative to the control condition, the complementary statistic being 22 of a possible 1,764, $p < .001$, with rank-biserial $r = .97$ and Cliff's delta = .97, 95% CI [0.91, 1.00]. The gain-score t-test agrees (difference = 20.50, 95% CI [17.87, 23.13], $g = 3.36$). All three subscales moved in the same direction, with tool selection changing by 38.1 points against 12.3, depth of pedagogical rationale by 33.8 against 11.9, and technical troubleshooting by 31.5 against 9.4; these subscale contrasts are exploratory and are not corrected for multiplicity. The difference was clearest where a scenario required adapting a resource for diverse learners (82% against 43% optimal responses) or aligning a tool with a stated objective (78% against 37%). The size of this difference is large by any benchmark, and the discussion treats its magnitude with corresponding caution.

RQ3 Pedagogical Readiness and Lesson Quality

Lesson-plan quality was measured only after the intervention, so the comparison for that outcome is between conditions at the post-test, and no improvement over time is claimed for it. Quality was higher in the experimental condition ($M = 4.18$, $SD = 0.57$) than in the control condition ($M = 3.10$, $SD = 0.80$), a difference of 1.08 points, 95% CI [0.78, 1.39], Welch $t(74.2) = 7.14$, $p < .001$, $g = 1.54$, 95% CI [1.06, 2.03]. Blinded expert ratings favoured the same condition ($M = 4.46$, $SD = 0.44$ against $M = 3.00$, $SD = 0.70$), a difference of 1.46, 95% CI [1.21, 1.71], Welch $t(68.9) = 11.46$, $p < .001$, $g = 2.48$, 95% CI [1.91, 3.05]. The expert evaluation, unlike lesson-plan quality, does have a baseline rating, and it was the same in the two conditions ($M = 2.90$, $SD = 0.60$). Over the term, that rating changed in the experimental condition (M change = 1.56, 95% CI [1.31, 1.81], $t(41) = 12.45$, $p < .001$) and did not change in the control condition (M change = 0.10, 95% CI [-0.20, 0.40], $t(41) = 0.66$, $p = .512$). The expert rubric separated the conditions on all four criteria: conceptual accuracy (92% against 78%), pedagogical appropriateness (88% against 65%), technological innovation (85% against 42%), and accessibility (76% against 39%). All four primary contrasts remain significant after the Holm correction.

The 168 archived lesson plans, one from each participant before and after the module, differed in kind and in degree. Control-condition plans leaned on static assets such as slides and PDF worksheets, whereas experimental-condition plans used dynamic 3D exploration in 42 of the 42 plans, GIS habitat analysis in 72%, AR dissection in 64%, and AI identification in 57%. In 83% of experimental-condition plans, a tool choice was tied to a learning-design principle such as cognitive load or multimedia learning, against 27% in the control condition. Interaction logs from the final performance task, which both conditions completed in the same environment after the same introductory session, point the same way. Participants in the experimental condition manipulated tools more often (14.7 against 6.2 actions per session), annotated more (82% against 31% of sessions), and tested hypotheses more (68% against 21%).

The thematic analysis organised these differences into four themes. Under contextualization of technology, reviewers noted that experimental-group lessons connect a 3D model to a specific misconception about limb homology rather than showing it for its own sake. Under inquiry orientation, they described tasks that ask students to predict an outcome and then check it against the virtual specimen. Accessibility and conceptual precision separated the groups less sharply but in the same direction. Representative excerpts are given in Appendix D. Table 3 reports the coding frame in full, including the three counter-codes that record the absence of a practice.

Table 3*Coding frame for the qualitative strand: themes, codes, and segment frequencies by group*

Theme / Code	Description	Segments	EG	CG
Contextualization of technology	Whether the digital tool is anchored in a specific biological idea or is present for its own sake.	96	63	33
Tool tied to a specific misconception	The plan names a known student error and introduces the tool at the point where that error arises, so that the representation does conceptual work the explanation alone cannot.	31	24	7
Representation matched to conceptual difficulty	The choice of representation follows from a property of the content, such as its three-dimensionality, its dynamics, or its spatial scale, and the plan states why a static image would not serve.	26	19	7
Tool used for display only (counter-code)	The tool appears without a learning task attached, and removing it would leave the lesson unchanged. Coded whenever the technology carries a presentational rather than an explanatory function.	22	7	15
Placement of the tool in the lesson sequence	The plan fixes when the tool enters, as a problem posed before the explanation, an illustration after it, or a check on understanding, and justifies that position.	17	13	4
Inquiry orientation	Whether the task positions the student as the one who asks and tests, or as the recipient of a demonstrated result.	88	58	30
Prediction before observation	Students commit to an expected outcome before the tool reveals it, so that the observation tests a claim instead of confirming a statement.	26	21	5
Student-generated question	The question under investigation is formulated by the student, and the tool is then used to pursue that question rather than a preset one.	22	16	6
Evidence used to revise an explanation	The task builds in a point at which the data obtained obliges the student to revise the initial explanation rather than record an expected result.	18	14	4
Confirmatory demonstration only (counter-code)	Work with the tool is limited to verifying what the instructor has already stated; the outcome is known in advance and no inference is required.	22	7	15
Accessibility	Whether the lesson is designed so that students with different equipment and preparation can reach the same objective.	66	38	28
Alternative route to the same task	The same objective is reachable by more than one path, so that a student who cannot use the primary representation still meets the content.	24	16	8
Adaptation for low-bandwidth or offline use	The plan anticipates unequal access to equipment and connectivity and provides a reduced-requirement version that preserves the biological task.	21	12	9
Graduated task difficulty	The task is tiered so that students entering with different levels of preparation work on the same biological content at an appropriate level of demand.	21	10	11
Conceptual precision	Whether the biological language accompanying the representation stays exact.	62	34	28
Structure distinguished from function	Annotations keep morphological structure separate from the function it serves, instead of naming a part by what it does.	23	15	8
Correct use of taxonomic terminology	Taxonomic rank, nomenclature, and morphological terms are used consistently and at the correct level of generality.	22	13	9
Ambiguous or conflated terminology (counter-code)	Terms are merged or used loosely, as when homology is treated as analogy, so that the representation transmits an imprecise concept.	17	6	11
Total (14 codes)		312	193	119

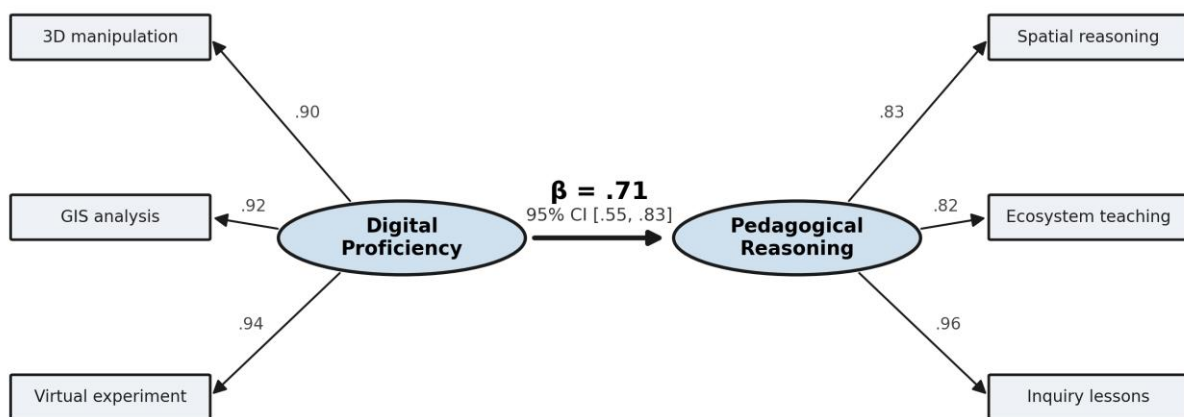
Note. The unit of analysis was the idea-bearing segment ($N = 312$). The corpus comprised the three expert evaluators' written comments, the 168 archived lesson plans (84 before and 84 after the module), and the virtual-laboratory interaction logs. Counter-codes record the absence of the practice a theme describes and are therefore expected to favor the control group. Intercoder reliability across the frame was Krippendorff's $\alpha = .82$.

RQ4 Structural Relations between Tool Proficiency and Pedagogical Reasoning

This question is exploratory, and the model describes associations rather than effects. The measurement model fitted the full sample well: $\chi^2(8) = 10.41$, $p = .238$, $\chi^2/df = 1.30$, CFI = .994, TLI = .990, RMSEA = .060, 90% CI [.000, .150], SRMR = .027. The wide upper bound of the RMSEA interval follows from the modest sample and the small number of degrees of freedom. The structural coefficient from Digital Proficiency to Pedagogical Reasoning was positive and substantial, $\beta = .71$, with a percentile bootstrap interval of [.55, .83] over 2,000 resamples. Estimated separately within each condition, the same coefficient was .84 in the experimental condition and .65 in the control condition, and the three matched indicator pairs were associated in both, with $r = .64$, .61, and .72 in the experimental condition and $r = .51$, .58, and .51 in the control condition. These group-specific values are descriptive: measurement invariance was not tested, 42 cases per condition will not support a multi-group model, and no test of the difference between conditions was carried out. Because tool proficiency and pedagogical reasoning were measured at the same point in time, the coefficient describes how the two vary together and carries no implication about which precedes the other. Figure 2 reports the model together with the group-specific associations and their intervals.

Figure 2

Structural model of competency relations, with the matched indicator associations reported separately for each condition



Matched indicator associations by group (exploratory)

Indicator pair	Experimental (n = 42)	Control (n = 42)
3D manipulation and spatial reasoning	.64 [.33, .82]	.51 [.26, .70]
GIS proficiency and ecosystem teaching	.61 [.31, .79]	.58 [.37, .74]
virtual experiment and inquiry lessons	.72 [.52, .85]	.51 [.28, .70]
Structural coefficient, group-specific model	.84	.65

Pearson r with percentile bootstrap 95% intervals (2000 resamples). Group estimates are reported side by side and are not compared formally; measurement invariance was not tested and the sample does not support a multi-group model.

Discussion

The four research questions were answered in the same direction: the zoology-specific digital module was associated with larger gains than conventional teaching paired with a separate ICT course, and the difference appeared on every outcome rather than on one of them. The pattern is easier to interpret against the two traditions the module was built on. Shulman (1986) argued that teaching expertise is not subject knowledge and pedagogy held separately but their fusion in pedagogical content knowledge, and Mishra and Koehler (2006) extended that fusion to technology, describing technological pedagogical content knowledge as a complex and situated form of knowledge rather than an additive sum of three competences. Situated accounts of learning make the same point from the other side, holding that knowledge is in part a product of the activity and context in which it is acquired, so that skill learned apart from its domain of use tends to remain there (Brown et al., 1989). If those positions hold, digital competence taught outside a discipline should transfer poorly into disciplinary teaching, which is what the control condition allows us to examine. Each result is read against the relevant literature below, followed by what the study can and cannot support.

RQ1 Subject Knowledge

The larger gains in the experimental condition, concentrated in application items and in anatomical and ecological reasoning, are consistent with evidence that immersive and three-dimensional representations aid spatial and systems understanding in biology (Reinke et al., 2021; Sharmin et al., 2023; Tung & Chang, 2024). The distribution of the difference within the test matters more than its overall size. Recall items separated the conditions least, while items that required students to combine content with a teaching decision separated them most, which locates the difference in how knowledge was organised for use rather than in how much of it was retained. Studies of anatomy instruction with digital specimens report a similar asymmetry, the clearest benefits appearing where a structure has to be related to its spatial arrangement rather than named (Kavvadia et al., 2023; Pandey et al., 2024). Read through situated cognition; this is the expected outcome: the representation was tied to a task, and the knowledge acquired carried the shape of that task (Brown et al., 1989).

RQ2 Digital Didactic Competence

Gains across all three subscales, and especially in matching a tool to an objective, align with work arguing that TPACK develops when technological, pedagogical, and content demands are met together rather than in separate courses (Valtonen et al., 2020; Von Kotzebue, 2022). Reviewing 55 studies, Voogt et al. (2013) reached a conclusion that bears directly on the present design: accounts of TPACK within specific subject domains were almost absent from the literature, and active involvement in redesigning and teaching technology-enhanced lessons was among the few developmental strategies with evidence behind it. The module was built along that line, and the subscale on which the conditions diverged most, selecting a tool for a stated objective, is the one that cannot be exercised without holding content and pedagogy together. The result also speaks to reports that pre-service biology teachers leave generic ICT training able to operate software but unable to deploy it for their subject (Adhani & Nursia, 2024; Nurbaya, 2023), and to evidence that disciplinary framing and institutional support, rather than access to equipment, distinguish stronger from weaker pre-service profiles (Tondeur et al., 2017). Embedding the training appears to close part of that gap.

RQ3 Pedagogical Readiness and Lesson Quality

Higher lesson-quality and expert scores, together with the shift from static assets to dynamic, inquiry-orientated designs, match the situated-learning claim that professional skill forms through authentic practice rather than decontextualised drill (Singer et al., 2011). Synthesising 19 qualitative

studies, Tondeur et al. (2012) identified authentic experience, reflection, feedback, and access to role models as the conditions under which pre-service teachers learn to integrate technology, and the weekly workshop cycle reproduced those conditions deliberately. The coded lesson plans locate the difference more precisely. What separated strong plans from weak ones was contextualisation, the connection of a tool to a specific conceptual difficulty, and this was also the code that discriminated most sharply between the conditions (Table 3). Heitink et al. (2017) describe the converse case in practice: teachers whose reasoning does not link a pedagogical strategy to the technology tend not to use the technology for that strategy at all, however available it is. The counter-codes in the present corpus behave the same way, with display-only tool use and confirmatory demonstration concentrated in the control condition. The baseline expert rating adds a detail worth keeping: it was the same in the two conditions and moved over the term only in the experimental one.

RQ4 Structural Relations

This is the most tentative part of the analysis and is reported as exploratory. Estimated on the full sample by maximum likelihood, the model satisfied the two-index criteria proposed by Hu and Bentler (1999), with CFI and TLI above their .95 threshold and an SRMR of .027 against their .08 benchmark; the measures entering the model and the estimation procedure are described in the Analytical Approach section, and their descriptive statistics appear in Table 2. Digital proficiency and pedagogical reasoning were strongly associated in the full sample, with a standardised coefficient of .71 and a bootstrap interval of [.55, .83]. Estimated within each condition the same coefficient was .84 in the experimental and .65 in the control condition, and the matched indicator pairs shown in Figure 2 were associated in both. Two conclusions follow, and they are worth separating. The association between tool proficiency and pedagogical reasoning is not confined to the experimental condition, so these data do not support the stronger claim that tool skill becomes pedagogically usable only when it has been acquired inside the discipline. What they do support is weaker and still substantive: the two constructs vary together wherever they were measured, and the level of both was higher where the preparation was discipline-embedded. This analysis does not test whether the two coefficients genuinely differ, for the reasons set out in the analytical approach, and they are reported side by side rather than contrasted. The pattern of association is consistent with Chai et al. (2013), who modelled the TPACK constructs in 550 pre-service teachers and found the basic knowledge factors acting on integrated knowledge indirectly, through intermediate combinations rather than by a direct route. One caution belongs with the fit statistics themselves. With eight degrees of freedom and 84 cases, the RMSEA confidence interval is wide by construction, and Kenny et al. (2015) show that RMSEA flags correctly specified models as poor fitting precisely in this range, so the point estimate of .060 should be read alongside the incremental indices rather than on its own. Because proficiency and reasoning were measured at the same time, none of this establishes which of them comes first.

Implications

For teacher educators the module offers a concrete route: identify the biological ideas that gain from visualisation, such as anatomy and ecological interaction, then build tool skill through tasks that teach those ideas. That students in the experimental condition were markedly better at aligning a tool with a learning goal—78% against 37% of optimal responses, points to the value of teaching digital-tool appraisal explicitly, a step conventional programmes often omit (Tondeur et al., 2012). The finding also bears on how competence frameworks are written. Instruments derived from DigCompEdu and comparable frameworks describe digital competence in general terms and are applied across subjects (Ghomi & Redecker, 2019; Tzafilkou et al., 2023), yet the capability that separated the conditions here is subject-specific, namely the judgement of which representation serves which biological idea. Voogt et al. (2013) noted the same absence of disciplinary specification in the research literature. These implications are addressed to course and programme design in teacher education, which is the level at

which the study was conducted. A single site and 84 participants cannot support recommendations about certification or national competence standards, and none are offered here.

Context of Implementation

The study was carried out in a Kazakhstani teacher-education programme, and the constraints that shaped the module are shared across the region. Surveys of digital competence among teachers and pre-service teachers in Kazakhstan report uneven infrastructure and a reliance on general ICT provision rather than subject-specific preparation (Berkimbayev, 2021; Nazyrova et al., 2025; Zhukabayeva et al., 2025), and an assessment of future biology specialists in the same system found readiness for digital instruction lagging behind stated curricular expectations (Smagulova & Kalieva, 2025). The module was designed to operate under those conditions, which is why the accessibility strand of the coding frame recorded whether a lesson offered an alternative route to the same task or a reduced-requirement version (Table 3). That strand separated the conditions least, and the modest difference is itself informative: designing for unequal access was the aspect of digital didactics that the module changed least, and it is where a revised version would concentrate. The pattern is not confined to Kazakhstan. Analyzing the digitalization of the education system in the Kyrgyz Republic, Sulaimanova and Egamberdieva (2025) describe the same reliance on general strategies for raising teachers' digital competence rather than on subject-specific preparation.

Limitations

Limitations of Design and Inference

The strongest limitation is the allocation procedure. Two intact academic groups were assigned to the conditions, so the comparison is not protected by randomization, and although the standardized baseline differences were small and every interval included zero (Table 1), intervals of that width at 42 cases per condition cannot establish equivalence. Adjusting for the pre-test reduces but does not remove the possibility that an unmeasured difference between the two groups contributed to the outcome. No procedural barrier separated the conditions during the term, and although the elements of the module were not presented to students as anything special, exchange of materials between the groups cannot be excluded; such exchange would make the conditions more alike and would work against the difference reported here rather than inflate it. Both conditions were taught by the same instructor, who is also an author of this study, which holds instructor quality constant but leaves open an expectancy effect favouring the condition that the instructor designed. The module was new to the students who received it, so part of the difference may reflect that novelty rather than the design principle behind it. The intervention lasted one semester with no follow-up, so nothing reported here speaks to whether the difference persists or reaches classroom practice.

Limitations of Measurement and Magnitude

The effect sizes were large, and the largest of them, digital didactic competence at $d = 3.38$, lies far outside the range typical of educational interventions. Analysing 1,942 effect sizes from 747 randomised trials of education interventions, Kraft (2020) proposes .20 as the threshold for a large effect on standardised achievement outcomes, which places the present estimates an order of magnitude above the field's own benchmark. Part of that magnitude reflects the single-site design, the researcher-developed instruments, and the contrast with an untailored ICT control rather than with an equally intensive alternative, so the absolute sizes should be read as an upper estimate pending replication with independent measures. Some constructs relied on self-report. Reviewing 107 TPACK studies, Willmark (2018) found self-report to be the dominant mode of assessment and performance evaluation of actual teaching to be rare, which is why lesson-plan ratings, micro-teaching, blinded

expert judgement, and interaction logs were included here, although the competence questionnaire itself remains a self-report measure. Blinding of the raters was incomplete in the way set out in the methodology section, since a plan that names a specific digital tool can betray the condition from which it came. The agreement between raters was computed on approximately one-fifth of the material and with unweighted coefficients; a weighted coefficient would suit an ordinal rubric better, and reporting one would have been preferable. The structural model, finally, rests on 84 cases and eight degrees of freedom, which is why it is presented as exploratory and why no comparison between conditions is drawn from it.

Future Research

The priorities that follow are longitudinal follow-up into early-career teaching, replication across biological subdisciplines and across institutions with different infrastructures, and lighter implementations of the module for settings without VR or AR equipment. A larger sample would also permit the multi-group model with measurement invariance that the present data cannot support, which is the only sound way to test whether the association between tool proficiency and pedagogical reasoning genuinely differs by condition, and it would give the model enough degrees of freedom for the fit indices to be informative in their own right (Kenny et al., 2015). A replication that sets the module against an equally intensive but subject-generic alternative would separate the contribution of disciplinary situating from that of additional instructional time, which the present design cannot fully disentangle. Where the institutional setting permits it, a design with random allocation would remove the main inferential limitation of the present study.

Conclusion

Embedding digital tools in the teaching of zoology, rather than teaching them alongside it, was associated with higher subject knowledge, digital didactic competence, and lesson quality among pre-service biology teachers, and tool proficiency and pedagogical reasoning varied together in both conditions. The contribution is not a new set of tools but a validated way of combining familiar ones into an assessed module, together with evidence, against an active control, that discipline-embedded digital preparation accompanies stronger teaching capability than a generic ICT course of the same length. Allocation was not random; the setting was one institution and one semester, and proficiency and reasoning were measured at the same point, so the immediate tasks are replication across settings, follow-up over time, and lighter implementations for resource-limited contexts. For teacher education the practical message is narrow: digital competence for biology teachers appears to be built more effectively through biology than beside it.

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Declaration of Interest

Authors declare no conflict of interest.

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Data Availability

The anonymised data supporting the findings of this study are available from the corresponding author on reasonable request. They are not publicly deposited, because the consent obtained from participants covered analysis and aggregate reporting by the research team rather than open publication of individual records.

Author Contributions

Zukhra Bagimbayeva – Conceptualization, Methodology, Investigation, Writing – original draft; Assiya Maimatayeva – Conceptualization, Methodology, Supervision; Zhadyra Kabatayeva – Investigation, Resources, Data curation; Kuralay Alipina – Investigation, Validation; Zhuldyz Tergenbayeva – Investigation, Project administration; Ruslan Safarov – Formal analysis, Software, Visualization, Writing – review and editing. All authors read and approved the final manuscript.

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Appendix

Appendix A

Comparative Thematic Plan of the "Zoology" Course (Fragment)

Week / Module	Topic	Control Activities	Group (CG)	Experimental Activities	Group (EG)	Digital Tools (EG only)
Week 1	Introduction to Zoology	- Traditional lecture with static Power Point presentation. - Laboratory work: Tinbergen's Four Questions (Mechanism, Development, Function, Evolution). - Board game "Lotto", creating an animal "passport" by filling in all the taxa on cardboard cards.		- Interactive lecture with 3D visualization. - Laboratory work: Tinbergen's Four Questions (Mechanism, Development, Function, Evolution). - Functional modeling of fundamentals of animal taxonomy on laptops.		- Animal Diversity Web (ADW) (Data source) - OneZoom Tree of Life Explorer (Phylogenetic visualization) - iTOL (Interactive Tree Of Life)
Weeks 2-7	Invertebrate zoology	- Examination of museum collections (pinned insects). - Identification using dichotomous paper keys. - Rote memorisation of orders/families.		"Digital collection" creation. - Field identification using AI-driven image recognition. - Creating a digital phylogenetic tree.		- iNaturalist / Seek - Google Lens - iTOL (Interactive Tree Of Life)
Weeks 8-13	Vertebrate zoology	- Traditional lecture using static diagrams. - Laboratory work: Dissection of preserved wet specimens (frogs). - Sketching organ systems in notebooks.		- Interactive lecture with 3D visualization. - Laboratory work: Virtual dissection with "undo" function and layer isolation. - Functional modeling of the circulatory system.		- Biosphera 3D (Comparative anatomy: Fish, Frog, Cat modules) - Froggipedia (AR interaction) - Emantras Virtual Frog Dissection (Skill training)
Week 14-15	Ecology & Biogeography	- Textbook study of habitat maps. - Analysis of static climate charts. - Discussion on local fauna.		- Geospatial analysis of species distribution. - Overlaying climate data on migration routes. - Project: "Mapping local biodiversity loss".		- QGIS / Google Earth Pro - DIVA-GIS - GBIF Database - IUCN Red List
Week 16	Final Assessment	- Theory: Standard written exam. - Performance Task: Solving a diagnostic biological problem using a Virtual Laboratory (without prior training, to measure digital intuition and baseline skill). - Oral defense of laboratory notebook.		- Theory: Standard written exam. - Performance Task: Solving a complex biological problem using a Virtual Laboratory (demonstrating acquired skills). - Defense of digital portfolio.		- LMS (Moodle) - Presentation Software - Virtual Dissection / Simulation Software (Both groups)

Appendix B

Sample Worksheets for the Four Tool Families

Each worksheet occupied one weekly workshop. Only the core task and the pedagogical-reflection prompt are reproduced here; full materials are available from the authors.

B1. Virtual Dissection (Frog Urogenital System)

Task: locate and label the kidneys, ureters, and gonads on the virtual specimen; record two structures you initially mis-identified and the cue that corrected you. Reflection: which feature of the virtual tool (undo, rotation, layer isolation) most helped a student who struggles with 3D relationships, and why?

B2. 3D / AR Morphology (Vertebrate Limb Homology)

Task: rotate and cross-section the forelimb of three vertebrates; mark the homologous bones and note where a 2D diagram would hide the relationship. Reflection: design a two-minute prompt that uses the model to surface, then correct, the common misconception that analogous limbs are homologous.

B3. GIS Species-Distribution Mapping (Local Passerine)

Task: import occurrence points, overlay a land-cover layer, and describe one pattern of habitat association and one likely sampling bias. Reflection: turn the map into an inquiry question that a school class could investigate with free data.

B4. AI Species Identification (Field Session)

Task: photograph and identify five organisms with an AI app; for each, record the top suggestion, your confidence, and the diagnostic feature you used to confirm or reject it. Reflection: where did the AI fail, and how would you use that failure as a teaching moment about taxonomic characters?

Appendix C

Scoring Rubrics and Sample Items

C1. Analytic Rubric for Open-Ended Subject-Knowledge Items (0–4 Per Item)

Level	Descriptor
4 (full)	Biological content correct and complete, and explicitly translated into a teaching move.
3 (proficient)	Content correct; teaching translation present but partial.
2 (developing)	Content largely correct; little or no pedagogical translation.
1 (limited)	Fragmentary content, or a serious conceptual error.
0	No creditable response.

C2. Sample Subject-Knowledge Items

MCQ (anatomy): In the amphibian heart, deoxygenated and oxygenated blood mix in the (a) left atrium; (b) right atrium; (c) single ventricle; (d) truncus arteriosus. [key: c]

Open-ended (application): A student claims the bat wing and the insect wing are homologous because both are used for flight. Outline, in three sentences, how you would use a 3D model to correct this. [scored with rubric C1]

C3. Digital Didactic Competence Questionnaire – Sample Items by Subscale (5-Point Likert, 1 = Strongly Disagree to 5 = Strongly Agree, Unless Noted)

Tool selection: “Given a zoology topic, I can choose the digital tool whose representation best fits the learning goal.” Pedagogical rationale (open, scored 0–3): “Explain why you would use a GIS map rather than a static distribution figure for teaching habitat fragmentation.” Technical troubleshooting (scenario): “A VR headset fails to load a model mid-lesson; state your first two actions.”

C4. Analytic Rubric For Lesson Plans And Micro-Teaching (Each Criterion 1–5).

Criterion	1–2	3	4–5
Conceptual accuracy	Errors present	Mostly accurate	Accurate and precise
Pedagogical appropriateness	Tool-led, goal unclear	Goal present	Tool serves an explicit goal
Technological integration	Decorative use	Functional use	Tool addresses a specific difficulty
Accessibility	Not considered	Partially considered	Differentiation designed in

Note. Inter-rater reliability on a common subset: ICC = .89 (open-ended items); κ = .84 (lesson-plan rubric); κ = .81 (micro-teaching rubric).

Appendix D

Representative Qualitative Excerpts by Theme

Excerpts are drawn from the three experts’ written comments on experimental-group lessons; each is labelled by the theme it illustrates.

Contextualization of Technology

“The 3D limb model is not shown for spectacle; it is used at the exact point where students confuse homology with analogy.” / “The GIS layer is tied to a question the class can actually test.”

Inquiry Orientation

“Students are asked to predict the internal arrangement before the virtual dissection reveals it, which turns the tool into a test of reasoning rather than a display.”

Accessibility

“The plan offers the same task through the model and through a labelled still, so learners who tire in VR are not excluded.”

Conceptual Precision

“Terminology is used carefully; the annotation distinguishes a structure from its function instead of collapsing the two.”

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Using the pentagram method to enhance critical thinking skills in ninth-grade physics students in Jordan

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ABSTRACT

The purpose of this study was to find out the effectiveness of the Pentagram technique to improve the ability of critical thinking among students in the ninth year of studying basic physics. To achieve this goal, we used a semi-experimental design and developed an experimental curriculum. The research sample included 46 ninth-grade students from the Mafraq Kasbah school, who were randomly assigned to either the experimental group (n = 23) or the control group (n = 23). Instructors taught an experimental group using the Pentagram methodology, while the control group received conventional instruction. Research revealed significant differences in critical thinking scores between the two groups. The experimental group has shown a remarkable improvement in critical thinking capabilities, with an average score before the test of 8.17 (SD = 4.01) and after the test of 18.43 (SD = 2.71). The control group had a pre-test score of 8.48 (SD = 4.57) and a post-test score of 13.52 (SD = 3.20). According to the independent test, the Pentagram method significantly improves critical thinking ability in physics learning. This clearly supports the effectiveness of the Pentagram technique in aiding learners' critical thinking.

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Introduction

Critical thinking is a rule-governed mental activity that produces predictable outcomes. It also requires a search for clear explanations. It emphasizes the process of making informed decisions, rather than falsely believing that one is making those choices based on sound internal biases (Siegfried & Colander, 2022). Critical thinking is defined as self-directed thinking, which includes the evaluation of information (Scheffer & Rubenfeld, 2000), and can be described as analytical reasoning to assess the validity of what has been read or heard, leading to the ability to identify evidence that enables more efficacious problem-solving. Knowledge related to critical thinking may vary and would underpin health professional education to become more reflective practitioners (Dwyer et al., 2014). Thinking ability is an essential part of current educational programs. Critical: Critical thinking. A critical-thinking or thinking-critically handler not only has an evaluative component, empirical evaluation, but also the dissection of causes and precursors, along with a deeper review of issues that are highly disputed and generate crises (Cheng & Wan, 2017). What counts in learners' experiences is that they are valuable

and have real effects. Enhancing the development of thinking skills is a current focus of global education policy planning in response to intellectual growth, especially among students (Vieira & Tenreiro-Vieira, 2016; Zhu et al., 2016). Therefore, it is a goal that should receive significant emphasis in the processes of learning and teaching. Consequently, educators regard the instruction of critical thinking skills as a top priority within schools today (Huda & Hashim, 2022).

Emphasis in science education has evolved from learning information to including the development of a variety of abilities in learners. Therefore, this transition needs a greater emphasis on critical thinking skills as well as different scientific processes such as observation, categorization, measurement, prediction, drawing conclusions, generating hypotheses, performing experiments, interpreting data, designing procedures, and so on (Turiman et al., 2012; Saido et al., 2018). These processes allow students to distinguish between facts and conclusions, detect causal links, draw inferences, and make sound judgments. Furthermore, the skills learned in scientific education have practical implications for tackling real-life challenges students face outside the classroom (Gualtieri & Finn, 2022).

One of the key goals of the physics curriculum is to encourage students to actively engage with the information they read or hear. Additionally, encourage children to talk and voice their ideas about age-appropriate issues and at their developmental stages (Gawlicz & Millei, 2022). Educators must move beyond traditional forms of pedagogy to cultivate a culture of inquiry among students and to develop their intellectual autonomy and freedom. Educators should also use contemporary teaching and learning techniques to encourage higher-order cognitive skills, i.e., analyzing, synthesizing, and evaluating (Hamzah et al., 2022). The Arab educational system has improved and developed physics instruction to increase students' cognitive potential (Abdelrahman, 2020). It forces people to think differently, which is especially important given the constant changes in our cultures. Critical thinking skills for children also prepare them to make decisions and meet the challenges of the twenty-first century (Bean & Melzer, 2021). Based on their observations of student teachers at Al-Bayt University and Al-Balqa Applied University, the authors found that the predominant teaching method in most schools is for teachers to stand at the front of the classroom and deliver lessons through lectures and explanations, with limited use of teaching aids to introduce new ideas or concepts. The instructor has a major responsibility for the educational process in this traditional method. The teacher may occasionally raise issues for class discussion, followed by summative exercises that students can complete independently or in groups. However, this conventional teaching style in basic physics education often makes the subject feel rigid and challenging for students. Consequently, students are unable to practice critical thinking skills, leading to a loss of motivation and a lack of desire to further engage with the subject (Fung & Liang, 2019; Ugwuozor, 2021; Banda & Nzabahimana, 2023).

There is a growing emphasis on selecting the most efficient teaching and learning methodologies due to the importance of physics education and the challenges it presents. While providing opportunities to develop cognitive, behavioral, and emotional skills in kids, these tactics aim to support improved learning outcomes for those students. This acknowledgment is consistent with the ongoing revolution in knowledge and information in the physics education sector. To address this problem, which is the underdevelopment of critical thinking abilities among students at the upper basic stage, the research was initiated. Previous research, such as Ghahremani et al. (2017), Drosos et al. (2018), and Adel (2021), has supported this claim.

Therefore, there is a need to use modern pedagogical techniques to address the problems faced by ninth-grade Jordanian students when using a new physics textbook. It is also important to make continuous efforts to use diverse methods, approaches, and processes that engage learners' attention and highlight their creative potential in scientific work, thereby developing learners' critical thinking. This allows them to have their problem-solving abilities reinforced in their setting. The purpose of this study is to evaluate the pentagram method, a new model for teaching inquiry and investigation. The aim is to assess its effectiveness in developing physics-reflective critical thinking among grade nine students in Jordan.

This study has been undertaken to meet the needs of twenty-first-century teachers who are willing to align their instructional practices with today's fast-paced, globalized world. The overarching goal of this effort is to improve physics instruction within science education more broadly. The study focuses on using the pentagram technique, which can develop critical thinking abilities, in physics lectures. This tactic helps teachers develop their students' critical-thinking abilities, thereby improving academic performance and motivating physics teachers to refine their teaching strategies, models, and methodologies. The study also offers a critical-thinking exam that industry specialists may use to their advantage. Its conclusions support the practical use of critical thinking skills for problem-solving and understanding cosmic events, benefiting ninth-grade students' fundamental education. The findings of this study will be useful to the Ministry of Education as they revise the physics curriculum's educational activities. The ministry's mistakes in revising physics textbooks may be reduced by using this scientific justification for change.

The importance of developing critical thinking skills in pupils across general education cannot be overstated, underscoring the need for modern strategies such as the pentagram strategy. As a result, the purpose of this study is to investigate the effectiveness of the pentagram technique in improving critical thinking abilities among female students at the higher basic stage. The next sections of the essay follow this structure: a survey of relevant literature on the study's keywords is offered. Section 3 outlines our study technique and data. Section 4 summarizes the main findings and gives a full commentary. Finally, section 5 underlines the study's conclusions.

Background

One of the main objectives of the physics curriculum is to encourage students to actively engage with the knowledge they learn from reading or listening. Students should be able to discuss and argue a range of topics while keeping in mind their age and developmental stage. Promotion of a classroom atmosphere that invites students to develop capacities for critical and intellectual freedom also requires a sense of comfort with challenging conversations with the instructor and their classmates (Beavers et al., 2017). Traditional pedagogical methods must be relinquished in order for educators to foster higher-order thinking processes such as analysis, synthesis, and evaluation (Russell, 2018).

In the past few years, the Arab region has made great strides in physics education by expanding students' access to more advanced educational opportunities. The intent of these programs is the improvement of student cognition and creativity by focusing on a wide range of types and levels of cognitive understanding. Power of Cognition: Strong, high-level cognitive skills endow students with the information they need to make critical decisions, change, and grow to meet the demands of the twenty-first century, especially in our rapidly changing culture.

The purpose of this research is to explore the nature and characteristics of the Pentagram Project, an approach to teaching that aims to develop critical thinking skills through five central learning domains: analysis, synthesis, evaluation, creativity, and reflection. This is not some abstract policy - this is a *modus operandi* that requires students to think critically as part of schooling. This research is significant because it used the Pentagram method to teach ninth-grade physics, an area with limited published work on such an integrated, multi-level approach.

Leicht et al. (2018) state that this UNESCO report is scholarly and aligns with the recognition of critical thinking as a core educational goal. The strategy highlights the need for education to keep pace with an ever-changing world. The research emphasizes the importance of cultivating cognitive skills that align with social and economic development. Teaching students to think critically will equip them to navigate and participate intelligently in that dynamic environment.

According to Bean and Melzer (2021), the ability of critical thinking involves the cognitive processes necessary for obtaining, maintaining, and using information, including analysis, planning, and evaluation, that are vital to sound judgments and conclusions. The distinction between "thinking" and "thinking" is essential to avoid misconceptions. In its broadest sense, it involves the pupil's ability to understand instructions, formulate unique concepts, and critically assess them. This technique builds

on the pupil's prior knowledge and valuable experience. On the contrary, cognitive abilities involve deliberate, focused mental processes used to process information, evaluate situations, and solve problems. Each of these talents increases the overall efficacy of critical thinking.

Pentagram Method

The survey and learning based on the event are central to Pentagram's teaching method. This method is based on the concept of knowledge organization, where students construct meaning and develop their own understanding. The theory of "trees," a new concept aligned with the principles of active learning, forms the basis of the Pentagram method (de la Torre Dece et al., 2019). The method emphasizes the research process to effectively acquire knowledge with the primary goal of supporting higher-order cognitive capabilities. According to Al-Assadi and Rahi Hadi al-Fatlawi (2023), this method includes management of students through five phases: acquiring knowledge, planning, decision-making, application, and evaluation.

The Pentagram method is an effective strategy for increasing students' motivation, capturing their attention, and improving their analytical skills. Introducing students to relevant real-world problems that require active involvement is an achievement (Saber & Salah Anwar, 2020). In addition, this method provides students with the tools and resources needed to address these challenges effectively. The Pentagram method relies heavily on technology because it facilitates the delivery of learning tasks and supports collaboration. The Pentagram method encourages students to work in teams or groups and to use technology to strengthen their critical-thinking skills. The Pentagram method, through technology, supports participants' learning and the development of students' critical thinking and problem-solving skills (de la Torre Dece et al., 2019).

In addition, the philosophical foundations of the Pentagram method support active learning, the development of critical thinking, and problem-solving. After this method, the instructors follow clearly defined steps to help students develop critical and creative thinking skills (Zaki & Zangan, 2023). The process begins with introducing students to a new topic or situation that stimulates their cognitive functions and promotes reflection, research, and discovery. This method promotes the search for innovative, adaptable solutions and embodies creativity. The Pentagram method promotes cognitive development and enhances students' problem-solving skills by supporting a dynamic learning environment (Jin et al., 2022).

Understanding that the learning process should not be limited to the mere transmission of information is essential. Instead of emphasizing Zaki and Zangan (2023), the focus should be on educating students through scientific thinking. According to Saber and Salah Anwar (2020), the Pentagram method includes several key attributes. First, it supports the development of critical thinking skills by involving students in activities such as planning, implementation, tracking, evaluation, and repair. It also increases students' self-esteem, promotes independence and responsibility, and helps them manage their learning process. In addition, the method supports the development of accurate ideas by presenting convincing evidence that aids effective decision-making and promotes critical analysis of the statement. In addition, the Pentagram method improves students' skills and allows them to plan and use their time more effectively.

Critical Thinking Skills

Old-fashioned teaching methods, lack of teachers' professional knowledge of modern pedagogical methodologies, inability to promote a culture of critical thinking, content and presentation strategies that discourage independent thinking and rely on rote memorization, distraction from electronic devices, and restrictions on free expression. These challenges prevent students from developing critical thinking skills essential for informed decision-making and personal development (Russell, 2018).

To solve these problems, teachers must adopt current pedagogical approaches that support critical thinking, receive adequate training and support, revise the curriculum to encourage

independent thinking, mitigate the effects of electronic distractions, and cultivate an environment that values free expression. Educators can facilitate the development of basic critical and decision-making skills in students (Momani et al., 2023).

The Pentagon technique is a systematic pedagogical strategy that structures knowledge to facilitate autonomous learning, which represents a promising approach. The Pentagon method, beyond being a mere strategy, is grounded in a broader educational theory of active learning and emphasizes student involvement through surveys and learning-based activities. This method helps students organize their ideas and develop their understanding by leading them through five stages: acquiring knowledge, planning, decision-making, application, and evaluation (de la Torre et al., 2019).

Excessive dependence by students on teachers' anxiety and teacher loss has hampered the development of critical thinking. Educational strategies, such as the Pentagon method, should support innovative teaching methods that promote critical thinking, provide teachers with training and support, and update the curriculum to support independent thinking. In addition, overcoming these problems requires supporting an environment that values freedom of expression and active student participation (Ülger & Çepni, 2020; Şahin et al., 2010). This shift requires a departure from traditional methods that emphasize memorization and indoctrination towards those who encourage students to actively become a role in education (Saïdo et al., 2018).

In recent years, there has been a significant shift in how the curriculum and teaching methods for physics and other scientific disciplines incorporate critical-thinking skills. This change emphasizes educational activities focused on student and teaching approaches that support autonomous learning. As students actively participate in scientific processes, the use of practical exercises and active learning strategies has become more important, improving teaching methods and helping students achieve their academic goals (Banda & Nzabahimana, 2023). The Pentagon method aligns with this educational shift and provides a structured framework that supports the development of critical thinking skills through active learning and student involvement.

Literature Review

Al-Gabry et al. (2023) conducted a study on software usability, grounded in the Pentagon theory, to draw geographical and historical conclusions. Using an experimental strategy, they used two diverse types of inference tests. The program was effective in increasing the dimensionality of both types of conclusions, as evidenced by significant differences favoring the experimental group. Similarly, Abumosa and Mashal (2018) examined the usefulness of the Pentagon approach in teaching the domestic economy to support design thinking and psychological well-being. Their study, using a descriptive-analytical half-method with two groups, supported the value of the Pentagon strategy in increasing creative thinking and psychological well-being.

Scientists have identified a link between the scores of experimental groups on psychological well-being evaluations and their performance on dimensional cognitive tests.

Sheldan and Qwaider (2018) conducted a study to evaluate the effectiveness of the curriculum based on the Pentagon theory in strengthening scientific reasoning and global civic thinking of science students. Their study included a semi-experimental design with one group, a scientific basis for the community, and a personality evaluation to evaluate global citizenship. The findings have shown the program's advantages in promoting scientific reasoning in society and cultivating global civic thinking. Meanwhile, al-Asadi and Rahi Hadi al-Fatlawi (2023) examined the effect of a pentagram approach to fifth-year chemistry. They found that students using this methodology performed better than a control group that studied using conventional methods.

He et al. (2021) have explored the value of using the Pentagon approach to improve the success of secondary school students in biology, enhance their critical thinking skills, and improve their communication. The study, which used the teacher manual and student activity booklets as part of the experimental design, revealed a statistically significant improvement in the experimental group's average score, particularly when using a dimensional research facility. Similarly, Zaki and Zangan

(2023) evaluated the effectiveness of the Pentagon approach in scientific education for improving life skills among secondary school students. The experimental design of their study has demonstrated the effectiveness of this approach in helping students acquire life skills, particularly in the cognitive component. However, emotional dimensions showed no statistically significant changes.

de la Torre Fonseca et al. (2019) also evaluated the impact of the Pentagon approach on the success of fourth-year physics students using the semi-exposure delivery method, assessing success with more than 40 participants through selection. The results indicated that the experimental group worked better than the control group.

A review of past research reveals a consistent use of experimental techniques to evaluate the effectiveness of the pentagram teaching strategy. In terms of sample size, this latest study aligns with numerous previous works, including those focused on physics by Sheldan and Qwaider (2018) and Zaki and Zangan (2023). This research parallels the study by Al-Asadi and Rahi Hadi Al-Fatlawi (2023), particularly in terms of academic focus.

The independent variable in this study, the use of the pentagram approach, is consistent with prior research. However, the dependent variable, critical thinking, distinguishes this study from others. The researcher used previous studies to develop the theoretical framework, study materials, and teacher guide. The researcher used similar procedures to identify a sample, collect data, and evaluate the findings.

Its specific emphasis on Jordan is what makes the manuscript especially interesting. This study is one of the first analyses to explore how the pentagram technique can affect critical thinking across the Arab world's local and regional contexts. Furthermore, it stands out for applying the method in Jordan's physics curriculum and using a sample of 9th-grade students. This research contributes to the existing literature on the impact of the pentagram approach on education and critical thinking in this context.

This research builds on the aforementioned studies and presents a new application of the pentagram method, yielding significant insights into its effect on critical thinking within a specific educational process.

Methods

The research, which used two experimental and control groups, a pre-test, and a post-test to address the problem, is semi-experimental in nature.

A sample of 46 ninth-graders from a school affiliated with the Directorate of Education in the Kasbah of Mafraq participated in this study during the second semester of 2022–2023.

Two sets of participants—one experimental group, consisting of 23 students who received instruction using the pentagram strategy, and the other control group, consisting of 23 students who received instruction using the traditional method—were created. The school was chosen specifically for its accessibility to the researcher and to ensure that the study's protocols would be followed correctly.

Educational Material And Study Tool

The instructor divided the teaching content into numerous parts. It started with an introduction that provided the instructor with a thorough breakdown of the pentagram strategy's steps and how to use them effectively. Additionally, the materials included basic recommendations and instructions that the instructor might use when implementing the stages of this strategy in the classroom. The materials provided a well-defined schedule that indicated the number of courses required to teach light refraction and its applications. Furthermore, we clearly specified the educational unit's outcomes and precise objectives for each lesson. We provided comprehensive lesson plans to facilitate class preparation. These plans included goals, teaching resources, a progression aligned with the stages of the pentagram technique, and mechanisms for assessing student success. Both the instructor and the pupils received detailed protocols to follow throughout the various phases of the pentagram method.

The panel of eight professional arbitrators, with expertise in curriculum and scientific teaching procedures, reviewed seven teaching plans. In addition, three physics professors who teach ninth-grade pupils at the primary education level are involved in the review process. The purpose of this full review was to confirm the legitimacy and adequacy of these proposals. We carefully integrated the broad points from the arbitrators' observations and recommendations into the final versions of the proposals. As a result, we have strengthened and refined methods to ensure their effective implementation in educational settings.

For data collection, we used a structured evaluation tool designed to assess critical-thinking capacity. The data collection process began with an exhaustive review of the literature and educational research to establish the core competencies of critical thinking. This summary included prominent studies, including those by Sheldan and Qwaider (2018) and Zaki and Zangan (2023). Prevalence. This review evaluated critical thinking skills, including analysis, induction, inference/conclusion drawing/interpretation, and deduction.

There were also questions on the assessment instrument with multiple-response options to measure these thinking skills. We provided clear instructions for students on how to conduct the exam, and each question offered four unique options. Appendix I: The final evaluation device is the definitive version of the evaluation tool, including all questions and options. This table contains a complete set of questions and their corresponding answers.

A group of competent arbitrators reviewed the evaluation tool to ensure its effectiveness.

We incorporated their comments into the final instrument and subsequently administered it to a second sample of 18 students who were not included in the first study group. This initial administration facilitated the evaluation of the questions' effectiveness and yielded preliminary data.

We have assessed test passages in terms of complexity, discrimination, and consistency. The difficulty coefficients for each question, ranging from 0.39 to 0.82, indicate that the test was slightly demanding. Discrimination coefficients ranging from 0.41 to 0.87 have demonstrated the ability to distinguish among various levels of critical thinking skills. The stability coefficient derived from the Kuder-Richardson equation was 0.85, indicating the test's reliability. The latest exam, which is described in detail in Appendix II: Distribution of Skill Examination in Critical Thinking, had 4 questions for analysis, 5 for induction, 5 for reasoning, 4 for explanation, 4 for and 3 for assessment, ensuring a thorough evaluation of critical thinking.

Study Procedures

The study followed procedures to achieve its goal, including an analysis of prior literature that identifies the study's problem and articulates its research questions. Scientists have also developed a technique to assess critical thinking ability and have demonstrated its validity and reliability. The Pentagon technique was used to create and verify the plans for the fifth module, which focused on light refraction and its applications. For the study, a sample was selected, and the experimental and control groups were randomly assigned. After an interview with a teacher who would conduct a study before the semester, an agreement was reached to implement lessons using the Pentagon technique. Selection process: A screening of critical-thinking abilities was implemented to normalize the groups.

The experiment took place over four weeks, during which the experimental group was exposed to the pentagram strategy and the control group received traditional instruction. All participants (in either group) were evaluated on their critical thinking at the end of the lecture. After correcting test takers' responses, the data were compiled. The data collected were analyzed using the SPSS software. These steps were taken to conduct a systematic and comprehensive study of the topic at various stages: from defining the research topic to implementing lesson plans and evaluating the impact on critical thinking skills.

The study followed a methodical process to achieve its aims, beginning with a review of the relevant literature to define the topic and develop the research questions. Educators have developed a

way to assess critical thinking skills that is valid and dependable. The Pentagon method was used to create and validate lesson plans for the fifth module on the refraction of light and its applications.

Table 1 describes the implementation process in detail by drilling down into course content as well as providing information regarding time spent on each item for both experimental and control groups:

Table 1

Course contents and time allocation for experimental and control groups

Group	Content	Time Allocation
Experimental	Introduction to Pentagon Strategy	1 session (45 mins)
	Light Refraction Theory	2 sessions (90 mins)
	Practical Applications	2 sessions (90 mins)
	Review and Assessment	1 session (45 mins)
Control	Introduction to Traditional Method	1 session (45 mins)
	Light Refraction Theory	2 sessions (90 mins)
	Practical Applications	2 sessions (90 mins)
	Review and Assessment	1 session (45 mins)

The experimental group received instruction based on the Pentagon strategy, while the control group received traditional instruction. Before the experiment, both groups were evaluated to determine baseline levels of critical thinking skills and to ensure their equivalence.

Over four weeks, the experimental group was instructed using the Pentagon system, while the control group used the conventional method. At the end of the instruction period, both groups performed a dimensional assessment of critical thinking. The answers were evaluated, and the data were assembled. Statistical analysis was conducted using SPSS to assess the effects of training approaches on critical thinking skills.

This comprehensive documentation of the study's implementation process ensures a systematic and careful approach, including the development of research questions, the implementation of lesson plans, and the evaluation of their impact on critical thinking skills.

Study Design

To address the research topic, the semi-experimental design was used to evaluate the effectiveness of the Pentagon strategy in strengthening critical thinking skills among ninth-grade physics students in Kasbah Mafraq. Based on the subsequent research variables, it is possible to identify teaching approaches, categorized as a pentagon and conventional strategies, as an independent variable (Dolk & Granat, 2012; Demirkan & Dolk, 2013). The dependent variable is the ability of critical thinking. As a result, the subsequent definition of the research proposal is relevant:

G1: $O \times O$

G2: $O - O$

Whereas:

- G1: Experimental group
- G2: control group
- X: Processing
- - : no processing
- O: Selection of critical thinking skills

Statistical Analysis

The critical-thinking test scores of the study sample were used to calculate the mean and standard deviation. A single-factor analysis of variance (ANOVA) was then used to examine the variation in these mean scores.

Findings

This study aimed to assess the effectiveness of the pentagram technique in enhancing the critical thinking abilities of ninth-grade physics students. The experimental group received pentagram-based training, while the control group received conventional instruction. We assessed baseline critical-thinking abilities using a pretest administered before the experiment and a posttest administered after it. What effect does the pentagram technique have on the development of critical thinking skills in ninth-grade physics students in Kasbah, Mafraq? Was this the research topic that the study set out to investigate? According to the research hypothesis, there would be no statistically significant difference (at the 0.05 significance level) in mean critical thinking test scores between the experimental group, which received pentagram strategy instruction, and the control group, which received traditional instruction. Table 2 presents the mean scores and standard deviations for the experimental and control groups on both pre-test and post-test critical thinking skills, as a function of the teaching technique variable. We generated this information to answer the study question and evaluate the hypothesis.

Appendix I includes sample materials related to the pentagram strategy to further clarify the pentagram technique and its application. Descriptions of the methodology are provided in the method section, which details the procedure, the use of the pentagram technique, and the three-stage process. These materials are intended to provide full details of the instructional approach used in this study.

Table 2

Based on the instruction-method variant, the mean and standard deviations of individual student scores in the study were computed to evaluate pre-test and post-test critical thinking skills

Group		Count		Pre-Test	Post-Test
Mean	SD	Mean	SD		
Experimental	23	8.17	4.01	18.43	2.71
Control	23	8.48	4.57	13.52	3.20

The results in Table 1 indicate observable differences in the mean scores of students from the experimental and control groups in evaluating dimensional and tribal critical thinking abilities. The students' critical thinking skills test scores were analyzed using analysis of covariance (ANCOVA), as shown in Table 2, to determine the significance of these differences.

Table 3

The analysis of covariance (ANCOVA) indicates a significant unilateral concomitant variation in the mean scores of the study participants on the test of dimensional critical thinking skills, by teaching method

Variation	Squares	Freedom	Mean Squares	P-Value	Sig.	Effect Size
Tribal Test	10.05	1	10.05	1.14	0.29	0.03
Teaching Method	281.05	1	281.05	32.03	0.00	0.42
Error	377.34	43	8.77	-	-	-
Total	664.98	45	-	-	-	-

Table 3 shows a statistically significant difference (p -value = 0.00) for the teaching method variable at the 0.05 significance level. The analysis of concurrent variance indicates that the impact size is 0.42, suggesting that the pentagram method (independent variable) accounts for 42% of the variance in critical thinking abilities (dependent variable). It is crucial to note, however, that the remaining 58% of the variance is attributable to other factors that were not evaluated and did not differ with the accompanying variable (tribal). This result lends credence to the hypothesis that the two groups are equal.

The adjusted mean scores of the students on the critical thinking skills exam were computed and displayed in Table 3 to identify which group the difference favors.

Table 4

The adjusted mean scores of individual students on the test of dimensional critical thinking skills

Group	Members	Adjusted Mean	SD
Experimental	23	18.45	0.62
Control	23	13.51	0.62

Note. Maximum score on the Test (25)

The adjusted mean score for the experimental group is 18.45, whereas the control group is 13.51, as shown in Table 4. This suggests that the pentagram technique has a considerable favorable influence on ninth-grade students' development of critical thinking skills. The study's findings reject the null hypothesis, and it can be concluded that there is a statistically significant difference (at a significance level of = 0.05) on the critical thinking skills test between the experimental group, taught using the pentagram strategy, and the control group, taught using the traditional method. Compared with traditional teaching techniques, these data demonstrate the pentagram strategy's usefulness in fostering critical thinking skills.

Discussion

The results suggest constructivist theoretical Perspectives that attribute the educational process to both educators and learners. One such theoretical approach is Constructivism, which holds that students learn through interactions with their environment and past experiences, resulting in optimal engagement and understanding. In this perspective, teachers are regarded not only as teachers but also as facilitators who can create a conducive learning environment that supports active involvement and engagement in amplifiability (Cheng & Wan, 2017). This is an effective way to promote self-confidence, increase understanding, and help children apply scientific knowledge and give it meaning (Allchin, 2014; Glaze, 2018). According to constructivist philosophy, creating these instructional contexts enables greater student interaction with the materials. This method is supported by studies highlighting the importance of student collaboration in improving learning outcomes (Wang & Liu, 2021).

The success of the Pentagram method, which follows an ordered, structured sequence of physical ideas for ninth graders, might be attributed to its compatibility with constructivism. This approach helps ensure an in-depth understanding of the content while also inspiring students to generate ideas that explain facts and solve problems (Gawlicz & Millei, 2022). The benefits of these methods in learning processes, as well as the reasons Pentagram technology is considered to help improve higher-order thinking, can be drawn from Hattie and Timperley's (2007) analysis of instructional strategies that focus on how students engage with technology. When focusing on the use of technology to support students' engagement, several studies suggest that such strategies lead to enhanced academic achievement, see [Freeman et al. (2014) and Michael (2006), who found that active learning approaches are more effective than traditional lectures.

A systematic method and the use of the Pentagram technique increase their effectiveness in promoting critical thinking skills. This sort of task requires students to search for a large amount of information from multiple sources and to generate interest, thereby encouraging research-based learning (Momani et al., 2023). Accordingly, students used various strategies to activate sensory and

motor experiences relevant to the topic, enriching their understanding through multiple codes, including images and diagrams (Saber & Salah Anwar, 2020; Mayer, 2009). Such a multifaceted approach is consistent with the inquiry into strategies to promote critical thinking and problem-solving expounded by Paul & Elder (2014) and KU (2009), who highlight the importance of engaging students in tasks that exercise their mental faculties and foster deep thought.

Investigations of active and problem-solving teaching strategies (Ghahremani et al., 2017; Momani et al., 2023) support the Pentagon model's focus on student learning and demonstrate its ability to reduce scattering and improve engagement. The systematic order of the method enables students to understand and practice physical concepts, leading to better critical thinking skills than traditional instruction (Al-Gabry et al., 2023). Research evidence indicates that adventure-based and interview-based learning can significantly improve critical thinking and problem-solving competencies (Hofstein & Lunetta, 2004; Toth et al., 2006). Research by Gijbels et al. (2005) states that inquiry and active learning can increase engagement and promote critical thinking skills.

Results showed that the experimental group (students who received instruction using the Pentagon technique) had better critical thinking skills than the control group (students who were taught using the traditional method). This supports previous findings that survey- and activity-based pedagogical approaches are effective (Demirkan & Dolk, 2013). (Johnson & Johnson, 1999; Blanchard et al., 2010), cooperative learning strategies and discoveries contribute to improving student achievements through deeper understanding and solving problems. The Pentagon is favored because it encourages independent idea generation and processing, which might in turn promote the development of new cognitive structures and improve critical thinking skills. The result of their experiment underscores the need for instructional measures that stimulate critical thinking and cognitive skills.

Additionally, the importance of peer work and discussions is evident in the results, as these activities help achieve academic objectives while fostering trust. Saido et al. (2018) highlight the importance of working together to develop critical thinking and build self-esteem. According to research, students who engage in collaborative learning are more likely to develop their skills as critical evaluators and synthesizers of information. Discovery-based learning and active participation promoted by the Pentagon technique significantly develop students' critical thinking skills. Researchers such as Abdelrahman (2020) and Abu Orabi et al. (2024) have shown that innovative pedagogical approaches can enhance creative and critical thinking skills.

The findings of the current study are consistent with those of Sheldan and Qwaider (2018), Zaki and Zangana (2023), and Al-Asadi and Rahi Hadi al-Fatlawi (2023), indicating that pentagram technology is effective in enhancing students' critical thinking abilities and diverse life skills. This contributes to the Pentagon technique's effectiveness in educational environments, as demonstrated by several studies that show its use in developing critical and creative abilities (Momani et al., 2023; Al KarabSheh et al., 2024; Abu Orabi et al., 2024). The use of the Pentagon approach in educational work follows a current trend in educational research that promotes evidence-based new methods of teaching and learning. This shift underscores the need for effective teaching methods that engage students in thinking critically and solving problems- skills necessary for academic achievement as well as life-long learning.

Conclusion and Implications

The paper was designed to evaluate the effectiveness of Pentagon's technical approach in developing learners' ability to think critically about basic physics in the ninth grade. The experiment-based curriculum has been developed and implemented using the experiment repository. The experimental and control groups, comprising 46 pupils each, were taught the lessons using Pentagon and a standard pre-test/post-test, respectively. Results: A considerable gap was observed between the average total critical thinking scores of the experimental and control groups, favoring the experimental

group, in assessing students' critical thinking in physics. The results show that the Pentagon method improved students' ability to think critically in basic physics in the ninth grade.

These results add to the literature demonstrating that the Pentagon method is an effective teaching tool for improving CT. The study emphasizes the need for an exploratory learning style in physics education that encourages learners to be actively involved, experiment, and discover on their own. The results have significant implications for teachers and textbook authors, emphasizing the need to integrate innovative instructional strategies, such as Pentagon's, into the physics teaching and learning process. Students can also build their understanding of the content and increase their ability to apply scientific reasoning and problem-solving skills as they develop as critical thinkers in both school and everyday life.

Future research can explore the long-term benefits of using the Pentagon methodology for critical thinking across various levels and courses. In addition, exploring the impact of this method on several aspects of students' learning, including motivation, conceptual understanding, and portability of skills, would provide a more comprehensive understanding of its potential benefits. The author of the study presents numerous recommendations derived from findings and subsequent debate. Science teachers in Jordan should be motivated to adopt the Pentagon attitude in teaching physics. This strategy can improve students' educational experience. Workshops should be conducted to train supervisors and instructors in physics and the natural sciences to facilitate implementation. These seminars aim to acquaint participants with the procedural phases of the Pentagon strategy, provide relevant exercises, outline methods for integrating these phases into proposals, and deliver lessons.

In addition, it is recommended that students engage in independent discovery of information that aligns with their critical-thinking abilities. This can be achieved by incorporating relevant activities into the procedural phases of the Pentagon method. In addition, external activities must be incorporated into strategic phases to improve critical thinking and facilitate the practical application of students' skills. The key recommendation is to involve those responsible for preparing physics textbooks in the reformulation process. They should connect the content to the procedural phase of the Pentagon technique and integrate activities that promote critical-thinking improvements. It is advisable to conduct analogous research of the Pentagon approach with other samples and variables. This would confirm and strengthen the study, making it easier to explore strategies and track progress.

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Appendix

Appendix I

Final assessment instrument

Question Number	Question	Options
1	What is the primary purpose of the pentagram technique in enhancing critical thinking?	A) Explanation B) Analysis

		C) Evaluation
		D) Induction
2	Which of the following best describes 'induction' in critical thinking?	A) Generalizing from specific instances
		B) Evaluating arguments
		C) Drawing conclusions
		D) Clarifying concepts
3	How does 'reasoning' contribute to problem-solving in physics?	A) By providing a solution
		B) By understanding principles
		C) By applying formulas
		D) By evaluating evidence
4	What is an effective method for assessing critical thinking skills in students?	A) Multiple-choice questions
		B) Essays
		C) Group discussions
		D) All of the above
5	How can 'analysis' be defined in the context of evaluating scientific data?	A) Breaking down information into components
		B) Combining data
		C) Summarizing findings
		D) Predicting outcomes
6	Which skill involves making reasoned judgments based on evidence?	A) Assessment
		B) Induction
		C) Inference
		D) Conclusion
7	What is the purpose of 'interpretation' in a scientific context?	A) To explain data
		B) To infer results
		C) To analyze methodology
		D) To apply theories
8	How is 'conclusion' used in critical thinking when solving physics problems?	A) To summarize results
		B) To evaluate methods
		C) To derive implications
		D) To generalize findings
9	Which question type is most suitable for assessing 'reasoning' skills?	A) True/False
		B) Multiple-choice
		C) Open-ended
		D) Fill-in-the-blank
10	What is a key indicator of effective critical thinking in students?	A) High test scores
		B) Clear explanations
		C) Active participation
		D) All of the above
11	How can 'induction' be applied in solving physics problems?	A) Generalizing from observations
		B) Testing hypotheses
		C) Analyzing data

		D) Predicting outcomes
12	Which of the following is an example of 'inference' in critical thinking?	A) Drawing conclusions from evidence B) Evaluating arguments C) Applying theories D) Summarizing information
13	What does 'analysis' involve when interpreting scientific data?	A) Breaking down data into components B) Summarizing results C) Testing hypotheses D) Making predictions
14	What is the role of 'explanation' in developing critical thinking skills?	A) To clarify concepts B) To challenge assumptions C) To evaluate evidence D) To formulate hypotheses
15	How can 'assessment' be used to evaluate scientific claims?	A) By analyzing evidence B) By comparing with theories C) By summarizing data D) By generalizing results
16	Which of the following methods best assesses 'interpretation' skills?	A) Essay questions B) Multiple-choice C) True/False D) Fill-in-the-blank
17	What is an appropriate way to assess 'conclusion' skills in students?	A) Asking for reasons behind conclusions B) Testing knowledge C) Evaluating understanding D) Comparing theories
18	How can students demonstrate 'reasoning' in their problem-solving approach?	A) By justifying their answers B) By memorizing formulas C) By summarizing results D) By repeating experiments
19	What type of questions are best for evaluating 'analysis' skills?	A) Complex problems B) True/False C) Simple recall D) Matching
20	How does 'conclusion' differ from 'inference' in critical thinking?	A) Conclusions are final judgments, while inferences are interpretations B) Conclusions are based on evidence, while inferences are assumptions C) Inferences are more general, while conclusions are specific D) There is no difference
21	Which skill involves evaluating the validity of arguments in scientific research?	A) Assessment B) Reasoning

		C) Induction
		D) Analysis
22	How is 'interpretation' essential for understanding experimental results?	A) It helps to explain what the results mean
		B) It identifies errors
		C) It summarizes data
		D) It verifies hypotheses
23	What type of question is best for assessing 'reasoning' in physics?	A) Calculations
		B) Theoretical explanations
		C) Application of concepts
		D) Data analysis
24	How can teachers effectively assess 'induction' in a classroom setting?	A) By asking students to generalize from case studies
		B) By giving multiple-choice tests
		C) By having students memorize facts
		D) By conducting practical experiments
25	What role does 'explanation' play in improving critical thinking abilities?	A) It clarifies understanding
		B) It helps in memorizing facts
		C) It tests recall
		D) It checks data accuracy

Appendix II

Critical thinking skills assessment breakdown

Skill Type	Number of Questions	Difficulty Coefficient (Representative Value)	Discrimination Coefficient (Representative Value)
Analysis	5	0.57	0.72
Induction	5	0.68	0.79
Reasoning	5	0.45	0.65
Explanation	5	0.52	0.83
Conclusion	5	0.39	0.7
Assessment	5	0.6	0.77

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Self-regulation profiles across various levels of science performance in TIMSS

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ABSTRACT

The research findings suggest that the academic achievements and learning processes of students are significantly influenced by their self-regulation and motivational factors. This study aimed to investigate the effects of four key self-regulation components, namely goal orientation, control of learning beliefs, rehearsal, and test anxiety, on the scientific performance of 5th- and 9th-grade students participating in the Trends in International Mathematics and Science Study (TIMSS). The research sample consisted of 776 students attending public schools in Oman, with self-regulation being assessed using the Motivated Strategies for Learning Questionnaire (MSLQ). To evaluate scientific proficiency, items resembling those found in TIMSS were developed and administered via a mobile application. The findings revealed noteworthy distinctions between students who performed well and those who performed poorly. High-achieving students exhibited greater levels of goal orientation, more effective control of learning beliefs, and a higher tendency to engage in rehearsal activities, while test anxiety did not exhibit a significant influence. These results were subjected to thorough analysis and discussion, with the study further offering insights into the potential implications for science education and the broader field of learning.

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Introduction

The performance of Omani students in the Trends in International Mathematics and Science Study (TIMSS) has recently garnered significant national attention. This attention stems from their consistent underperformance in science and mathematics, scoring below the established cutoff point in these subjects since 2007 (Mullis et al., 2020). Nevertheless, the Omani government's concerted efforts in the realm of science education have yielded some improvements in TIMSS scores, with regional comparisons indicating that Omani scores now exceed those of select Middle Eastern nations. Notwithstanding these improvements, Omani students' performance in TIMSS science assessments continues to fall below the established threshold.

It is worth highlighting that the Omani government's emphasis on this issue aligns with global endeavours to investigate various factors influencing students' performance in TIMSS assessments, as

evidenced by research conducted by Kang and Cogan (2020) and Wang and Liou (2018), which explore factors such as metacognition and motivation, as discussed by Michaelides et al. (2019).

Key Factors Influencing Student Science Performance in TIMSS

Student performance in TIMSS science assessments is shaped by a constellation of interrelated factors operating at the individual, parental, instructional, and systemic levels. At the individual level, affective characteristics such as positive attitudes toward science, enjoyment, high self-confidence, and low science-related anxiety are strongly associated with better achievement, as they enhance motivation and engagement (Balfaqeeh et al., 2022; Pongsophon, 2023; Topçu et al., 2016). Confidence in and liking of science also synergistically support performance across STEM domains (Balfaqeeh et al., 2022). Recent findings from Omani studies further point out the importance of cognitive and metacognitive factors in shaping science achievement. One of the main shortcomings in Omani students' performance in TIMSS was their difficulty in applying learned knowledge to unfamiliar contexts, along with challenges in interpreting shapes and graphs and connecting scientific concepts to everyday natural phenomena (Shahat et al., 2022). Al-Balushi et al. (2022a) reported that low-performing students exhibited significantly higher levels of mind wandering (MW) during science assessments than their high-performing peers, especially in grade 5, where attentional gaps remained consistent across the test. These attentional lapses suggest that attentional regulation—a key component of self-regulation—plays a critical role in test performance. In a complementary study, Al-Balushi et al. (2022b) found that Omani students who scored higher in a TIMSS-like science test outperformed others across four core metacognitive skills, including planning, monitoring, and evaluation. These findings highlight the pivotal role of metacognitive development in science achievement and point to the need for explicit instruction in these skills within the Omani context. From the parental perspective, parental education and involvement significantly contribute to academic success by fostering a positive learning environment and attitudes toward education (Mullis et al., 2020; Topçu et al., 2016). Instructional and classroom-level factors—particularly teacher specialisation, qualifications, and the use of inquiry-based pedagogies—have a positive impact on science achievement (Martin et al., 2016). Furthermore, the school disciplinary climate, availability of instructional resources, and an institutional emphasis on academic excellence contribute to favourable outcomes (Pongsophon, 2023). On a systemic level, disparities in socioeconomic status (SES), national education investment, urban-rural school differences, and curricular emphasis on science content shape achievement gaps across countries (Caponera & Losito, 2016; Mullis et al., 2020). A holistic approach that integrates psychological, pedagogical, and policy-level strategies is essential to address these multilayered determinants and to promote equity in science education globally.

Self-Regulation and Student Learning

Al-Harthy and Was (2018) conducted research indicating that students in grades 1-6 in Oman did not exhibit characteristics of agent learners, suggesting a lack of awareness and control over their learning progress. The study identified overconfidence in predicting their learning outcomes as a contributing factor to this phenomenon. It is important to note that metacognitive monitoring components, such as awareness and control, have been discussed in the context of self-regulation procedures in prior research (Al-Harthy & Was, 2013; Zimmerman & Moylan, 2009). Importantly, it has been found that students' awareness of task requirements, difficulty and value, as well as their control over goal and standards settings, attention focus, strategy selection, time monitoring, execution, feedback use and play, play a positive role in students' self-regulation. In addition to these findings, one recent study conducted by Fujita et al. (2024) reviewed the importance of self-regulation constructs

related to motivational approach. These constructs are goal-switching, goal pursuit, and feedback. It is important to note that in literature self-regulation has been conceptualised differently according to purpose and field of research. However, the research has emphasised the two broad components: cognition (e.g., goal settings) and motivation (e.g., effort regulation). In our study, these components are well incorporated into the self-regulation cyclical phases discussed below.

Self-regulation is a complex process in which learners utilise their cognitive and motivational capacities in academic tasks through a self-orientated approach (Billore et al., 2023; Suryawati et al., 2024). The literature of self-regulation has confirmed the positive impact self-regulation has in different contexts, such as academic performance (Ogbonneya & Nworie, 2024), problematic smartphone use (Xiao et al., 2025), learning online (Younis, 2024), critical thinking and problem solving (Zhou et al., 2024). Importantly, although the role of self-regulated learning has received attention in science education literature (e.g., Bene et al., 2021; Karaca et al., 2023; Tanti et al., 2018; Zheng et al., 2020), a research gap exists regarding the influence of students' self-regulation on their performance in the Trends in International Mathematics and Science Study (TIMSS), particularly when considering the cognitive levels of test items as clustering variables.

Relationship Between Student Science Performance and Self-Regulation Skills and potential research gaps in relation to TIMSS results

Self-regulation strategies play a crucial role in shaping students' performance in science assessments by promoting autonomy, goal-directed behaviour, and reflective learning. Numerous studies have confirmed that key self-regulatory processes—such as goal-setting, time management, planning, self-evaluation, and metacognitive monitoring—are significant predictors of academic achievement in science and mathematics (Aydin et al., 2019; Magsino, 2021; Mutawah et al., 2017). These skills enhance academic resilience and performance by linking motivation, particularly self-efficacy and intrinsic interest, with sustained learning efforts (Zheng & Li, 2016). While self-regulation is widely acknowledged as a driver of success, its direct role within the TIMSS framework remains underexplored, as current models tend to emphasise instructional and institutional variables over individual cognitive-behavioural traits (Panadero, 2017; Zimmerman, 2002). Early evidence suggests that students with high metacognitive awareness and strategic learning behaviours perform better in science, yet these factors are not systematically assessed in TIMSS analyses (Artelt et al., 2003). Moreover, cross-national studies indicate that the manifestation and impact of self-regulation vary by cultural and educational context, necessitating more context-sensitive and theoretically grounded approaches (Ker, 2017). To better understand the mediating role of self-regulation in science achievement, future TIMSS research should incorporate validated psychological instruments and multilevel analytic strategies that capture these nuanced learner-centred dimensions. Such efforts would not only enrich the explanatory power of TIMSS data but also guide evidence-based educational interventions aimed at fostering self-regulated learning in diverse student populations.

Despite growing interest in the psychological correlates of academic achievement, research directly examining the relationship between self-regulated learning (SRL) strategies and student performance on large-scale international assessments such as the Trends in International Mathematics and Science Study (TIMSS) remains limited. While SRL components—including goal setting, self-monitoring, and strategic resource management—are well established as predictors of academic success (Zimmerman, 2002), their integration into TIMSS-based analytical models has been minimal. Most TIMSS-related studies emphasise contextual and curricular variables, with limited exploration of cognitive-behavioural processes such as SRL. Moreover, cross-cultural analyses utilising TIMSS data rarely assess how SRL strategies may mediate science achievement across educational systems. This lack of mediation and multilevel modelling reflects a broader methodological gap. Studies such as those by Zimmerman (2002) and Panadero (2017) highlight the effectiveness of SRL in promoting academic success, yet these insights have not been fully operationalised in TIMSS datasets. Thus, incorporating validated SRL measures and using longitudinal or hierarchical models could yield a more

comprehensive understanding of science performance drivers in global educational contexts. Consequently, the present study posits that the subpar performance of Omani students in TIMSS science assessments may be attributed to their insufficient mastery of self-regulation strategies. As a result, they may resort to haphazard approaches that diverge significantly from effective methods of science learning. This study aims to offer insights into the correlation between self-regulation and the science performance of Omani students in TIMSS.

Research Focus

Understanding the mechanisms underlying students' science achievement in international large-scale assessments has become increasingly important for shaping evidence-based educational reform. This study investigates the role of self-regulation in shaping Omani students' performance in the Trends in International Mathematics and Science Study (TIMSS), with a particular emphasis on cognitive and motivational self-regulatory processes such as goal orientation, control of learning beliefs, and rehearsal strategy use. The persistent underperformance of Omani students in TIMSS science assessments has raised concerns about the quality of science learning and instructional support in the region, necessitating targeted inquiry into psychological and pedagogical contributors beyond structural factors.

Extensive literature confirms that self-regulation—a process by which learners plan, monitor, and reflect on their cognition, motivation, and behaviour—plays a vital role in academic performance, especially in complex and inquiry-based domains like science (Zimmerman, 2002; Panadero, 2017). This process includes both cognitive components (e.g., goal setting, metacognitive monitoring) and motivational elements (e.g., effort regulation, self-efficacy), which enable students to take agency over their learning (Billore et al., 2023; Fujita et al., 2024). Importantly, studies have shown that students with high levels of self-regulation perform better in both classroom settings and standardised tests due to their capacity to persist through difficult tasks and apply strategic learning techniques (Aydin et al., 2019; Zheng & Li, 2016).

Despite this robust evidence base, the role of self-regulation has been underexplored within the TIMSS framework, where analyses have traditionally prioritised instructional quality, socioeconomic status, and curricular coverage (Artelt et al., 2003; Mullis et al., 2020). Moreover, while TIMSS assesses science reasoning through cognitively demanding tasks, it does not directly capture the learner characteristics—such as motivational beliefs and metacognitive control—that may mediate student success. The situation in Oman adds another layer of complexity, as systemic issues such as rigid curricula and limited student agency have been identified as barriers to deeper science learning (Al-Harthy, 2016).

The current study addresses this critical research gap by linking self-regulation constructs to performance in TIMSS science items of varying cognitive demand. It offers a novel contribution by examining how specific components of self-regulation (goal orientation, control of beliefs, rehearsal strategy) relate to TIMSS outcomes within the Omani context, where performance profiles are stratified by grade level and item complexity. Furthermore, this research responds to calls for more context-sensitive educational models by accounting for cultural and assessment-specific factors, such as the low-stakes nature of TIMSS and the use of digital assessment formats (e.g., the TOSS platform), which may influence the manifestation of test anxiety and strategy use.

By synthesising insights across the domains of assessment, science learning, self-regulation, and TIMSS, this study advances a learner-centred perspective on international performance gaps and informs pedagogical and policy-level interventions aimed at fostering science achievement through self-regulatory development.

The social cognitive model of self-regulation, composed of distinct cyclical phases (Zimmerman & Moylan, 2009), affords a lucid comprehension of this impact:

1. During the *forethought phase*, students engage in task analysis, set standards and objectives, strategise for task execution, forecast outcomes, and adjust their learning task's values.

2. In the *performance phase*, students initiate the implementation of learning strategies and the utilisation of self-control tactics.
3. In the *self-reflection phase*, students continually evaluate their task performance against the standards and objectives initially set in the forethought phase.

Throughout the self-reflection phase, students encounter both positive and negative self-assessment emotions, which lead to either adaptive or defensive decision-making. In our study, self-regulation is operationalised as students' capacity to adapt their objectives, manage their beliefs, employ learning strategies via rehearsal, and cope with anxiety.

Self-regulation has been postulated to be inherently self-guided (Zimmerman, 2002), implying that the processes of science learning strategies rely on self-initiated implementation of the three self-regulation phases discussed above. Multiple studies substantiate this notion and emphasise the vital functions of students' learning goal orientation, task value, and self-efficacy in the domain of science learning (Kokkinos & Voulgaridou, 2018). Specifically, students' conception of learning in science correlates positively with their learning performance, and this self-perception influences their goal-setting and value adaptation. Consequently, students with low science performance tend to perceive themselves as lacking proficiency in science (Aurah, 2017). Such students are inclined to establish low-level goals (e.g., avoidance goals), place diminished value or interest in learning, and consequently resort to ineffective learning methods.

During the performance phase (phase #2), students frequently grapple with task-specific components such as science concepts and reasoning, often executing inefficient self-observation and self-control strategies as a result. To effectively manage these components, students necessitate ongoing and efficient self-instruction, visualisation, time management, and continual evaluation. Our hypothesis posits that students' ability to observe and regulate themselves hinges on their self-efficacy, objectives, and values established during the self-regulation phase (phase #1). Consequently, students with low-level objectives (e.g., avoidance goals) and limited appreciation for science learning are prone to struggle with self-instruction and exhibit ineffective self-control strategies. This struggle, in turn, manifests in various ways, including ineffective self-responses and defensive decision-making, such as attributing their poor performance to external factors. Additionally, these students may exhibit withdrawal behaviours, such as avoidance of science-related activities and limited class participation.

Cognitive abilities and scientific reasoning constitute critical determinants of students' academic performance. Scientific reasoning, entailing the formulation of hypotheses, experimentation, and evidence verification, represents a fundamental component of scientific inquiry and knowledge construction (Gillies et al., 2014; Saido et al., 2015). Saido et al. (2015) investigated the higher-order thinking skills of seventh-grade students based on Bloom's Taxonomy of the Cognitive Domain. Their findings revealed suboptimal performance in the domains of analysis, synthesis, and evaluation. The study underscores the necessity of higher-order thinking skills for comprehending science education. Hence, we assert strongly that active and constructive processes are imperative for the facilitation of scientific reasoning operations. From this standpoint, we hypothesise that self-regulation, as previously explicated, could constitute a significant contributing factor to students' scientific knowledge and reasoning performance.

Research Aim and Research Questions

Despite extensive evidence highlighting self-regulation strategies—such as goal-setting, time management, and metacognitive monitoring—as key predictors of science achievement (Aydin et al., 2019; Mutawah et al., 2017; Zheng & Li, 2016), their role remains underexamined within the TIMSS framework, with no prior research systematically investigating how these strategies differentiate between low and high-performing students in TIMSS science assessments (Magsino, 2021; Panadero, 2017). In light of this research gap, the present study has articulated two primary objectives. Firstly, it seeks to investigate the contribution of self-regulation to students' performance in TIMSS assessments.

Secondly, the study endeavours to explore this phenomenon in the context of the varying cognitive levels present in TIMSS test items, distinguishing between higher-order cognitive demands, which involve reasoning and inference abilities, and lower-order cognitive requirements, which focus on recalling facts and information. The findings of this study hold the potential to make substantial contributions to the enhancement of science education and the preparation for TIMSS assessments. Furthermore, the outcomes of this research are expected to lay the foundation for subsequent enquiries, including the development of intervention programmes targeted at improving science education and optimising TIMSS preparation. To address these overarching research objectives, the study is guided by the following research questions:

1. To what extent does the self-regulation of 5th- and 9th-grade students differ between low and high-performing groups in TIMSS-like science tests?
2. How does the self-regulation of 5th- and 9th-grade students vary between low and high performers across different cognitive levels of TIMSS-like science test items?

Method

Participants and Context

The study incorporated a total of 776 participants, drawn through a random selection process from 11 schools situated in socioeconomically middle-class regions across three governorates in Oman, specifically Muscat, AlDakhliya, and AlBatina South. The sample consisted of 342 fifth-grade students and 434 ninth-grade students, with the former consisting exclusively of girls and the latter of 60% girls and 40% boys. It is essential to note that Omani schools practise co-education for grades 1-4, wherein both male and female students coexist and are instructed by female teachers. However, from grades 5 through 12, female students attend segregated schools and are instructed by teachers of the same gender. The study proposal underwent meticulous ethical scrutiny by both the Ministry of Education and the funding organisation. Following the requisite approvals, the schools secured parental consent for their students to partake in the study, subjecting the study to their internal ethical reviews before granting permission for the participation of students and teachers.

Design and Procedure

The research design entailed the selection of 11 schools, from each of which two classes were randomly selected to partake in the study. Research assistants, who were science teachers and supervisors, were trained in administering TIMSS-like science assessments and the coordination of data collection procedures. In addition, a technical support team trained teachers to use the utilisation of a mobile application, namely the Trends in Oman Science Study (TOSS), developed by the research team. The technical team remained readily available to address any potential technical challenges encountered during the data collection process.

The TOSS application was installed on iPads, which were provided to each student. Furthermore, the students received login credentials and comprehensive instructions regarding iPad usage and the operation of the TOSS application. The study's objectives were elucidated to the participants by their teachers, following which they completed the TIMSS-like science assessments and answered the test items via the iPad interface. Notably, distinct versions of the TIMSS-like test were created for each grade level (5 and 9), and the assignment of a specific test version to participants was executed through a random allocation process.

Instruments

TIMSS-Like Tests

The development of TIMSS-like assessments was an intricate and meticulous undertaking, comprising multiple phases. Initially, the services of an internationally recognised expert in TIMSS assessments were enlisted to provide training to a cadre of 15 research assistants, all of whom were science teachers and supervisors. This training was specifically focused on the crafting of test items in accordance with the principles governing TIMSS assessments. Following the completion of training, a rigorous selection process resulted in the designation of nine science teachers for the actual development of test items.

In total, 20 equivalent test versions, each encompassing 24 items, were meticulously constructed for the fifth-grade level, while 18 corresponding test versions, comprising 27 items each, were designed for the ninth-grade level. The research assistants were entrusted with the responsibility of assembling the test versions, ensuring their strict alignment with the comprehensive TIMSS framework, as delineated in the work of Mullis and Martin (2017). This framework encompassed various science domains, including life sciences, physical sciences, and Earth sciences for the fourth-grade level, and biology, chemistry, physics, and Earth sciences for the eighth-grade level. The framework also encompassed the cognitive domains of the items, such as knowledge, application, and reasoning, in addition to the diverse item formats, which included textual, pictorial, multiple-choice, and short open-ended formats.

For the fifth-grade level, each test consisted of 24 items, comprising 11 items designed to evaluate knowledge and 13 to assess application and reasoning abilities. Similarly, for the ninth-grade level, each test contained 27 items, with 8 items tailored to gauge knowledge and 19 items dedicated to evaluating application and reasoning proficiencies. To ensure broad content coverage and minimise repetition effects, the 20 fifth-grade and 18 ninth-grade test versions were systematically assigned to students using a planned rotation across classrooms. Each student received only one test version, and care was taken to balance the distribution of test forms across schools and demographic subgroups. All test versions were constructed to be equivalent in terms of structure, content domains, cognitive demands, and item formats, as guided by the TIMSS framework. Throughout the development process, emphasis was placed on maintaining parallel item specifications and balanced difficulty distributions across versions. Expert reviews at multiple stages helped ensure that the test forms were functionally comparable, allowing for meaningful aggregation and interpretation of student performance data across the different versions.

The development of the TIMSS-like tests adhered to a rigorous protocol. The process commenced with the introduction of an international TIMSS expert to train 15 science teachers and supervisors, who served as research assistants, in the formulation of test items congruent with the TIMSS framework. Subsequently, nine individuals were meticulously selected to craft the actual test items. In total, 20 test versions, each comprising 24 items, were meticulously constructed for the fifth-grade level, while 18 corresponding test versions, comprising 27 items each, were designed for the ninth-grade level. These items were methodically aligned with the TIMSS framework in terms of science domains, cognitive domains, and item types. A subset of items necessitated the creation of illustrative materials, which were expertly crafted by five graphic designers. Following the initial item development, a comprehensive review was undertaken by six science assessment experts, who had undergone specialised training in the realm of TIMSS item design. Subsequently, a second review was conducted by a seasoned international TIMSS expert.

The TIMSS-like assessments were subsequently pilot-tested on 1,163 students, across two classrooms per test version. Items exhibiting suboptimal reliability were subject to revision, resulting in the final versions of the tests, which demonstrated commendable Cronbach's alpha reliability coefficients ranging from 0.65 to 0.88 (with an average of 0.77) for both the fifth and ninth-grade levels. In addition to assessing internal consistency through Cronbach's alpha, the development process of the

TIMSS-like assessments incorporated multiple layers of expert-driven content validation and quality control to ensure the robustness of the instruments. Item construction was guided strictly by the TIMSS assessment framework, with explicit alignment to its cognitive and content domains. All test items underwent iterative review and refinement by trained science educators and TIMSS specialists to evaluate their clarity, alignment, and representativeness of the intended constructs. Furthermore, through pilot testing across two classrooms per test version, items with low reliability were identified and revised, a process through which aspects of item discrimination and content coherence were indirectly captured. Taken together, a comprehensive foundation for content validity was provided by these steps, and the overall interpretability and fairness of the final test forms were enhanced.

Self-Regulation

The central theme of the present investigation was self-regulation, and for the purpose of this study, the Motivated Strategies for Learning Questionnaire (MSLQ) (Duncan et al., 2015; Pintrich & de Groot, 1990) served as the foundational instrument. The original MSLQ comprises 55 items categorised into five distinct subscales. However, in the context of this study, a judicious selection of 20 items was made, specifically tailored to the level and context of the students' science learning. These 20 items, in turn, were employed to assess four fundamental sub-scales: goal orientation (6 items), control of learning beliefs (5 items), rehearsal (6 items), and test anxiety (3 items). To enhance content validity, it underwent a comprehensive review by seven esteemed faculty members, and their invaluable feedback was thoughtfully incorporated. Subsequently, the adapted instrument was subjected to a pilot test, involving 630 fifth-grade students and 542 ninth-grade students, culminating in commendable Cronbach's alpha coefficients of 0.93 for the fifth-grade level and 0.91 for the ninth-grade level. Table 1 illustrates the inter-domain and domain-to-total correlations for the self-regulation instrument across grades 5 and 9, providing evidence for its construct validity. The high correlations between each domain and the overall self-regulation score (e.g., grade 5: Goal Orientation = .940, Rehearsal = .931; grade 9: Goal Orientation = .943, Control of Learning Beliefs = .912) suggest that each domain contributes meaningfully to the overarching construct of self-regulation. This supports the relevance and representativeness of each domain, aligning with principles of content validity. Moreover, inter-domain correlations are moderate to high, particularly between cognitively related domains such as Goal Orientation and Rehearsal (grade 5: .842, grade 9: .852) and Control of Learning Beliefs and Rehearsal (grade 5: .722, grade 9: .778). These findings indicate conceptual coherence without redundancy, a desirable trait in multidimensional constructs. Test anxiety, while still positively correlated with self-regulation (grade 5: .599, grade 9: .605), shows relatively weaker associations with other domains, which is theoretically justifiable. It reflects an affective regulation component that is related but distinct from metacognitive strategies, further supporting construct differentiation within the instrument.

Table 1

Inter-domain and domain-to-total correlations for the self-regulation instrument by grade level (grades 5 and 9)

Dimension	Goal Orientation	Control of Learning Beliefs	Rehearsal	Test Anxiety	Self-Regulation
Goal Orientation	—	0.763 (G5)	0.842 (G5)	0.590 (G5)	0.940 (G5)
Control of Learning Beliefs	0.811 (G9)	—	0.722 (G5)	0.526 (G5)	0.875 (G5)
Rehearsal	0.852 (G9)	0.778 (G9)	—	0.532 (G5)	0.931 (G5)
Test Anxiety	0.534 (G9)	0.617 (G9)	0.516 (G9)	—	0.605 (G5)
Self-Regulation	0.943 (G9)	0.912 (G9)	0.936 (G9)	0.599 (G9)	—

Note. Upper triangle values represent grade 5 correlations. Lower triangle values represent grade 9 correlations. All values are Pearson correlation coefficients between dimensions and total self-regulation score.

To categorise the 776 participants into low and high achievers, their performance on the total score and on both lower-level and higher-level items from the TIMSS-like science test was employed. Median scores were strategically utilised to establish cut-off thresholds, effectively demarcating individuals as low- or high-performing (see Table 2). These cut-off scores were instrumental in the classification of participants into low and high-performance categories based on the total score, lower-level items, and higher-level items of the TIMSS-like science test for both grade levels.

Table 2

Number of items and cutoff scores of low and high performance in the lower-level, higher-level items and total score of the TIMSS-like test for the two grade levels

Grade	Lower-level items		Higher-level items		All items	
	Number of items	Cut-off score	Number of items	Cutoff score	Number of items	Cutoff score
Five	11	4	13	4	24	8
Nine	8	3	19	8	27	11

Results

This section presents an overview of the findings related to self-regulation in each grade level, alongside the independent variables, namely TIMSS total score, lower-level items, and higher-level items. The descriptive statistics, including means and standard deviations, are displayed in Table 3 for the four MSLQ subscales concerning the two performance levels and the three TIMSS-like measures for fifth-grade students. Additionally, Table 4 furnishes the results of the one-way Multivariate Analysis of Variance (MANOVA) concerning the equality of these means.

The results elucidated significant disparities in the four self-regulation variables across the two performance levels in relation to the TIMSS total score, lower-level items, and higher-level items. To expound, the findings indicated that for fifth-grade students, Wilks's Λ was 0.95, yielding $F(4, 487) = 6.46$, $p < .001$, and $\eta^2 = 0.05$ in the case of the TIMSS total score. Similarly, Wilks's Λ was 0.98, resulting in $F(4, 487) = 3.05$, $p < .017$, and $\eta^2 = 0.024$ for lower-level items, and Wilks's Λ was 0.96, with $F(4, 487) = 5.00$, $p < .001$, and $\eta^2 = 0.039$ for higher-level items. Furthermore, the between-subjects tests unveiled that fifth-grade students who performed at a higher level across all three measures of TIMSS-like tests exhibited more robust self-regulation concerning goal orientation, control of learning beliefs, and rehearsal, as compared to their lower-performing counterparts. However, both higher and lower performers displayed no significant differences in test anxiety, indicating comparable levels of anxiety in both groups.

Subsequently, we present the results for ninth-grade students. Table 5 furnishes the descriptive statistics for the four MSLQ subscales concerning the two performance levels for the three measures of TIMSS-like assessments (total, lower level, and higher level), while Table 6 presents the outcomes of the one-way MANOVA examining the equality of these means.

The outcomes unveiled noteworthy differences in the four self-regulation variables across the two performance levels, specifically in the context of the TIMSS total score, lower-level items, and higher-level items. Specifically, for ninth-grade students, Wilks's Λ values were 0.91, 0.94, and 0.91 for the TIMSS total score, lower-level items, and higher-level items, respectively. These values corresponded to $F(4, 452)$ values of 10.70, 7.36, and 11.04, with p -values of less than 0.001 for all three measures. Furthermore, the subsequent analysis revealed that ninth-grade students who performed at a higher level across the three TIMSS-like tests displayed enhanced self-regulation with regard to goal orientation, control of learning beliefs, and rehearsal, as compared to their lower-performing peers. Nevertheless, there were no significant differences between both groups concerning test anxiety, signifying equivalent levels of test anxiety among both high and low performers.

Table 3*Descriptive statistics of self-regulation for fifth-grade students*

Self-regulation skills	Performance in TIMSS-like	Total test score		Lower-level items		Higher-level items	
		Low(n=230), High(n=262)		Low(n=249), High(n=243)		Low(n=238), High(n=254)	
		M	SD	M	SD	M	SD
Goal Orientation	Low	3.37	0.98	3.45	0.98	3.40	1.00
	High	3.79	0.88	3.74	0.91	3.77	0.87
Control of Learning Beliefs	Low	3.42	1.00	3.52	0.98	3.43	1.01
	High	3.82	0.93	3.74	0.98	3.81	0.92
Rehearsal	Low	3.44	1.04	3.52	1.01	3.49	1.04
	High	3.87	0.91	3.82	0.95	3.84	0.91
Text Anxiety	Low	3.12	0.68	3.15	0.65	3.15	0.69
	High	3.29	0.62	3.26	0.65	3.26	0.61

Table 4*Multivariate analysis of variance (MANOVA) results exploring between-subjects effects for self-regulation and grade five TIMSS-like performance (df = 1, 490)*

Self-regulation skills	Effect	Total test score			Lower-level items ^b			Higher-level items		
		MS	F	<i>p</i> -value	MS	F	<i>p</i> -value	MS	F	<i>p</i> -value
Goal Orientation	Performance	21.11	24.11	0.000	9.46	10.41	0.001	16.90	18.92	0.000
	Error	0.88			0.90			0.89		
Control of Learning Beliefs	Performance	17.52	18.50	0.000	5.14	5.29	0.02	15.95	16.79	0.000
	Error	0.94			0.97			0.95		
Rehearsal	Performance	22.06	23.19	0.000	10.50	10.77	0.001	15.07	15.61	0.000
	Error	0.95			0.97			0.96		
Text Anxiety	Performance	2.85	6.99	0.008	1.02	2.50	0.11	1.13	2.75	0.098
	Error	0.40			0.41			0.41		

Note. ^a: Wilks' Lambda = 0.95, F = 6.46, P = 0.000, ^b: Wilks' Lambda = 0.97, F = 3.05, P = 0.017, ^c: Wilks' Lambda = 0.96, F = 4.99, P = 0.001

Table 5*Summary of descriptive statistics concerning self-regulation in the ninth grade*

Self-regulation skills	Performance in TIMSS-like	Total test score		Lower-level items		Higher-level items	
		Low(n=221), High(n=236)		Low(n=225), High(n=232)		Low(n=223), High(n=234)	
		M	SD	M	SD	M	SD
Goal Orientation	Low	3.55	0.92	3.58	0.95	3.55	1.00
	High	3.94	0.69	3.91	0.66	3.93	0.87
Control of Learning Beliefs	Low	3.61	0.89	3.65	0.89	3.60	1.01
	High	4.04	0.72	4.02	0.72	4.05	0.92
Rehearsal	Low	3.62	0.96	3.66	0.95	3.66	1.04
	High	4.07	0.66	4.05	0.69	4.04	0.91
Text Anxiety	Low	3.19	0.63	3.17	0.59	3.21	0.69
	High	3.21	0.51	3.23	0.55	3.20	0.61

Table 6

Multivariate analysis of variance (MANOVA) results exploring between-subjects effects for self-regulation and grade nine TIMSS-like performance ($df = 1, 455$)

Self-Regulation	Effect	Total test score			Lower-level items ^b			Higher-level items		
		MS	F	P	MS	F	P	MS	F	P
Goal Orientation	Performance	17.02	25.94	0.000	12.79	19.22	0.000	16.23	24.67	0.000
	Error	0.65			0.66			0.65		
Control of Learning Beliefs	Performance	21.74	33.34	0.000	16.01	24.08	0.000	23.76	36.68	0.000
	Error	0.65			0.66			0.64		
Rehearsal	Performance	22.47	32.85	0.000	17.52	25.22	0.000	16.97	24.39	0.000
	Error	0.68			0.69			0.96		
Text Anxiety	Performance	0.00	0.00	0.94	0.29	0.92	0.33	0.12	0.39	0.53
	Error	0.32			0.32			0.32		

Note. ^a: Wilks' Lambda = 0.91, F = 10.70, P = 0.000, ^b: Wilks' Lambda = 0.93, F = 7.35, P = 0.000, ^c: Wilks' Lambda = 0.91, F = 11.04, P = 0.000

Discussion

The present study has unveiled several noteworthy findings. Firstly, the self-regulation variables, encompassing goal orientation, control of learning beliefs, and rehearsal, exhibited significant discrepancies across diverse levels of TIMSS-like science test scores, which include total scores as well as items of both lower and higher cognitive levels. Secondly, these findings were consistent across both fifth and ninth grades. In particular, students achieving higher TIMSS scores in both grades demonstrated a more robust goal orientation, superior control of learning beliefs, and a more extensive use of learning strategies through rehearsal.

The present study reinforces the critical role of self-regulation in explaining student performance differentials in the TIMSS science assessment. Our findings indicate that students who perform at higher levels tend to demonstrate stronger mastery and performance-approach goal orientations, suggesting they are more likely to engage in goal-directed, self-monitoring behaviours that are conducive to academic success. This aligns with the broader self-regulation literature, which emphasises the interplay of cognitive (e.g., goal-setting, planning, feedback use) and motivational (e.g., self-efficacy, effort regulation) components in academic performance (Fujita et al., 2024; Billore et al., 2023). Students with mastery and performance-approach goals were also more likely to rate themselves as persistent and to maintain task focus—behaviours linked to sustained goal pursuit and strategic effort application (Aydin et al., 2019; Zheng & Li, 2016). In contrast, students adopting performance-avoidance orientations displayed lower persistence and self-belief, which corresponds with prior evidence that such goals are often associated with anxiety and disengagement in academic settings (Ker, 2017).

Moreover, this study extends the literature by applying self-regulation theory within the underexplored context of TIMSS, where individual-level cognitive-behavioural factors are frequently overshadowed by structural variables, such as teacher quality or school resources (Panadero, 2017; Zimmerman, 2002). Our findings suggest that incorporating validated self-regulatory constructs—such as feedback responsiveness, time management, and metacognitive awareness—into future TIMSS analyses could significantly enhance the explanatory power of international assessments. Importantly, the identification of performance profiles based on self-regulatory traits offers a promising avenue for tailored interventions. These findings emphasise the necessity of culturally responsive and theoretically grounded educational practices that foster goal-setting, autonomy, and reflective learning in science classrooms worldwide (Artelt et al., 2003; Mutawah et al., 2017). In doing so, educational systems may

better equip students to thrive not only in assessments but also in lifelong scientific inquiry and problem-solving.

The results of our study align with the cyclical self-regulation model informed by social cognitive theory, which emphasises goal setting, self-monitoring, and adaptive regulation across task phases (Zimmerman, 2002; Panadero, 2017). Specifically, we found that students with higher TIMSS science performance were more inclined to elevate their academic goals and perceive greater control over their learning processes. This pattern held true across both low- and high-cognitive-demand items, suggesting that high achievers consistently apply metacognitive strategies and regulate effort in response to task complexity. These findings echo the broader literature, which emphasises that self-regulated learners actively monitor their performance and modify their goals based on task evaluations (Billore et al., 2023; Fujita et al., 2024).

Furthermore, our analysis points out the importance of controlling learning beliefs in differentiating TIMSS performance. High-performing students reported greater belief in their capacity to influence learning outcomes—a construct strongly tied to academic confidence and emotional regulation. This aligns with research showing that a strong sense of control is positively associated with adaptive academic emotions like enjoyment and pride and inversely related to anxiety and shame (Ker, 2017; Zheng & Li, 2016). Emotional engagement, fuelled by these beliefs, likely enhances test performance by reducing cognitive overload and promoting sustained effort (Garn et al., 2017). In light of these findings, it is plausible that high-achieving students possess not only cognitive advantages but also motivational dispositions—such as optimism and strategic perseverance—that enable them to maintain effortful engagement during assessments.

Finally, our results reinforce the established connection between self-regulation, goal orientation, and academic learning strategies. Specifically, high-achieving students in our sample exhibited greater use of rehearsal, a surface-level strategy often employed to maintain attention and prepare content for deeper processing (Akyol et al., 2010). While rehearsal alone may not yield profound understanding, its integration within a broader self-regulatory framework—particularly when paired with goal-setting and feedback use—can serve as a scaffold for higher-order learning strategies (Mutawah et al., 2017; Aydin et al., 2019). Given the complexity of science reasoning required in TIMSS items, these findings suggest that even foundational strategies like rehearsal can play a critical supporting role when embedded within effective self-regulation cycles.

Our findings suggest that the effective use of learning strategies—particularly rehearsal—is intricately linked to students' self-regulatory capacities, especially their ability to set adaptive goals and manage emotional responses to academic tasks. Rehearsal, typically classified as a surface-level strategy, plays a preparatory role by facilitating attention and retention, which are foundational for the deployment of deeper cognitive processes such as elaboration, summarisation, and inferencing (Akyol et al., 2010; Billore et al., 2023). This aligns with the view that goal setting and emotional regulation, as key components of self-regulation, provide the motivational structure needed to guide strategy use effectively (Fujita et al., 2024; Zimmerman, 2002).

High-performing TIMSS students in our study reported a greater reliance on learning behaviours associated with both rehearsal and elaboration. For example, responses to metacognitive self-rating items (e.g., “I ask myself questions to ensure I grasp the material I have been studying”) suggest that these students actively engaged in strategies that support self-monitoring and comprehension. These behaviours reflect the integration of cognitive and motivational aspects of self-regulation, which have been shown to enhance learning persistence and performance, particularly in science (Aydin et al., 2019; Zheng & Li, 2016). Although our study did not specifically isolate different strategy types, the reported use of elaborative prompts implies a layered strategy repertoire—where surface strategies like rehearsal function as stepping stones toward more sophisticated learning approaches.

Additionally, the difference in rehearsal strategy use between high-performing ninth-grade and fifth-grade students may reflect developmental trends in metacognitive awareness and prior knowledge accumulation. As observed in prior research, students with more extensive content knowledge are

better equipped to deploy rehearsal selectively and in coordination with higher-order strategies (Akyol et al., 2010). This developmental perspective supports the idea that strategy sophistication evolves through iterative self-regulatory practice, reinforced by academic experience and feedback loops (Panadero, 2017; Billore et al., 2023). Hence, our findings emphasise the importance of promoting not only self-regulatory goals and motivational beliefs but also flexible strategy use tailored to students' cognitive development and subject-matter familiarity.

Previous research had not ventured into exploring the relationship between students' self-regulation and science achievement in TIMSS, with cognitive items being categorised as either knowledge (low-level) or reasoning and application (high-level) clustering variables. Our study, however, harnessed MANOVA to scrutinise this connection, unearthing significant disparities between students with loftier goals, control of beliefs, and the utilisation of learning strategies through rehearsal, who performed more commendably in both low and high cognitive items of TIMSS. Curiously, the finding that test anxiety did not significantly differ between low- and high-performing students in this study merits closer examination. One likely explanation lies in the low-stakes nature of the TIMSS assessment, both in the context of this study and in its official international administration. TIMSS results do not influence students' grades, academic progression, or school placement, which likely minimizes the perceived consequences of the test. As a result, students may approach TIMSS with less pressure and fewer anxiety-driven performance constraints compared to high-stakes national exams. This diminished pressure may allow other psychological variables—such as goal orientation, control of learning beliefs, and rehearsal strategies—to exert a stronger influence on performance (Aydin et al., 2019; Zheng & Li, 2016). Additionally, the use of the TOSS digital platform may have further reduced anxiety by offering a more familiar and less formal test-taking experience, consistent with research suggesting that technology-based assessments can foster autonomy and emotional comfort (Billore et al., 2023).

These findings align with prior Omani research highlighting the significance of cognitive and metacognitive regulation in science assessment contexts. As shown by Al-Balushi et al. (2022a, 2022b), lower-performing students demonstrate higher levels of mind wandering and weaker metacognitive skills—factors that directly impact TIMSS science test performance. These patterns mirror our findings, which emphasize the role of goal-setting, control of learning beliefs, and rehearsal strategies in differentiating TIMSS performance levels. Collectively, the evidence points to a systemic need within Omani science education to move beyond content delivery and toward explicit instruction in self-regulation and metacognitive control as means to reduce achievement gaps.

Conclusion and Implications

This study offers valuable insights into the performance of 5th- and 9th-grade students in Oman participating in the TIMSS assessment. This research represents the first of its kind within Oman to probe the interrelationships among students' goal orientations, beliefs control, rehearsal-based learning strategies, anxiety levels, and their TIMSS performance. The study harnessed a sample of 776 students who undertook the Trends in Oman Science Study (TOSS). Our initial research question, aimed at discerning the extent of variations in self-regulation between low and high TIMSS achievers in 5th and 9th grades, was addressed through a rigorous MANOVA analysis. The findings underscored marked distinctions between high and low TIMSS performers. Precisely, high-performing students in both grade levels exhibited discernible disparities from their low-performing counterparts in terms of their capacity to establish loftier goals, exercise control over their learning beliefs, and employ learning strategies characterised by rehearsal.

Prior investigations have neglected to investigate the manner in which self-regulation within the realm of science education aligns with TIMSS performance while concurrently considering cognitive items as clustering variables. These cognitive items are categorised into knowledge (representing lower-level cognition) and reasoning and application (indicating higher-level cognitive skills). Our extensive

MANOVA scrutiny divulged substantial variations between students characterised by elevated goals, robust control over beliefs, and a penchant for learning strategies involving rehearsal. These differences manifested in both lower and higher cognitive items encompassed in the TIMSS assessment. Curiously, the study unearthed no significant indications of heightened anxiety levels among students spanning both grade levels. This finding intimates that the TIMSS assessment may exert a comparatively reduced degree of stress upon students when juxtaposed with conventional science courses or other disciplines. This propensity could be attributed to the fact that successful performance in the TIMSS test does not constitute a prerequisite for students to advance to the succeeding grade.

The implications arising from this study are multifaceted, with direct relevance to instructional design, teacher professional development, and educational policy. First, the findings underscore the importance of cultivating students' self-regulation skills—particularly goal adaptation, control of learning beliefs, and strategic rehearsal—as these elements are significantly associated with higher TIMSS science performance. This highlights the need for a pedagogical shift from teacher-centred to learner-centred approaches, where students are explicitly taught to set goals, monitor their understanding, and reflect on their progress. To facilitate this transformation, science teachers should be equipped with structured classroom strategies that foster metacognitive engagement. For example, embedding regular self-assessment prompts, goal-setting activities at the start of science units, and reflection journals can help students internalise self-regulation as part of their learning routine. Additionally, technology-enhanced instruction allows learners to adjust the pace of their learning based on their individual needs, thereby promoting self-regulated learning (Chohan et al., 2024; Reinoso-Tapia et al., 2024).

Professional development programs should also prioritize building teachers' capacity to scaffold these self-regulatory behaviours. Training modules could include modelling think-alouds for strategy use, integrating formative feedback loops, and designing tasks that promote autonomy and cognitive challenge. Such efforts would support a system-wide progression in self-regulatory capacity from early grades through secondary school, aligning with the study's call for continuity in fostering learner agency from Grade 1 to Grade 12.

This study's findings related to motivational constructs offer a foundational basis for boosting TIMSS performance at scale. Future research should expand these insights into cross-national investigations, aiming to develop motivational profiles that account for both systemic variables and localised policy environments. In the interim, curriculum designers and school leaders in Oman and comparable contexts can begin by auditing current science instruction for its alignment with motivational principles—such as relevance, autonomy support, and emotional engagement—and iteratively adapt teaching practices to reflect evidence-based motivational and self-regulation frameworks.

Beyond instructional shifts and teacher training in self-regulation, this study also highlights the importance of assessment design in fostering student engagement and reducing performance-related stress. Given that TIMSS is a low-stakes assessment with no direct consequences on students' grades or academic progression, its format provides a valuable model for promoting performance in emotionally supportive conditions. Teachers can leverage this insight by embedding similar low-stakes, TIMSS-style assessment tasks into routine classroom practice, encouraging students to engage with cognitively demanding science items without the pressure associated with high-stakes testing. This environment creates space for students to rehearse goal-setting, self-monitoring, and reflection strategies—skills that contribute to sustained academic growth. Teacher professional development should therefore include explicit training on implementing formative assessments that activate self-regulatory behaviours, such as structured rehearsal exercises, self-questioning routines, and timely feedback cycles. These practical interventions can help students internalise effective learning strategies and transfer them across contexts, ultimately supporting both immediate academic performance and long-term learner autonomy.

Future research endeavours should focus on scrutinising teaching practices within Omani schools to elevate students' levels of agency in the context of science curriculum learning. In addition,

the motivational facets of students' TIMSS performance assume paramount importance in heightening their performance. Thus, it is advisable to embark on a cross-country analysis aimed at constructing a more comprehensive motivational profile, which takes into account variations in the educational system and environmental policies.

One notable limitation of this study concerns the sample composition, particularly the gender imbalance in the Grade 5 cohort. While the overall sample size ($n = 776$) is robust, the Grade 5 participants were exclusively female due to the single-sex schooling structure at that level in Oman. This gender homogeneity presents a potential confounding variable when interpreting differences between the Grade 5 and Grade 9 cohorts and limits the generalisability of findings to all Omani students. Future studies should aim to include more balanced gender representation or conduct stratified analyses to better capture the variability attributable to gender, thereby enhancing the ecological validity of the findings.

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Methodological framework for integrating sustainable development goals in pre-service biology teacher education

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ABSTRACT

This study explores how the Sustainable Development Goals (SDGs) can be meaningfully integrated into pre-service biology teacher education, with a particular focus on the development of sustainability-related competencies. A mixed-methods design combined survey data from 120 pre-service biology teachers with semi-structured interviews conducted with 15 university instructors involved in teacher training. The results suggest that although future teachers generally understand the concept of sustainable development and recognise its relevance to biology education, their readiness to apply the SDGs in practice remains at a moderate level. Paired-samples t-test analysis demonstrated statistically significant improvements across all measured competency dimensions following the SDG-orientated methodological intervention ($p < .001$). The largest improvement was observed in the ability to design SDG-based biology lessons ($\Delta M = +1.08$, Cohen's $d = 0.94$), indicating a strong practical effect. The main challenges were associated with lesson planning, interdisciplinary connections, and the assessment of sustainability competencies. Student-centred approaches, such as project-based learning, inquiry activities, and collaborative reflection, were linked to greater pedagogical confidence and methodological readiness, whereas traditional lecture-based methods had less influence. Interview data further revealed fragmented curriculum integration and an absence of clear methodological guidance. The study highlights the importance of systematically incorporating SDG-focused methodological components into biology teacher education programmes and offers practical suggestions for curriculum design and teaching practice in the context of education for sustainable development. It contributes to the literature by combining validated competency assessment, mixed-methods analysis, and intervention-based evidence within the under-represented Central Asian context of pre-service biology teacher education.

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Introduction

Contemporary education systems operate within a rapidly globalising world where economic, environmental, and social challenges increasingly intersect. Under these conditions, education is expected not only to transmit disciplinary knowledge but also to contribute to the long-term sustainability of societies (UNESCO, 2017). In this context, the Sustainable Development Goals (SDGs) have emerged as a key international framework guiding educational transformation and curriculum renewal, and higher education institutions are widely regarded as central actors in their achievement (Chankseliani & McCowan, 2021). Their integration into teacher education is especially significant, as teachers directly influence how future generations understand environmental responsibility, social justice, and civic engagement (Mulà & Tilbury, 2025). Biology occupies a distinctive position within this process. As a natural science discipline, it addresses fundamental issues related to ecosystem stability, biodiversity loss, human health, and climate change — areas that closely align with the core priorities of sustainable development (Jeronen et al., 2017; Jackson et al., 2023). Consequently, the professional preparation of future biology teachers represents a particularly appropriate educational context for embedding SDG principles in a systematic and pedagogically meaningful way. Nevertheless, despite this conceptual alignment, the integration of SDGs into pre-service biology teacher education remains uneven and insufficiently structured in many higher education institutions, and existing approaches often lack methodological coherence and a clearly articulated pedagogical rationale (Ferrer-Estévez & Chalmeta, 2021; Leal Filho et al., 2019).

Although international policy frameworks and strategic documents consistently emphasise the role of education in achieving the Sustainable Development Goals, their practical implementation within teacher education programs remains problematic (Bourn et al., 2017). A substantial body of research has examined the sustainability competencies future teachers require and the pedagogical approaches capable of developing them: seminal frameworks by Wiek et al. (2011) and Rieckmann (2012, 2018) identified the core competencies underlying sustainability-orientated practice, while Lozano et al. (2017, 2019, 2022) demonstrated that active, student-centred methods such as project-based and problem-based learning are more effective than traditional instruction for developing these competencies. In biology education specifically, Bezeljak et al. (2020) found that pre-service teachers are relatively confident in the environmental dimension of sustainability but struggle to connect it with its economic and social dimensions, and a recent bibliometric review by Jeronen et al. (2026) confirmed that holistic studies at the intersection of biology and Education for Sustainable Development (ESD) remain limited. This gap is particularly visible in the preparation of future biology teachers: a systematic review of 158 publications by Fischer et al. (2022) found that the assessment of learning outcomes and the promotion of systemic change remain the least developed areas of research on teacher ESD, and current teacher training curricula continue to introduce SDG-related content in a fragmented manner, without consistent methodological support. Instructional strategies often remain predominantly theoretical, while assessment practices are rarely aligned with the evaluation of sustainability-related competencies, producing a disconnect between curriculum content, teaching methods, and assessment tools that limits future biology teachers' ability to translate sustainability concepts into effective classroom practice (Sinakou et al., 2018).

What remains largely absent from this literature, however, is empirical evidence from Central Asia. Existing regional studies indicate that ESD implementation across universities is uneven and that student awareness of the SDGs remains low (Bespalyy et al., 2024), that teacher preparation in Kazakhstan is affected by fragmented curricula and weak institutional support (Yelubayeva et al., 2023), and that motivational and reflective aspects of professional readiness among biology students are frequently underestimated (Nurgaliyeva et al., 2022). More recent Kazakhstani studies have identified a persistent gap between declared attitudes and actual teaching skills among pre-service biology teachers (Abiltayeva et al., 2025), as well as a weak representation of critical thinking, a key competence of Target 4.7, in the stated learning outcomes of teacher education programmes (Kabysheva, 2025). None of these studies, however, combines validated competency measurement with an intervention-based

design capable of demonstrating whether structured methodological training can change this picture, and this is the gap the present study addresses. The study is grounded in the conceptual understanding of sustainable development as a multidimensional phenomenon that encompasses economic, environmental, and social dimensions. Education is viewed as a central mechanism for fostering the knowledge, values, and competencies required to support sustainable societal development. From this perspective, teacher education plays a mediating role between global sustainability agendas and classroom-level educational practice. The pedagogical framework of the study draws on constructivist learning theory, the competency-based approach, and principles of interdisciplinary education. Constructivist theory emphasises that learning occurs through active engagement and meaning-making rather than through passive knowledge transmission. The competency-based approach enables the evaluation of future teachers' readiness for professional practice, particularly in complex and value-laden domains such as sustainable development (Rieckmann, 2012). Interdisciplinary learning, in turn, facilitates the integration of biological knowledge with broader ecological, social, and ethical contexts, which is essential for addressing sustainability challenges (Wiek et al., 2011). The originality of this study lies in several important aspects. First, the study examines SDG integration specifically within pre-service biology teacher education, an area that remains under-represented in current ESD research. Second, the study combines quantitative, qualitative, and quasi-experimental intervention data within a single mixed-methods framework. Third, the research adapts and validates SDG-related competency instruments for the educational and cultural context of Kazakhstan. Finally, the study provides empirical evidence from Central Asia, a region that remains insufficiently represented in international literature on Education for Sustainable Development.

Research Questions

This study addresses the following research questions:

1. What is the level of readiness of pre-service biology teachers to integrate SDGs into teaching practice?
2. Which pedagogical approaches most effectively support the development of SDG-related competencies?
3. What methodological challenges hinder the implementation of SDGs in biology teacher education?

Research Hypotheses

- H1. Structured SDG-orientated methodological training significantly improves pedagogical competence.
- H2. Active learning approaches (e.g., project-based and inquiry-based learning) enhance pedagogical confidence in SDG implementation.
- H3. Interdisciplinary and reflective instruction improves overall readiness for integrating SDGs into teaching practice.

Aim of the Study

The aim of this study is to identify and empirically validate the methodological foundations for integrating Sustainable Development Goals (SDGs) into pre-service biology teacher education. In particular, the study seeks to examine the effectiveness of SDG-orientated pedagogical approaches in developing sustainability-related competencies, including pedagogical confidence, methodological competence, and interdisciplinary teaching skills among future biology teachers.

Literature Review

The issue of integrating the SDGs into the preparation of future biology teachers has emerged at the intersection of three research areas. These include education for sustainable development (ESD),

subject specific teacher training methods, and the competence-based approach in teacher education. These areas developed relatively independently over several decades. However, the adoption of the 2030 Agenda and its Target 4.7 gave them a common direction. A review of existing studies makes it possible to trace how the academic community gradually moved from general frameworks to more specific questions of pedagogy, competencies, and assessment. It also allows us to identify the gaps that justify the need for the present study. The theoretical foundation of ESD was formed in works that appeared before the adoption of the 2030 Agenda. Sterling (2001) introduced an important distinction between education about sustainability as an update of content and sustainable education as a transformation of values and meanings within the system. Tilbury (2011), working under UNESCO, summarized global experience and identified five key pedagogical principles of ESD. She emphasized the role of teacher preparation as a strategic factor for systemic change. UNESCO (2017) further developed these ideas by outlining learning objectives and suggested activities for each of the 17 SDG. Vare and Scott (2007) proposed an analytical distinction between ESD 1 and ESD 2. The first focuses on informed behavior, while the second aims to develop critical thinking and the ability to act in conditions of uncertainty. This framework is widely used in current research on teacher education. Wals (2015) developed the idea of transgressive learning and argued that environmental and social crises require not simple adaptation but a deeper reconsideration of existing models. Later studies that focus on higher education practice show that the institutional response remains uneven. Chankseliani and McCowan (2021) identified significant differences in how universities support the full range of the SDGs. Ferrer-Estévez and Chalmeta (2021) showed that active teaching approaches are still not sufficiently represented in official curricula. Leal Filho et al. (2019) found that the main barriers to integrating the SDGs into higher education include limited teacher training, inflexible curricula, and weak institutional support.

At the same time, a separate line of research focused on sustainability competencies was formed. The work of Wiek et al. (2011) became one of the most widely cited frameworks. It identified five core competencies. These include systems thinking, anticipatory competence, normative competence, strategic competence, and interpersonal competence. A decade later, Brundiers et al. (2021) updated this framework based on a Delphi study. They added competencies of integration and implementation. Rieckmann (2012, 2018), in a series of studies, defined eight key competencies in ESD. He placed strong emphasis on values and critical reflection. Barth et al. (2007) showed that sustainability competencies in higher education are most effectively developed through interdisciplinary and self-directed learning. Bertschy et al. (2013) made an important distinction. They separated competencies for learners in sustainability from the professional competencies of teachers in ESD. This distinction was further developed by Cebrián and Junyent (2015). They proposed a seven-component professional model and showed that students in teacher education programs have a limited awareness of their own competencies in this field. Lozano et al. (2017, 2019, 2022) created a matrix that links competencies with teaching approaches. Their findings confirmed that case studies, problem-based learning, and project-based learning are more effective than traditional lectures for developing sustainability competencies. Mogensen and Schnack (2010) pointed out that the tradition of action competence, rooted in the German concept of *Bildung*, offers a democratic alternative to an instrumental view of competencies.

A separate line of research focuses on teacher education in the context of sustainable development. Mulà and Tilbury (2025) identified eight catalytic entry points for embedding ESD into teacher education programs across European countries. Fischer et al. (2022) conducted a systematic review of 158 publications and found that the assessment of learning outcomes and the promotion of systemic change remain the least developed areas in research on teacher ESD. Bourn et al. (2017) documented a persistent gap between policy declarations on ESD and actual teaching practice in teacher education programs. Sinakou et al. (2018, 2019) showed that even academics working in this field often rely on partial rather than holistic understandings of sustainable development. This affects what they communicate to their students. Vare et al. (2019) described the Rounder Sense of Purpose project, where twelve professional competencies for teachers in ESD were defined for European teacher education programs. Darling-Hammond et al. (2017) identified seven features of effective professional

development for teachers. These features are closely aligned with active learning approaches that are widely used in ESD.

Biology education has been studied in the context of sustainable development less often than other natural science disciplines. However, interest in this topic has grown in recent years. Bezeljak et al. (2020) compared Slovenian and Austrian student teachers and found that future biology teachers are confident in the environmental aspects of sustainability but have difficulty linking them with economic and social dimensions. Jeronen et al. (2017), in a review of teaching methods in biology and ESD, concluded that outdoor learning, fieldwork, and project-based learning are the most effective for developing environmental literacy. A later bibliometric analysis by Jeronen et al. (2026) confirmed that holistic studies at the intersection of biology and ESD remain limited. Jackson et al. (2023) described the redesign of the school biology curriculum around socio-scientific issues aligned with the SDG. Their study showed that disciplinary rigor and a value-orientated focus on sustainability do not contradict each other. Boeve-de Pauw et al. (2015), based on a sample of more than 2,000 Swedish students, demonstrated that holistic and pluralistic approaches to teaching ESD can significantly influence students' ways of thinking. Active and student-centred teaching methods form one of the most developed areas in this body of literature. Krajcik and Blumenfeld (2006) identified five key features of project-based learning that are still used as a reference in curriculum design. Pedaste et al. (2015) synthesized research on inquiry-based learning into a five-phase cycle, which has become a standard planning tool in science teacher education. Markula and Aksela (2022) examined how teachers implement project-based learning in school science courses and noted that environmental and sustainability-related topics often serve as the driving questions of projects. Strat et al. (2024), in a systematic review of 142 studies, found that future science teachers learn inquiry-based learning successfully as students, but face difficulties when applying it in their role as teachers. Kalsoom and Khanam (2017) showed, using data from Pakistan, that inquiry activities related to the SDG significantly increase environmental awareness among teacher education students. Lozano et al. (2019, 2022) summarized data from 13 European universities and confirmed that problem-based and project-based learning consistently appear as the most effective approaches for developing sustainability competencies. Rieckmann (2012) and Cebrián et al. (2020) emphasized the role of reflective and interdisciplinary practices in the development of professional identity in ESD.

Issues of assessment and curriculum integration in ESD form a separate problem area in the research literature. Sinakou et al. (2018) found that even among teacher educators, a simplified and mainly environmental understanding of sustainability prevails. This narrows the range of competencies that are developed. Leal Filho et al. (2019) systematized institutional barriers that hinder the implementation of ESD and identified the lack of targeted teacher training as the main challenge. Lozano et al. (2019) showed that the assessment of sustainability competencies remains the weakest element in university teaching practice. Boeve-de Pauw et al. (2015) warned that positive changes in values do not always lead to corresponding changes in behavior. For this reason, assessment tools should address several levels of readiness. Cebrián et al. (2020) identified the development of reliable diagnostic tools as one of the key priorities in current research. The context of Kazakhstan and Central Asia requires special attention, since international studies rarely focus on this region. Yelubayeva et al. (2023), in a qualitative study, identified the main challenges of ESD in Kazakhstan. These include insufficient teacher preparation, fragmented curricula, and weak institutional support. Nurgaliyeva et al. (2022) examined practice-orientated training of biology students in Kazakhstani universities and showed that motivational and reflective aspects of professional readiness are often underestimated. Abiltayeva et al. (2025) conducted a survey of future biology teachers in Kazakhstan and revealed a clear gap between declared attitudes and actual teaching skills. This finding is consistent with international research that points to a mismatch between knowledge and teaching confidence. Kabysheva (2025) carried out a computer-based analysis of bachelor's level teacher education programs in Kazakhstan and found that critical thinking, as a key competence of Target 4.7, is weakly represented in stated learning outcomes. Saparbaikyzy et al. (2026) provided quasi-experimental evidence that project-based environmental education significantly improves social and environmental values and

behavior among school students in Kazakhstan. This supports the potential of active learning methods in this national context. Bepalyy et al. (2024) conducted a comparative study in four Central Asian countries (Kazakhstan, Tajikistan, Kyrgyzstan, and Uzbekistan) and concluded that student awareness of the SDGs remains low, while the integration of ESD into university programs is uneven.

The review makes it possible to identify several key gaps that justify the need for the present study. First, although the international knowledge base on sustainability competencies and active learning methods is extensive, studies that focus specifically on teacher education in biology remain limited. The Central Asian context is also almost absent in this field. Second, in cases where the preparation of biology teachers has been examined, researchers consistently report that environmental knowledge is well developed. At the same time, the integration of economic and social dimensions of sustainability remains weak. Third, there is a clear lack of data on the actual use of project-based and inquiry-based learning by Kazakhstani students in biology teacher education programs, despite existing policy declarations. Fourth, the field requires more intervention-based studies that combine the content of the SDGs, competence frameworks, and active teaching methods within a single instructional design with measurable outcomes. Finally, there is a shortage of assessment tools that are sensitive to the educational and linguistic context of Kazakhstan. Such tools are needed to track the development of professional readiness among future biology teachers. These gaps define the research focus of the present study.

Methods

Research Design

This study employed a mixed-methods research design integrating quantitative and qualitative strands within a convergent parallel model (Creswell & Plano Clark, 2018). Quantitative data captured the distribution and magnitude of SDG-related readiness across the full participant sample, while qualitative data from instructor interviews illuminated pedagogical conditions and institutional constraints shaping that readiness. A quasi-experimental pre-post component was embedded within the quantitative strand to evaluate the effect of the authorial instructional module on a volunteer subgroup. Combining these two strands with the embedded quasi-experimental component allowed methodological triangulation, strengthening the credibility and interpretive depth of the findings.

Institutional Context and Participants

The study was conducted at Korkyt Ata Kyzylorda University (Kazakhstan), an institution offering an accredited pre-service programme for biology teacher education. The quantitative phase involved 120 pre-service biology teachers (female 74%, male 26%; mean age = 20.8 years, SD = 1.4) enrolled across Years 2, 3, and 4: Year 2 ($n = 38$, 31.7%), Year 3 ($n = 45$, 37.5%), and Year 4 ($n = 37$, 30.8%). Purposive sampling ensured variation in academic year and prior exposure to sustainability-related coursework.

The qualitative phase involved 15 university instructors responsible for biology pedagogy, environmental education, or curriculum design courses. Purposive sampling criteria included a minimum of five years of experience in pre-service teacher education, direct involvement in biology methodology or ESD-related courses, and willingness to reflect critically on current practice. A subgroup of 60 students drawn from Years 3 and 4 also participated in the instructional intervention. Participation was voluntary and had no bearing on academic assessment.

Instructional Intervention

The SDG-focused instructional intervention was built around two interlocking components developed by the lead author specifically for pre-service biology teacher education in Kazakhstan. The

first component was the authorial course "Kazakhstan Bioresources and Sustainable Development," comprising 30 contact hours and approximately 40 hours of independent and collaborative project work, delivered over one academic semester (15 weeks). The course was structured in three sequential blocks. The first block (Weeks 1–3) consisted of thematic seminars in which students analysed linkages between seven SDGs (2, 3, 4, 6, 13, 14 and 15), together with Targets 4.7 and 4.c of SDG 4, and core biology curriculum topics, drawing on Kazakhstani ecological contexts: the Aral Sea crisis, Tian Shan glacier retreat, steppe ecosystem degradation, and regional biodiversity loss. The second block (Weeks 4–11) centred on project-based learning, during which students, in groups of three or four, identified a locally relevant sustainability problem, formulated a driving question, conducted inquiry activities, and developed a complete biology lesson sequence that integrated SDG content with active teaching strategies. Projects were subject to structured peer feedback. The third block (Weeks 12–15) focused on reflective practice through written reflective journals, group discussions, and individual professional development plans.

The second component was the School EcoClub, implemented during the students' teaching practicum at general education schools in Kyzylorda. Operating under the methodological supervision of the university department, students planned and led club activities aligned with the UN 2030 Agenda across two formats. Within biology lessons, SDG-orientated content was integrated into the existing curriculum in agreement with the mentor teacher. In extracurricular sessions, students organised thematic meetings, field observations of local ecological sites, and project-based environmental initiatives that addressed regional sustainability challenges. EcoClub activities were documented through reflective diaries, mentor evaluations, and a portfolio of completed events.

Prior to the main study, the course tasks and instruments were piloted with five students not included in the main sample. Minor revisions were made to task instructions and two questionnaire items on the basis of pilot feedback.

Research Instruments

Three instruments were used. The first was the SDG Readiness Questionnaire (SRQ), a structured 24-item measure given to all 120 participants. Items assessed six dimensions on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree): knowledge of SDGs, understanding of sustainability concepts, ability to integrate SDGs into biology lessons, use of SDG-orientated teaching methods, ability to design interdisciplinary SDG tasks, and assessment of sustainability competencies. The questionnaire was developed with reference to prior ESD research (Cebrián & Junyent, 2015; Sinakou et al., 2019) and reviewed for content validity by three experts in biology education and ESD. Internal consistency was satisfactory (Cronbach's $\alpha = .81$), with subscale reliabilities ranging from $\alpha = .73$ to $\alpha = .79$.

To further ensure construct validity, exploratory factor analysis (EFA) was conducted prior to the main analysis. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was .82, indicating good suitability for factor analysis, while Bartlett's Test of Sphericity was statistically significant ($\chi^2 = 846.31$, $p < .001$). Factor loadings for all retained items exceeded .60, confirming acceptable construct validity of the instrument.

The second instrument was the SDG Competency Self-Assessment Scale (SCAS), an authorial adaptation of the Instrument for Measuring Student Sustainability Competencies (Waltner et al., 2019) developed for the Kazakhstani context. The original instrument was translated, content-adapted to local ecological referents (Aral Sea, Tian Shan glaciers, steppe ecosystems), subjected to expert review by eight specialists, piloted with 24 students, and refined on the basis of item analysis. The finalised 20-item scale comprises four subscales measuring gnoseological (G), praxiological (P), axiological (A), and motivational (M) dimensions of SDG-related competency. Internal consistency of the adapted scale was acceptable at both time points (pre: $\alpha = .83$; post: $\alpha = .85$). The SCAS was administered to the intervention subgroup ($n = 60$) one week before the course began (M-0) and one week after its conclusion (M-4). A five-point monitoring system spanning checkpoints M-0 through M-4 tracked competency trajectories

across the full semester, with M-1 and M-2 providing formative mid-course data and M-3 capturing teaching practicum outcomes evaluated by the mentor teacher, the university supervisor, and the student's own reflective report.

The third instrument was a semi-structured interview protocol used with the 15 teacher educators. The 12-question protocol addressed three thematic areas: current practices and challenges in SDG integration, perceptions of effective pedagogical approaches, and recommendations for curriculum reform. The protocol was informed by Fischer et al. (2022) and piloted with two instructors outside the main sample. Interviews lasted 35–55 minutes ($M = 44$ min), were audio-recorded with participants' consent, and were conducted in participants' preferred language (Kazakh or Russian). Transcripts were produced verbatim and translated into English by a certified bilingual translator, with back-translation by a second independent translator; discrepancies were resolved through consensus.

Procedure

Data collection unfolded in three sequential stages within one academic semester. In Stage 1, the SRQ was distributed electronically to all 120 participants via an institutional survey platform. Participants had two weeks to complete the questionnaire; one reminder was sent at the midpoint. The response rate was 100%. In Stage 2, the one-semester instructional intervention was delivered to the volunteer subgroup of 60 students. The SCAS was administered at M-0 (one week before the first session) and M-4 (one week after the final session). To minimise response bias, both administrations used anonymous participant codes. Monitoring checkpoints M-1, M-2, and M-3 were embedded at fixed points during the semester. In Stage 3, semi-structured interviews were conducted with the 15 teacher educators in an online or in-person format according to participant preference.

Data Analysis

Quantitative data from the SRQ were analysed using descriptive statistics (means, standard deviations, frequency distributions) to characterise SDG readiness across dimensions and years of study. Pearson product-moment correlations examined associations between reported frequency of specific teaching methods and overall SRQ scores. For the pre-post comparison of SCAS data, paired-samples t-tests were applied to each of the four subscales (G, P, A, M), with effect sizes calculated using Cohen's d . All quantitative analyses were conducted in IBM SPSS Statistics (Version 27) with α set at .05.

Qualitative interview data were analysed through reflexive thematic analysis following Braun and Clarke's (2022) six-phase procedure. Initial coding was conducted by the lead researcher; a second researcher independently coded 30% of the transcripts. Inter-rater reliability was substantial (Cohen's $\kappa = .76$), and discrepancies were resolved through discussion. Quantitative and qualitative findings were integrated at the interpretation stage by mapping thematic categories onto the readiness dimensions identified quantitatively.

Ethical Considerations

The study was approved by the Research Ethics Committee of Korkyt Ata Kyzylorda University prior to data collection. All participants received a written information sheet detailing the study's purpose, procedures, data handling practices, and their right to withdraw at any time without consequence. Informed consent was obtained in writing before any data were collected. Students in the intervention subgroup were explicitly informed that participation was voluntary and would not affect their course grades or academic standing. All data were anonymised at the point of transcription and stored on a password-protected institutional server accessible only to the research team. No personally identifiable information is reported in this article.

Results

Preparation Level of Future Teachers for SDG Implementation

Quantitative analysis showed that the level of preparation of future biology teachers regarding the integration of the Sustainable Development Goals (SDGs) into pedagogical practice was heterogeneous. The level of preparation was assessed on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree) according to several criteria. In particular, the levels of conceptual knowledge of SDGs, understanding of sustainable development principles, ability to integrate SDGs into the content of biology lessons, use of SDG-orientated teaching methods, development of interdisciplinary tasks and assessment of sustainable development competencies were considered. The results showed that future biology teachers' theoretical awareness and conceptual understanding of the concepts of SDGs and sustainable development were at an average level. However, it was found that the competencies related to methodological preparation and assessment were relatively poorly developed. In particular, participants showed high confidence in understanding the importance of SDGs for the biology subject, but they felt less confident in developing SDG-integrated lesson plans, systematically using active learning strategies, and assessing students' sustainable development competencies. This trend clearly demonstrates the imbalance between the level of knowledge-based preparation and practical pedagogical capabilities of future teachers. That is, there is a gap between awareness of sustainable development principles and the ability to effectively implement them in the actual teaching process. Overall, the results obtained confirm that future biology teachers have initial preparation for implementing SDG, but systematic methodological training is needed to translate this preparation into effective and sustainable classroom practice.

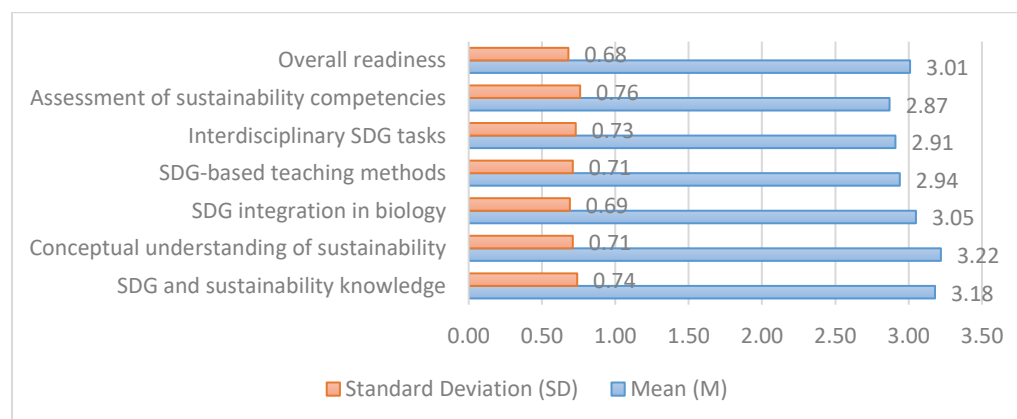
Table 1

Mean indicators of SDG-related preparation (N = 120)

Dimension of Readiness	Mean (M)	Standard Deviation (SD)
Knowledge of SDGs	3.18	0.74
Understanding of sustainability concepts	3.22	0.71
Ability to integrate SDGs into biology lessons	3.05	0.69
Use of SDG-oriented teaching methods	2.94	0.71
Designing interdisciplinary SDG tasks	2.91	0.73
Assessment of sustainability competencies	2.87	0.76
Overall readiness	3.01	0.68

Figure 1

Mean scores of SDG-related readiness among pre-service biology teachers



The results indicated that the overall level of preparation of future biology teachers was average across all measured dimensions ($M = 3.01$, $SD = 0.68$). Relatively high averages were observed in dimensions related to conceptual understanding, namely, the level of knowledge of the Sustainable Development Goals ($M = 3.18$, $SD = 0.74$) and understanding of the concepts of sustainable development ($M = 3.22$, $SD = 0.71$). These results indicate that the respondents have a basic theoretical understanding of the principles of sustainable development. In addition, lower averages were found for methodological and practical dimensions. In particular, the indicators of the use of teaching methods focused on SDG ($M = 2.94$, $SD = 0.71$), the development of interdisciplinary SDG tasks ($M = 2.91$, $SD = 0.73$) and the assessment of sustainable development competencies ($M = 2.87$, $SD = 0.76$) remained at a low level. This means that, although future biology teachers have theoretical preparation on sustainable development issues, their skills for effective implementation and assessment in the teaching process are insufficiently developed.

Distribution of Preparation Levels

To better illustrate differences in the level of preparedness for implementing the Sustainable Development Goals (SDGs), respondents were classified into three groups based on their composite readiness scores: low, moderate, and high. This categorisation made it possible to examine not only overall trends but also the extent to which future biology teachers differ in their capacity to apply SDG-related principles in educational practice. The analysis indicates that the largest group of respondents falls within the moderate readiness category. The analysis indicates that many pre-service biology teachers possess a general awareness of the SDGs and recognise their relevance to biology education; however, their ability to apply these principles in a methodologically confident manner remains limited. Such respondents appear to be at a transitional stage between theoretical understanding and practical implementation. At the same time, a considerable proportion of participants demonstrated a low level of readiness. This group is characterised by insufficient practical experience and uncertainty in selecting appropriate SDG-orientated instructional and assessment strategies. These respondents are likely to require substantial methodological support to move beyond declarative knowledge toward effective classroom application. Only a smaller segment of the sample reported a high level of readiness. This finding suggests that comprehensive and systematic competence in integrating SDGs into biology teaching is not yet common among future teachers. Overall, the distribution pattern reflects uneven preparation levels and points to structural gaps in current teacher education programmes.

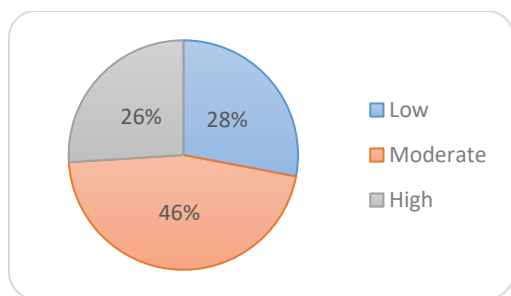
Table 2

Distribution of preparation levels of pre-service biology teachers for SDG implementation

Readiness Level	Score Range	Percentage
Low	1.0–2.4	28%
Moderate	2.5–3.4	46%
High	3.5–5.0	26%

Figure 2

Distribution of pre-service biology teachers' readiness levels for SDG implementation



As shown in Table 2 and Figure 2, nearly half of the respondents (46%) fall within the moderate readiness category. This suggests that while many future biology teachers have acquired basic knowledge and general awareness of the Sustainable Development Goals, they do not yet demonstrate sufficient methodological confidence for consistent classroom implementation. In addition, more than one quarter of participants (28%) display low readiness, indicating limited experience and hesitation in applying SDG-orientated teaching and assessment approaches. Only 26% of respondents report a high level of preparedness, confirming that advanced competence in systematically integrating SDGs into biology instruction remains relatively rare. Taken together, these findings underscore the need for targeted and structured methodological training within teacher education programmes.

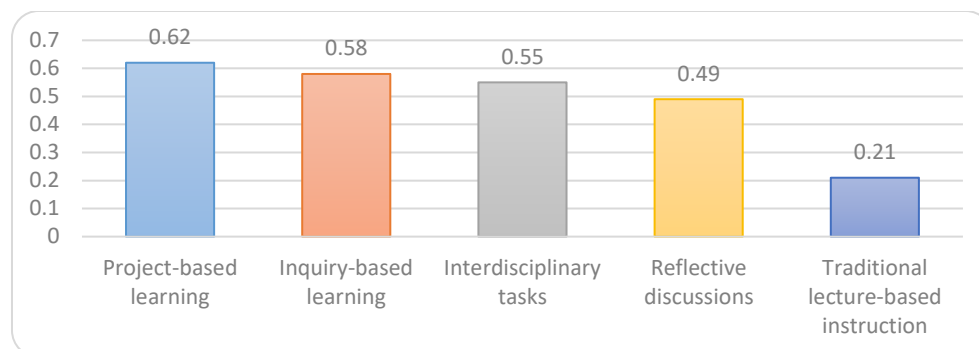
Relationship between Teaching Methods and Competency Development

To examine the relationship between instructional approaches and the development of SDG-related competencies, a Pearson correlation analysis was conducted. The analysis focused on identifying associations between commonly used teaching methods and indicators of pedagogical confidence, methodological preparedness, and sustainability-orientated competence among pre-service biology teachers.

Table 3

Correlations between teaching methods and SDG-related competencies

Teaching Method	r	Significance (p)
Project-based learning	0.62	< .01
Inquiry-based learning	0.58	< .01
Interdisciplinary tasks	0.55	< .01
Reflective discussions	0.49	< .01
Traditional lecture-based instruction	0.21	> .05

Figure 3*Correlation between teaching methods and SDG-related competencies*

Active, student-centred teaching methods—project-based learning, inquiry-based learning and interdisciplinary assignments—were found to have strong positive correlations with the development of SDG-related competencies in future biology teachers. These methods were found to be strongly associated with higher levels of pedagogical confidence, methodological preparedness and the ability to integrate sustainable development concepts into biology lessons. In contrast, traditional lecture-based teaching showed a weak and statistically insignificant association with the development of SDG-related competencies, indicating limited effectiveness in developing practical pedagogical skills for sustainable development.

Survey Results Students' Attitudes and Beliefs

The attitudes of future biology teachers towards the integration of the SDGs into the educational process were investigated through an extended survey in terms of their perception of the relevance of the subject, pedagogical confidence and methodological needs. The survey results indicated that the vast majority of respondents consider the SDGs important for biology as a subject and acknowledge that they increase the social and practical significance of their biology lessons. However, despite these positive views, only a significant minority of students noted that they felt confident in teaching topics related to SDG. At the same time, the majority of participants clearly indicated the need for additional methodological training aimed at implementing SDGs. These results point to a clear discrepancy between students' recognition of the importance of sustainable development and their perceived ability to teach it effectively, highlighting the necessity of structured, practice-orientated methodological preparation in biology teacher education programmes.

Table 4*Students' attitudes toward the integration of SDGs*

Survey Statement	Strongly Agree	Agree	Neutral	Disagree
SDGs are relevant to biology education	48%	34%	12%	6%
SDGs increase the social relevance of biology lessons	41%	35%	16%	8%
SDGs help connect biology with real-life problems	45%	33%	14%	8%
I feel confident teaching SDG-related topics	12%	22%	36%	30%
I need more methodological training on SDGs	52%	36%	8%	4%
SDGs should be systematically included in teacher education programs	57%	31%	7%	5%

The findings presented in Table 4 indicate an overall positive orientation of prospective biology teachers toward the Sustainable Development Goals (SDGs). A substantial proportion of respondents

perceive SDGs as an essential component of biology education (82%) and agree that their integration enhances the social relevance of biology lessons (76%). In addition, most participants (78%) acknowledge that SDGs facilitate meaningful connections between biological content and real-world sustainability challenges, thereby increasing the applied value of the subject.

Despite this generally favourable perception, the level of self-reported pedagogical confidence remains comparatively low. Only 34% of respondents indicated that they feel confident teaching SDG-related topics, while a considerable share expressed neutral or negative responses, reflecting uncertainty in practical classroom implementation. At the same time, an overwhelming majority of participants (88%) emphasised the need for additional methodological training specifically focused on SDG integration. Strong support was also expressed for the systematic inclusion of SDGs in teacher education programmes, with 88% of respondents agreeing with this position.

Taken together, these results reveal a clear discrepancy between positive attitudes toward sustainable development and insufficient pedagogical confidence, emphasizing the necessity of structured and methodologically grounded support in preparing future biology teachers.

Qualitative Results

The thematic analysis of semi-structured interviews conducted with teacher educators (N = 15) revealed three closely related themes concerning the integration of Sustainable Development Goals in pre-service biology teacher education.

First, participants consistently pointed to deficiencies within existing curricula, including the fragmented and episodic inclusion of SDG-related content, the absence of coherent methodological guidance, and limited emphasis on assessing sustainability-related competencies. As one respondent noted, “SDGs are formally mentioned in the curriculum, but teachers lack concrete methodological tools for their effective implementation.”

Second, teacher educators identified several pedagogical practices as particularly effective for integrating SDGs. These included project-based learning centred on local environmental issues, inquiry-orientated laboratory activities addressing real-life sustainability challenges, and reflective group discussions that connect biological knowledge with ethical and social considerations. Such approaches were viewed as enabling more profound engagement with sustainability concepts and supporting applied learning.

Third, the interview data revealed clear expectations on the part of students. According to participants, future teachers seek more practice-orientated and classroom-focused preparation, access to concrete examples of SDG-integrated biology lessons, and transparent criteria for evaluating sustainability-related competencies. Collectively, these themes highlight both existing methodological gaps and significant pedagogical potential for strengthening SDG integration in biology teacher education programmes.

Table 5

Main themes identified in teacher educator interviews

Theme	Description	Representative Quote
Curriculum fragmentation	SDGs are integrated inconsistently across courses	“SDGs are formally mentioned in the curriculum, but teachers lack concrete methodological tools.”
Methodological limitations	Lack of assessment criteria and practical teaching models	“There are few examples of SDG-oriented biology lesson plans.”
Importance of active learning	Project-based and inquiry approaches increase engagement	“Students learn sustainability concepts more effectively through practical activities.”
Need for practice-oriented training	Students require classroom-focused methodological preparation	“Future teachers need more opportunities to apply SDGs in real teaching contexts.”

Comparative Analysis of Pre- and Post-Intervention Competency Levels

A subgroup of participants ($n = 60$) completed a self-assessment of SDG-related competencies before and after participation in SDG-orientated instructional activities designed to enhance methodological readiness. This pre-post comparison aimed to examine changes in pedagogical confidence, methodological competence, and overall preparedness to integrate SDGs into biology teaching practice.

Table 6 presents the comparative results of competency levels before and after the intervention.

Table 6

Pre- and Post-intervention changes in SDG-related competencies among pre-service biology teachers

Competency Dimension	Before (M)	After (M)	Change
Pedagogical confidence	2.96	3.87	+0.91
Methodological competence	2.88	3.79	+0.91
Ability to design SDG-based lessons	2.74	3.82	+1.08
Interdisciplinary teaching skills	2.81	3.76	+0.95
Overall SDG readiness	2.92	3.83	+0.91

Figure 5

Comparison of competency levels before and after SDG-oriented methodological training

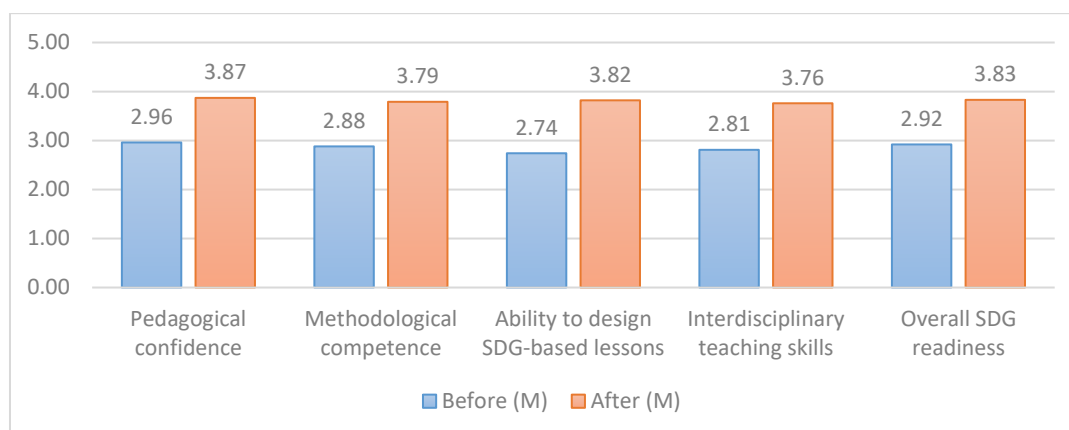


Table 7

Paired-Samples t-Test results for pre- and post-intervention competency scores

Competency Dimension	t	p	Cohen's d
Pedagogical confidence	8.42	< .001	0.91
Methodological competence	8.17	< .001	0.88
Ability to design SDG-based lessons	9.11	< .001	0.94
Interdisciplinary teaching skills	8.36	< .001	0.89
Overall SDG readiness	8.58	< .001	0.92

To examine the statistical significance of the observed changes, paired-samples t-tests were conducted for all competency dimensions measured before and after the intervention. The results demonstrated statistically significant improvements across all variables ($p < .001$). Effect size analysis using Cohen's d indicated moderate to strong practical effects of the intervention.

After the methodological training focused on SDGs, a clear and consistent increase was observed in all competence dimensions. This suggests that structured training interventions effectively

increase future biology teachers' pedagogical confidence, methodological competence and ability to design lessons based on sustainable development ideas. The observed positive changes indicate that targeted training focused on SDGs contributes to the development of not only the theoretical understanding of future teachers but also the practical pedagogical skills necessary to integrate sustainable development principles into the teaching process of biology. Overall, the results indicated that the readiness of future biology teachers to implement the Sustainable Development Goals is at an average level. Although this readiness rests on a sufficient theoretical understanding of the concepts of sustainable development and the SDGs, methodological and assessment competences remain insufficient. The results of the study clearly showed that active, student-centred teaching methods, such as project-based learning, research tasks and interdisciplinary activities, play an important role in the development of professional competences related to SDGs. It was also found that there is a clear gap between students' positive attitudes towards sustainable development ideas and their low pedagogical confidence in teaching topics related to SDG, which indicates gaps in practical training. Most importantly, the results of the "before-after" analysis proved that structured methodological training focused on SDG has a statistically and practically significant positive impact on pedagogical confidence, methodological competence and the level of general professional training, demonstrating the effectiveness of targeted teaching interventions in the training of future biology teachers.

Integration of Quantitative and Qualitative Findings

The integration of quantitative and qualitative findings revealed strong convergence across the data strands. Quantitative findings identified moderate overall readiness and weak methodological competencies among pre-service biology teachers, while qualitative interview data helped explain the underlying reasons for these patterns, including fragmented curriculum implementation and insufficient methodological guidance. At the same time, both data strands consistently highlighted the effectiveness of active, student-centred pedagogical approaches in supporting SDG-related competency development. The integration of findings therefore strengthened the interpretive validity of the study through methodological triangulation.

Discussion

The results of this study revealed several important patterns related to the implementation of the Sustainable Development Goals (SDGs) in the process of training future biology teachers. In general, the data obtained indicate that the readiness of future biology teachers to integrate SDGs into pedagogical practice is at an average level. Although this readiness rests on a relatively high conceptual understanding of sustainable development and the SDGs, methodological and assessment-related competencies remain weak. The results of the quantitative analysis showed that active, student-centred pedagogical approaches, such as project-based learning and inquiry-based learning, are closely associated with a high level of pedagogical confidence and competencies related to sustainable development, while the impact of traditional lecture-based teaching was limited. In addition, the qualitative data not only revealed persistent problems such as inconsistency in curricula and insufficient methodological guidelines but also showed a high demand from students for practice-orientated and reflective forms of learning. The significant positive changes identified during the "before-after" comparison prove that targeted methodological training focused on SDGs can significantly enhance professional readiness. On this empirical basis, the aim of the study was to identify methodological foundations for implementing the SDGs in the training of future biology teachers and to analyse pedagogical practices that contribute to the formation of sustainable development competencies. Accordingly, the discussion is structured around three main aspects: comparison with previous research, explanation of the effectiveness of individual teaching methods, and analysis of the results in terms of the proposed hypotheses (H1–H3). The results of the study are largely consistent with previous international research in the field of Education for Sustainable Development (ESD) and teacher training.

Many works note that prospective teachers have a positive attitude towards sustainable development ideas and an average level of theoretical understanding but face difficulties in implementing these ideas in concrete pedagogical practice and assessment systems (Anyolo et al., 2018; Evans et al., 2017; Imara & Altınay, 2021). The average level of preparation found in this study supports these findings and suggests that the challenges of integrating SDG are not specific to individual countries or institutions but rather a common trend across teacher education systems. Research in science and biology teacher education also shows that sustainable development topics are often presented in a fragmented manner and are not sufficiently integrated into methodological training (Borg et al., 2014; Büssing et al., 2019). The qualitative findings of this study also support these findings by identifying a lack of coherence in curricula, a lack of systematic methodological guidance, and insufficient attention to assessing sustainable development competencies. This study also fills the gaps in the literature empirically by combining quantitative indicators with qualitative teacher opinions through a mixed-methods design.

One of the central outcomes of the present research is the clearly articulated relationship between active, learner-orientated instructional practices and the development of SDG-related competencies among future biology teachers. The pedagogical value of project-based and inquiry-based learning can be interpreted through the lens of constructivist learning theory, which conceptualises learning as an active process of meaning-making grounded in engagement with authentic problems (Rieckmann, 2012; Sterling, 2010). Within such learning environments, sustainability is no longer treated as an abstract or declarative concept but is explored through concrete environmental, biological, and social contexts. In particular, project-based learning demonstrates a strong capacity to connect biological knowledge with both local and global sustainability challenges. By engaging students in the analysis and resolution of real-world issues, this approach enhances applied understanding and reinforces the professional relevance of sustainability-orientated instruction. These findings resonate with the conclusions of Leal Filho et al. (2016), who emphasise the potential of project-based learning to foster sustainability competencies in higher education settings. Inquiry-based learning complements this process by promoting analytical reasoning, critical thinking, and problem-solving skills, all of which are essential for addressing the complex and multifaceted nature of sustainable development. By contrast, the limited contribution of traditional lecture-based instruction observed in this study aligns with earlier research indicating that transmissive teaching models are insufficient for cultivating higher-order sustainability competencies (Cotton et al., 2007; Summers et al., 2005). Such approaches tend to prioritise content delivery over engagement, thereby restricting opportunities for reflection, application, and professional skill formation. The findings therefore reinforce the necessity of moving beyond content-centred instruction toward pedagogical models that emphasise participation, reflection, and contextualised learning. Qualitative evidence further demonstrates the importance of reflective group discussions and interdisciplinary learning in strengthening the integration of sustainability within teacher education. Reflective practices enable future teachers to critically reconsider their learning experiences, articulate their understanding of sustainable development concepts, and establish meaningful links between theoretical knowledge and pedagogical action. This reflective dimension has been widely identified as a key factor in the development of professional identity and pedagogical self-confidence in sustainability education (Tilbury, 2011; Wiek et al., 2011). Interdisciplinary learning, in turn, allows sustainability issues to be approached holistically, integrating biological perspectives with social, ethical, and environmental considerations. Such integration supports the development of systems thinking, which is consistently recognised as a core competence in education for sustainable development (Barth et al., 2007; Mogren et al., 2019). In this regard, interdisciplinary and reflective approaches emerge not as supplementary elements but as foundational components of SDG-orientated teacher preparation. The empirical results of the study provide consistent support for all three research hypotheses. The first hypothesis (H1), which assumed that the introduction of structured, SDG-orientated methodological modules would enhance pedagogical competence, was confirmed through significant improvements in methodological skills, lesson design capacity, and overall professional readiness. These outcomes correspond with earlier findings highlighting the importance of systematic methodological preparation in sustainability-focused teacher education (Anyolo et al., 2018; Sleurs,

2008). The second hypothesis (H2), proposing that the regular use of project-based and inquiry-based learning would increase pedagogical confidence, was likewise supported by strong correlations between active instructional methods and confidence indicators, as well as by notable gains following the instructional intervention.

The effect sizes observed in the pre-post analysis further indicate that the intervention produced not only statistically significant but also practically meaningful improvements in SDG-related competencies. In particular, the strongest effect was associated with the ability to design SDG-based biology lessons, suggesting that practice-orientated instructional experiences may play a decisive role in strengthening methodological readiness among future teachers.

This result is consistent with research demonstrating the role of experiential learning in strengthening teacher self-efficacy (Darling-Hammond et al., 2017). The third hypothesis (H3), which emphasised the role of interdisciplinary and reflective learning in enhancing overall professional preparedness, received full support from both qualitative evidence and measurable improvements in interdisciplinary teaching skills and general readiness for SDG implementation. These findings align with prior scholarship that identifies reflective and interdisciplinary experiences as critical for the formation of comprehensive sustainability competencies (Sterling, 2010; Wiek et al., 2011). Taken together, the discussion confirms that the primary objective of the study—namely, the identification of methodological foundations for integrating Sustainable Development Goals into the preparation of future biology teachers—has been successfully achieved. The findings indicate that meaningful SDG integration requires more than formal inclusion in curricular documents; it depends on methodologically grounded, practice-orientated pedagogical strategies. The combination of structured methodological modules with project-based, inquiry-driven, and reflective interdisciplinary approaches significantly strengthens sustainability-related competencies and prepares future biology teachers to respond effectively to global sustainable development challenges through educational practice.

Conclusion

The present study set out to examine the methodological foundations for integrating the Sustainable Development Goals (SDGs) into the preparation of future biology teachers and to identify pedagogical practices that support the development of sustainability-related competencies. The findings demonstrate that when SDGs are embedded in teacher education through a structured and methodologically grounded approach, this integration has a clear and positive effect on professional competence, pedagogical self-confidence, and overall readiness to address sustainability challenges in future teaching practice. The results indicate that prospective biology teachers generally possess a basic conceptual understanding of sustainable development and recognise the relevance of SDGs within biology education. However, in the absence of systematic methodological support, this conceptual awareness does not readily translate into effective classroom practice. In particular, persistent difficulties were observed in lesson planning, interdisciplinary integration, and the assessment of sustainability-related competencies. These findings confirm that declarative knowledge of SDGs alone is insufficient to ensure meaningful pedagogical implementation.

At the same time, the study provides empirical evidence that SDG-orientated methodological training, especially when grounded in project-based learning, research-orientated tasks, and reflective group activities, substantially enhances professional readiness. Improvements in pedagogical confidence, methodological competence, and interdisciplinary teaching skills highlight the importance of practice-orientated instructional approaches that allow future teachers to connect biological content with real-world sustainability issues. Such approaches create opportunities for students to move beyond abstract discussions and engage with sustainability as a concrete educational and professional concern. Despite these positive outcomes, several structural challenges remain. The analysis revealed a lack of coherent methodological guidelines and a limited availability of practical, SDG-integrated lesson models within existing curricula. These constraints continue to hinder the systematic implementation

of sustainability-orientated pedagogy and point to the need for stronger institutional support within teacher education programmes. The study also has certain limitations that should be acknowledged. The sample was drawn from a single higher education institution, which may restrict the generalizability of the findings. In addition, the analysis focused on a selected group of SDGs most directly related to biology education and did not address the full breadth of the SDG framework. Future research could expand the institutional scope, include a larger and more diverse participant pool, and explore SDG integration across other subject areas to provide a more comprehensive perspective. From a practical standpoint, the findings carry important implications for teacher educators, curriculum designers, and higher education institutions. The results suggest that SDGs should not be incorporated into curricula merely at a declarative level but should be supported by clearly defined methodological modules that explicitly address lesson design, instructional strategies, and assessment practices. Embedding SDG-focused modules within biology pedagogy courses may help position sustainable development as an integral component of professional training rather than an isolated topic. Such modules should include authentic project work linked to local and global sustainability challenges, inquiry-based tasks that foster critical thinking, and structured opportunities for reflection.

Equally important is the professional development of university instructors involved in teacher education. Providing educators with methodological resources, concrete examples of SDG-integrated lessons, and appropriate assessment tools can support more consistent and effective implementation of sustainability-orientated teaching. In addition, interdisciplinary collaboration among departments may further strengthen SDG integration by promoting systems thinking and a holistic understanding of sustainability. In conclusion, the study demonstrates that a coherent, methodologically sound, and practice-orientated approach to SDG integration represents an effective pathway for strengthening sustainability education in pre-service biology teacher training. By aligning curriculum content, teaching methods, and assessment practices with the principles of education for sustainable development, teacher education programmes can better prepare future biology teachers to contribute meaningfully to the achievement of the Sustainable Development Goals through school education.

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Integrating the culturo-techno-contextual approach into science teacher education: Microteaching practices on socioscientific issues

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ABSTRACT

The Culturo-Techno-Contextual Approach (CTCA) offers an innovative model in science education by integrating cultural heritage, technology mediation, and local context. This study aims to examine the processes through which pre-service science teachers (PSTs) integrate CTCA into the teaching of socioscientific issues (SSIs) and their microteaching practices during this process. The study was designed as a case study, and the data collection tools consisted of the CTCA-based lesson plans, microteaching video recordings, and PSTs' views on lesson plan preparation and practices. The results of the study revealed that the PSTs prepared strong lesson plans in terms of local context and technology use. They demonstrated strong performance in the dimensions of technology use and digital summary message delivery in microteaching. The results indicate that CTCA offers an effective framework for teaching SSIs in science teacher education; however, skills related to developing cultural context, conceptual clarification, and discussion management need to be supported.

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Introduction

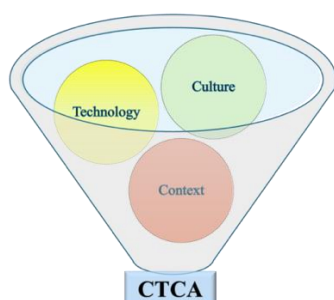
The rapid changes, dilemmas, and complex global challenges in contemporary society necessitate that individuals possess 21st-century skills, such as collaboration, communication, and particularly critical thinking (Adam et al., 2026). In addition to critical thinking skills, recent research has emphasised the necessity of 21st-century competencies, including problem-solving, information literacy, and digital literacy, alongside the continuously evolving requirement for digital competence (Silber-Varod et al., 2019). Globally, the disconnect between scientific content and real-world context in science education affects students' academic achievement and critical thinking skills (Adam et al., 2025). To address these challenges and integrate students' daily lives, cultural heritage, and technological competencies into science education, Okebukola introduced the Culturo-Techno-Contextual Approach (CTCA) in 2015 (Okebukola, 2020).

Culturo-Techno-Contextual Approach: Components and Implementation Steps

The CTCA fuses three core pillars: the culture in which students are immersed, the technology with which teachers and students increasingly interact, and the local context that reflects the unique identity of each educational institution (Okebukola, 2020; Figure 1).

Figure 1

Components of the culturo-techno-contextual approach



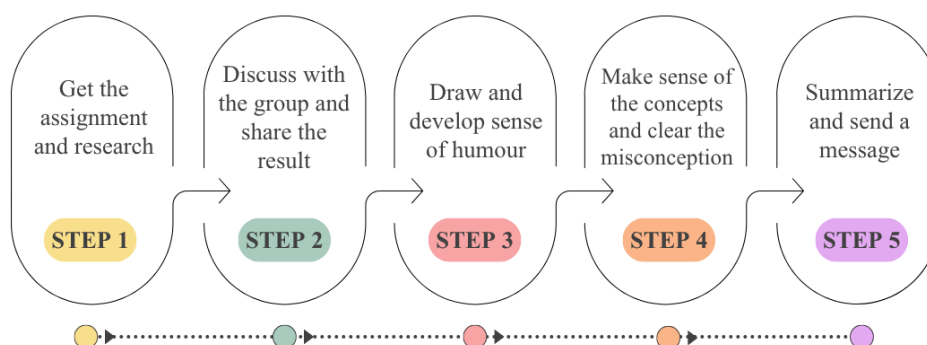
Note. Okebukola, 2020

The CTCA is grounded in Kwame Nkrumah's ethnophilosophy for the cultural component, Martin Heidegger's technophilosophy for technology, and Michael Williams' contextualism for the context (Onowugbeda et al., 2024b). The cultural component represents the indigenous knowledge inherent to individuals. Here, indigenous knowledge refers to how individuals acquire understanding of the world order and evaluate how to use this knowledge to enhance their quality of life. With the emergence of the COVID-19 pandemic, technology-integrated courses have gained prominence across all educational levels, from primary school to university (Crompton et al., 2021; Ives, 2021). The technology component has emerged from the increasing prevalence of technology-enhanced interactive lessons that prioritize such integration in science education (Ademola et al., 2022). Meanwhile, the context component provides a framework that allows for the consideration of the specific circumstances and conditions in which individuals are situated.

In the implementation of CTCA, two types of interaction from Vygotsky's social constructivism theory feature prominently: acquiring knowledge about local/cultural practices related to the concept at hand and facilitating group interaction with peers. Building upon these two core interactions, Okebukola (2020) proposed a five-step implementation process for CTCA within the classroom environment (Figure 2).

Figure 2

The diagram of implementation steps of CTCA



Note. Okebukola, 2020

In the first step of this process, a pre-class assignment is given regarding local practices related to the subject matter and resources accessible via the internet. In the second step, group work is conducted based on the assignment from the first step, and students are encouraged to present their findings. In the third step, the lesson progresses by having students draw examples related to the topic from their immediate environment (context) and incorporating a humorous perspective (e.g., cartoons). The fourth step encompasses cultural practices and web resources shared within the classroom. In the final step, a concise summary of the content is sent to the students through online channels.

Grounded in theoretical foundations such as Vygotsky's social constructivist theory and Ausubel's meaningful learning theory, the CTCA is well suited to teaching socioscientific issues (SSIs) that are particularly controversial and involve social dimensions (Tekin & Aslan, 2025). The imperative for technology integration, particularly in the aftermath of the COVID-19 pandemic and the February 2023 Kahramanmaraş earthquakes in Türkiye, has further underscored the significance of CTCA's technological component in science courses. Furthermore, in Türkiye, a nation with a multicultural structure characterised by diverse demographic and cultural traits across seven distinct geographical regions, this approach, grounded in local knowledge and cultural practices, holds substantial potential for fostering diversity in science education.

To illustrate, a topic such as biodiversity carries markedly different local/cultural characteristics depending on the region in which it is taught: in one locality, this might involve traditional ecological practices or culturally significant endemic species, while in another, it might draw on region-specific agricultural or fishing practices tied to local biodiversity. The technological characteristics of the same topic might, in turn, involve the use of citizen-science mobile applications for species identification or region-specific biodiversity-monitoring platforms. A particularly illustrative case from the region in which the present study was conducted is Tuz Gölü (Salt Lake) in Aksaray, a nationally significant saline lake and protected wetland whose shrinking water levels have become a pressing local socioscientific concern. Its local/cultural dimension encompasses the region's long-standing salt-harvesting tradition, the lake's role in regional tourism, and its ecological significance as a breeding ground for flamingos, while its technological dimension can be approached through satellite-based remote sensing and geographic information system (GIS) mapping used to monitor the lake's shrinkage over time. This context-sensitive, technology-integrated structure is what allows CTCA to be adapted flexibly across topics and regions, a flexibility further elaborated in the Procedure section.

An Integrated Theoretical Framework

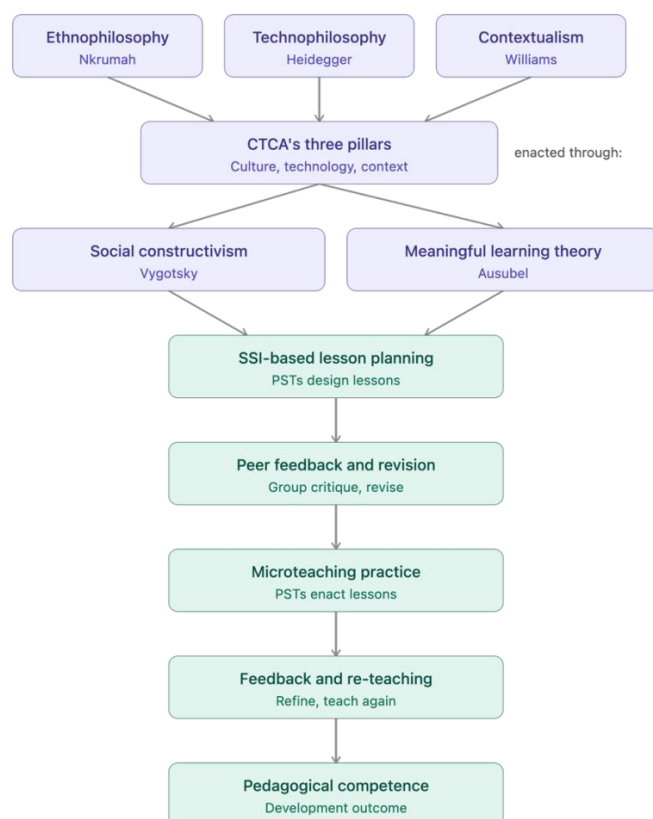
CTCA draws on five perspectives (ethnophilosophy, technophilosophy, contextualism, social constructivism, and meaningful learning theory), which converge into a coherent rationale operating at two levels. First, ethnophilosophy, technophilosophy, and contextualism justify why culture, technology, and context belong together as one structure rather than separate add-ons, each addressing a condition of science learning (indigenous knowledge, technological mediation, local relevance) that alone would leave the others unaddressed. Second, social constructivism and meaningful learning theory explain how learning proceeds once these pillars are enacted: the former through interaction, acquiring local knowledge and peer collaboration, the latter through grounding instruction in learners' existing cultural and technological frames, producing more durable understanding (Ausubel, 1968). The first level thus establishes what CTCA integrates and why; the second, how that integration becomes learning, and it is this process-oriented level that most directly grounds CTCA's suitability for SSIs, which, being controversial and inherently social, are learned through the same socially mediated processes CTCA structures.

Just as CTCA structures student learning around social interaction and meaningful content, the process examined here structures PSTs' own professional learning similarly: they construct understanding through group-based lesson planning, act on peer and instructor feedback, and refine

practice through microteaching and reteaching, a cycle that is itself socially constructed and meaningful in Vygotskian and Ausubelian terms, now applied to pedagogical rather than content knowledge. This reflexive extension connects CTCA's theoretical foundations to the practice-based, socially mediated account of teacher learning developed below (Grossman et al., 2009; Lave & Wenger, 1991; Shulman, 1987), summarised as the conceptual pathway in Figure 3.

Figure 3

An integrated theoretical framework linking CTCA's philosophical and learning-theoretical foundations



This diagram clarifies the study's logic at every stage: the philosophical pillars justify CTCA's content structure, the learning theories explain how that structure produces understanding, and this mechanism, reapplied to PSTs' own planning and teaching cycle, explains how CTCA is expected to develop their pedagogical competence, the study's outcome of interest. The following section situates CTCA relative to other instructional frameworks in science teacher education.

Situating CTCA within Related Instructional Frameworks

CTCA's structure invites comparison with other frameworks in science teacher education, clarifying both its overlaps and its distinctiveness. Its cultural pillar shares affinities with Culturally Responsive Teaching (CRT), which similarly centres on students' cultural backgrounds as pedagogical resources (Gay, 2010; Ladson-Billings, 1995); unlike CRT, however, CTCA treats culture as one of three interdependent components coordinated with technology and context within a specified sequence of steps. A similar relationship holds with place-based education, which grounds learning in the ecological, social, and historical particulars of students' local environment (Smith, 2002); CTCA's

context pillar overlaps with this orientation, but place-based education specifies neither a structured technology role nor a stepwise sequence. CTCA's technology pillar resonates with Technological Pedagogical Content Knowledge (TPACK), which theorises integrating technology with pedagogy and content (Mishra & Koehler, 2006); whereas TPACK offers a general account of what teachers need to know, CTCA offers a more prescriptive, step-based procedure within a specific cultural and contextual frame.

More broadly, transforming subject matter into a teachable, learner-adapted form, central to Shulman's (1986) construct of Pedagogical Content Knowledge (PCK) and to the pedagogical reasoning discussed below, is precisely the task CTCA structures for PSTs designing lessons around locally and technologically situated SSI content. CTCA also shares features with Inquiry-Based Science Education, particularly its emphasis on investigation and evidence-based reasoning (Minner et al., 2010), but differs in anchoring inquiry in local/cultural material and technology from the outset, rather than treating context as incidental. In relation to SSI pedagogy, the broader field within which this study is situated, CTCA functions less as a competing framework than as a structured instructional vehicle: where SSI pedagogy establishes why controversial issues merit dedicated attention, CTCA offers one systematic answer to how they might be planned and taught, treating local and technological relevance as integral. CTCA thus does not replace these frameworks so much as recombine elements of each —culture, technology, and context— into a single, sequenced structure whose distinctiveness lies in this integration and whose implementation by prospective teachers has not previously been examined within CTCA research or these adjacent literatures.

Rationale and Aim of the Present Study

Recent studies have indicated that CTCA significantly enhances academic achievement, critical thinking, and knowledge retention across science education (Adam et al., 2025; Adam et al., 2026; Olusegun et al., 2024; Onowugbeda et al., 2024a), with positive effects reported across diverse content areas, including genetics (Adebayo et al., 2022), nutrition and metabolism (Adam et al., 2025), ecology (Ademola et al., 2022), and STEM more broadly (Oladejo et al., 2025). Together, this work shows a consistent pattern: positive effects appear robust across content domains, suggesting CTCA's benefits are not narrowly topic dependent. At the same time, this literature shares a methodological limitation: each study evaluates CTCA as a fixed treatment, designed and delivered by a researcher or teacher and assessed through its effects on students, with implementation itself held constant rather than examined. Consequently, this literature offers limited insight into how PSTs interpret CTCA's implementation steps, what decisions they make when translating its cultural and technological components into a lesson, and where they encounter difficulty. Although CTCA is relatively recent, research on its adaptation for teaching SSIs has gained momentum, emphasising the need to conceptualise its implementation steps and developing concrete examples. In Türkiye, this approach was first addressed by Tekin and Aslan (2025), who used artificial intelligence to exemplify SSIs and detailed CTCA's implementation steps, though again through a researcher-constructed example rather than one designed by prospective teachers themselves.

This gap is consequential given the instructional role SSI-based materials already play in science classrooms. Teachers frequently use such materials to engage students in discussion and decision-making around controversial scientific issues (Kokolaki & Stavrou, 2023), such discussions are typically structured around risk-benefit analysis (Schenk et al., 2021), ethical reflection (Nadlir et al., 2025), and multiple perspectives (Kristensen & Knain, 2024). Because CTCA lesson planning is inherently linked to these same concerns, it may serve as a novel example of how pre-service teachers develop and implement SSI-based materials, provided the planning process itself, not only its rationale, is examined. This is consistent with the teacher education literature, which treats lesson planning as a core professional competence (Zaragoza et al., 2023) and high-quality lesson plans as foundational to high-quality instruction (Großmann & Krüger, 2024). Engaging with CTCA holistically, its planning and implementation dimensions alike, therefore stands to contribute

significantly to pre-service teachers' professional development, and to the design and implementation of SSI-based lesson plans within the CTCA framework as a means of fostering a high-quality learning environment in terms of cultural sensitivity, technology integration and pedagogical design skills (Okebukola, 2020).

This shift, from CTCA's effects on student learning to a professional competency developed during teacher preparation, is a change in the theoretical object, not merely of population. Investigating CTCA with students addresses instructional effectiveness: does the approach improve outcomes for those who receive it? Investigating it with pre-service teachers addresses a different question, one of pedagogical reasoning and professional formation (Shulman, 1987). Where a student encounters CTCA as a finished product, a PST must first comprehend its theoretical commitments — Nkrumah's ethnophilosophy, Heidegger's philosophy of technology, Williams' contextualism — and transform the approach into a coherent, teachable design, a task Shulman (1987) calls pedagogical reasoning: transforming subject matter into forms pedagogically powerful and adapted to learners. This cannot be inferred from studies of CTCA's effects on students, however positive, since it concerns a distinct capacity: designing for CTCA rather than merely learning through it.

This distinction also carries methodological consequences that separate the present study from prior CTCA research. The iterative structure adopted here, in which PSTs plan, receive peer feedback, revise, microteach, and are given the chance to reteach, reflects a practice-based approach to teacher preparation in which core practices are rehearsed and refined under supervision before independent enactment (Grossman et al., 2009), with no analogue in single-session, researcher-delivered CTCA interventions. Moreover, because PSTs are simultaneously being socialised into the professional identity of a science teacher, their engagement with CTCA is bound up with a trajectory of increasing participation in teaching practice itself (Lave & Wenger, 1991), rather than a one-off encounter with a novel method. Findings on how PSTs plan and enact CTCA-based lessons therefore cannot be assumed to mirror findings on how school students respond to CTCA instruction; the two literatures address related but theoretically distinct phenomena. In this respect, the study is the first to jointly examine PSTs' performance and perspectives in planning and microteaching SSI-content lessons based on the CTCA, thereby highlighting the reflections of this approach within the teacher education context. In line with this aim, the study addressed the following research questions:

- What is PSTs' performance in preparing CTCA-based lesson plans?
- What are PSTs' perspectives on planning CTCA-based lessons?
- What is PSTs' performance in integrating CTCA into microteaching practices?
- What are the perspectives of PSTs on microteaching CTCA-based lesson plans?

Method

Design

This study employs a qualitative case study design to explore PSTs' perspectives on their microteaching within the framework of a CTCA to SSIs. Case study methodology is defined as a research approach that facilitates an intensive investigation of an uncontrollable phenomenon, specifically addressing the “how” and “why” questions (Yıldırım & Şimşek, 2021). The study was conducted in three main stages: informing participants about the CTCA, preparing CTCA-based lesson plans, and microteaching. These stages enabled the process to progress within its natural setting and allowed PSTs' perspectives regarding lesson planning and microteaching to be directly reflected in the study. Since the CTCA is still a relatively new approach, this design was chosen to provide a clearer understanding of its implementation process in the literature.

Participants

The study was conducted with the participation of 34 PSTs (26 female, 8 male) enrolled in the third year of the Science Teacher Education Program at a university located in central Türkiye. The participants consisted of students enrolled in a one academic semester course taught by the researcher. To enable possible classroom observations, participants were selected using a convenience sampling method. Most of the participants graduated from public high schools and came from middle- to lower-middle socioeconomic backgrounds. Participation in the study was entirely voluntary. During the lesson planning and microteaching processes, the PSTs worked in groups of three to four members. Participants were anonymised using codes such as PST1, PST2, and so forth throughout the reporting of the findings.

Data Collection Tools

In this study, lesson plans created by PSTs, microteaching video recordings, and interview form focused on lesson plan and microteaching experiences served as data collection tools. Participants structured their lesson plans following the CTCA steps outlined in Figure 2 (An example lesson plan is provided in the appendix). Following the planning phase, participants performed 10 to 15-minute microteaching sessions aligned with their respective designs. To explore the PSTs' perspectives during lesson planning and microteaching, a semi-structured interview form was developed. This form was designed in alignment with the implementation steps proposed by Okebukola (2020) and was structured into two sections focusing on lesson planning and the microteaching process, respectively. To ensure the validity of the instrument, expert opinions were sought from three faculty members. Two experts specialize in science education, while the third is an expert in the field of educational measurement and evaluation. Reflecting the experts' feedback on the evolving nature of the CTCA, an additional item was incorporated to elicit suggestions for refining the CTCA implementation steps within the lesson preparation process. After this revision, the instrument was re-evaluated by the experts, and the final form was finalized once the experts reached consensus.

Procedure

Ethical approval for this study was obtained from the Aksaray University Ethics Committee (No: 2025-41; Date: 21.01.2025). The research was conducted over a 12-week period during the spring semester of the 2024-2025 academic year, within the scope of a course taught by the researcher. During the first week, information was provided regarding the course content, weekly syllabus, the working procedures for the PSTs, and the academic resources available for their use. In the second week, PSTs were informed about critical considerations for selecting topics within the framework of the CTCA, specifically focusing on local relevance and technological integration. Based on these criteria, they selected topics from the science curriculum (Ministry of National Education [MoNE], 2024) and established work plans in groups of three to four. The topics (SSIs) and learning outcomes determined by each group are presented in Table 1.

Table 1

SSIs and learning outcomes determined by PSTs

Groups and PSTs	Topic (SSIs)	Grade	Learning outcomes
G1 (PST1-PST3)	Cardiovascular health	7	FB.7.3.2.3. Gathering information on what needs to be done to maintain a healthy cardiovascular system
G2 (PST4-PST6)	Biodiversity	6	FB.6.7.1.1 Being able to question the importance of biodiversity for wildlife
G3 (PST7-PST9)	Acidic and basic materials	8	FB.8.5.4.3. The ability to use inferential reasoning based on the 'pH' values relating to the acidity and basicity of substances

G4 (PST10-PST12)	Climate change	8	FB.8.1.2.1. The ability to compare climate and weather events
G5 (PST13-PST15)	Biodiversity	6	FB.6.7.1.1 Being able to question the importance of biodiversity for wildlife
G6 (PST16-PST17)	Household waste and recycling	5	FB.5.7.1.1. The ability to classify recyclable and non-recyclable materials in household waste
G7 (PST18-PST21)	Efficient use of resources	7	FB.7.7.2.1 The ability to question the importance of using resources efficiently
G8 (PST22-PST24)	Environmental concerns	6	FB.6.7.2.2. The ability to solve problems relating to the environment in their immediate surroundings or within the country
G9 (PST25-PST28)	Environmental adaptation	8	FB.8.3.4.2. The ability to draw scientific conclusions regarding the adaptation of living organisms to their environment
G10 (PST29-PST31)	Biodiversity	6	FB.6.7.1.2. The ability to predict factors threatening biodiversity based on research data
G11 (PST32-PST34)	Biodiversity	6	FB.6.7.1.2. The ability to predict factors threatening biodiversity based on research data

The notation 'FB.6.7.1.2' specifies the grade level, unit, and topic of the learning outcome.

In the third week, the local/cultural and technological characteristics of the topics selected by the groups were identified. During this phase, an in-class brainstorming session was conducted in which classmates provided insights into the local features of their respective regions related to the chosen topics. In the same week, each group shared their assignment prompts designed for the first step of the CTCA (Step 1: Get the assignment and research). During the fourth and fifth weeks, the PSTs prepared lesson plans based on the CTCA, considering the critical considerations and suggestions provided by their peers. In the sixth week, these lesson plans were reviewed by other groups. During this stage, feedback regarding the alignment of the learning outcomes with the nature of the CTCA, the correct implementation of the CTCA steps, and the aspects of the lesson plans requiring improvement was presented to the respective groups. In the seventh week, each group updated their lesson plans in accordance with the suggestions provided and shared the final versions with the researcher. Additionally, during this week, the PSTs shared their views on the lesson plan preparation process with the researcher via online platforms. Weeks 8 through 12 encompassed the groups' microteaching processes. Adhering to the previously scheduled dates, three groups conducted microteaching each week, with the final two groups completing their sessions in the last week. During this process, groups performed a 10–15-minute presentation of their lesson plans. These teaching sessions were video recorded. The microteaching videos were subsequently reviewed by the instructor and students to provide feedback. PSTs provided feedback through peer assessment forms. The lesson plans and videos were evaluated using the 'CTCA-Based Lesson Evaluation Rubric' developed by the researcher. Following the feedback, participants were provided with the opportunity to reteach after revising their plans, and the microteaching process was concluded with the last set of feedback (Applebee, 1976; McKnight, 1971). Following the conclusion of the microteaching cycle, participants from each group provided their feedback regarding the process through online platforms. The overall research process is summarized in Figure 4.

Figure 4*12-week research process*

Data Analysis

The 'CTCA-Based Lesson Evaluation Rubric', developed by the researcher, was used to evaluate the PSTs' lesson plans and microteaching videos. This rubric was developed specifically for this study rather than adapted from an existing instrument, drawing on the relevant literature to inform its criteria. Developed based on the relevant literature, this rubric is a four-level analytic rubric consisting of eight criteria in total: three criteria under the section 'Inclusion of the Basic Components of CTCA' and five criteria under the section 'Alignment with the CTCA Implementation Process' (Adam et al., 2026; Okebukola, 2020; Okyere Darko & Ekwam, 2025). The full wording of each criterion, together with its descriptor at each of the four performance levels, is provided in Appendix Table 4. The evaluation levels were structured as 'Successful (4)', 'Acceptable (3)', 'Needs improvement (2)', and 'Insufficient (1)', according to the extent to which the relevant criteria were reflected in the lesson plans and microteaching practices. Since an equal-interval scoring structure was assumed across the rubric levels, an arithmetic interpretation was used in evaluating the scores (Moskal, 2002). Accordingly, the score intervals were calculated using the formula 'score interval coefficient = (highest score – lowest score) / number of levels' (Kan, 2016). Based on this calculation, the mean scores obtained from the rubric were interpreted as follows: 1.00–1.75 = weak relationship with CTCA, 1.76–2.50 = moderate level, 2.51–3.25 = acceptable level of CTCA implementation, and 3.26–4.00 = full alignment with CTCA. To establish content validity, an initial draft of the rubric was reviewed by two faculty members in the field of science education, who provided written and verbal feedback on the clarity and appropriateness of each criterion rather than completing a structured validation form; this feedback led to revisions in the wording of several criteria, after which the researcher and the two experts reached consensus on the final version. The rubric was not piloted with a separate sample prior to the main data collection, a limitation addressed in the Discussion section. The data obtained from the rubric were subjected to descriptive analysis, and the groups' levels of lesson planning and implementation were evaluated based on their mean scores.

The data obtained through the interview form were analysed using content analysis, a qualitative analysis methods. In content analysis, similar units of data are coded and grouped into categories and themes to facilitate interpretation (Yıldırım & Şimşek, 2021). Patton's (2002) inductive content analysis model was applied during the analysis process. Analysis was conducted manually using word-processing and spreadsheet tools. Responses provided by the participants to the open-ended questions were coded at the level of meaning units, through an inductive, line-by-line reading of the transcripts in which codes were generated directly from participants' own expressions rather

than from a predetermined coding scheme; subsequently, conceptually similar codes were grouped into categories, and categories were organized into themes (Elo & Kyngäs, 2008). The resulting themes represented broader patterns across participants' planning and microteaching experiences. The entire analysis process was conducted by the researcher. Additionally, to ensure the reliability of the research data, a faculty member expert in the field of science education accompanied the author during the analysis. In this process, ideas were exchanged with the expert regarding the categorization of PSTs' opinions; disagreements in coding were resolved through discussion between the researcher and the expert until consensus was reached, and necessary revisions were made (Cohen et al., 2007).

For inter-coder reliability, Miles and Huberman's (1994) reliability formula ($\text{reliability} = \frac{\text{agreement}}{\text{agreement} + \text{disagreement}} \times 100$) was used and the inter-coder agreement rate was calculated as 90%. Several additional strategies were employed to strengthen the trustworthiness of the qualitative findings, following Lincoln and Guba's (1985) criteria. Credibility was supported through methodological triangulation, in which the interview findings were examined alongside evidence from the CTCA-Based Lesson Evaluation Rubric scores and the microteaching video recordings, allowing convergence across these three data sources to be considered. The science education expert who supported the coding process also engaged in ongoing reflective discussions with the researcher throughout the analysis, serving a peer-debriefing function by prompting the researcher to justify and reconsider interpretive decisions. Dependability and confirmability were further supported through a written audit trail documenting coding decisions and their rationale throughout the analysis process. Finally, transferability was supported through the thick description provided throughout the Method section, including detailed information on participants' backgrounds, the 12-week research procedure, and the specific topics, grade levels, and learning outcomes addressed by each group (Table 1), allowing readers to judge the applicability of the findings to their own contexts.

Given the researcher's multiple roles as course instructor, CTCA intervention designer, rubric evaluator, interviewer, and data analyst, several procedures were implemented to manage the potential power imbalance these multiple roles could create and to minimise researcher bias. First, participants were informed, both verbally and in the written consent form, that their participation in the study was entirely voluntary and would not influence their course grade in any way; consistent with this, rubric scores assigned to lesson plans and microteaching performances were used solely for research purposes and did not contribute to participants' course assessment, which was conducted independently through separate course requirements. Second, to reduce participants' potential reluctance to express critical views given the researcher's authority as their instructor, feedback on the lesson planning and microteaching processes was collected through an anonymous online survey (Google Forms) that did not record participants' identities, and this data collection took place after course grades had been finalised. Third, to minimise researcher bias during coding, interpretation, and reporting, the analytical procedures described above, including a second coder for inter-coder reliability, ongoing peer debriefing with the science education expert, methodological triangulation across data sources, and a written audit trail, were employed throughout the analysis.

Results

Pre-service Science Teachers' Performance in Preparing CTCA-Based Lesson Plans

The results regarding the lesson plans prepared by PSTs and analysed using the CTCA-Based Lesson Evaluation Rubric are presented in Table 2.

Table 2*PSTs' performance in preparing CTCA-based lesson plans*

Group	SSI	Score									Evaluation
		C1	C2	C3	C4	C5	C6	C7	C8	M	
G1	Cardiovascular health	3	3	3	4	4	3	3	4	3.38	Successful
G2	Biodiversity	3	3	3	3	3	3	2	3	2.99	Acceptable
G3	Acidic and basic materials	2	4	2	3	3	3	3	2	2.75	Acceptable
G4	Climate change	4	4	4	4	4	4	4	3	3.88	Successful
G5	Biodiversity	3	4	4	3	3	4	3	4	3.50	Successful
G6	Household waste and recycling	3	3	3	2	3	3	3	3	2.88	Acceptable
G7	Efficient use of resources	3	4	4	4	4	4	3	4	3.75	Successful
G8	Environmental concerns	2	3	3	2	3	3	3	3	2.75	Acceptable
G9	Environmental adaptation	2	3	3	3	3	3	3	3	2.88	Acceptable
G10	Biodiversity	3	3	4	3	3	3	3	3	3.13	Acceptable
G11	Biodiversity	3	3	4	3	3	3	3	3	3.13	Acceptable
M		2.82	3.36	3.36	3.09	3.27	3.27	3.00	3.18	3.17	

Note. C1: Cultural Context, C2: Technology Mediation, C3: Local Context, C4: Pre-Lesson Preparation, C5: Group Discussion and Sharing, C6: Drawing–Humour–Concretization, C7: Conceptual Clarification, C8: Digital Summary Message; M: Mean

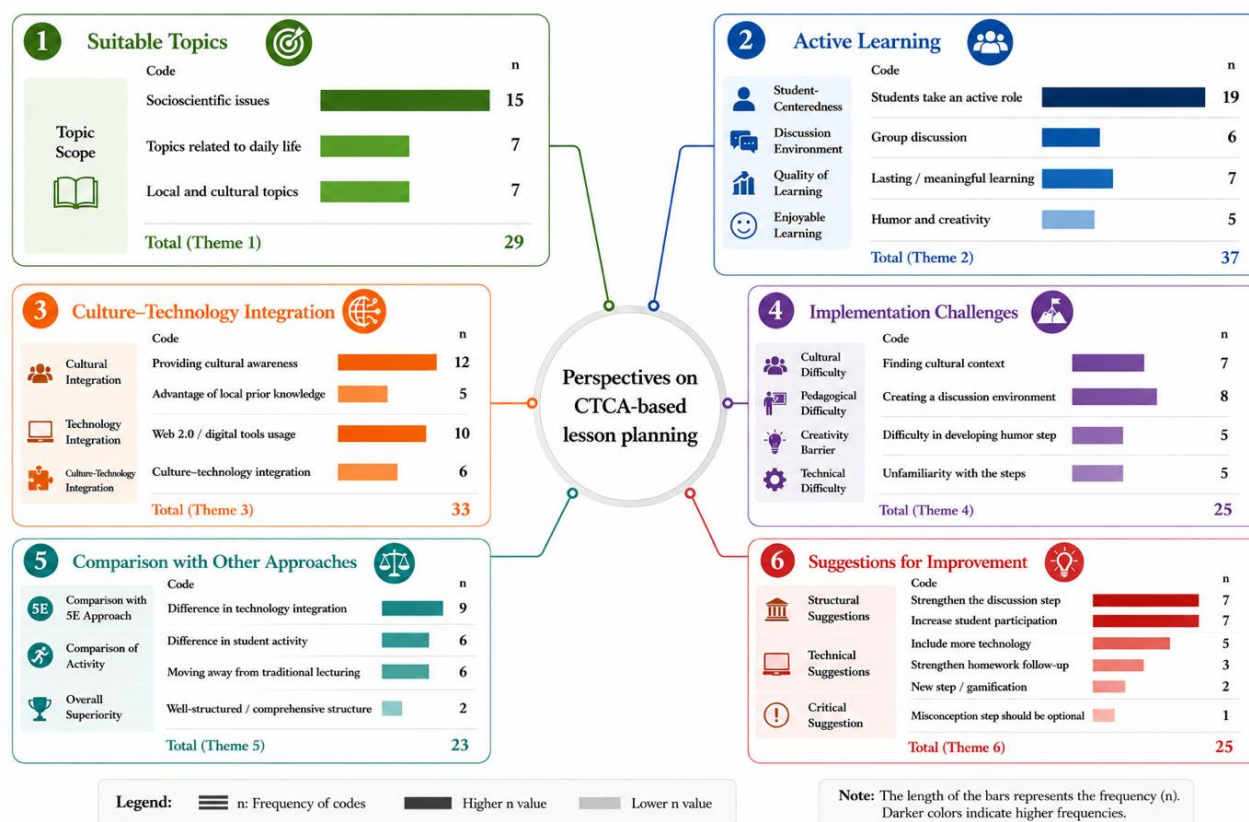
As shown in Table 2, most PSTs incorporated the CTCA implementation steps into their lesson plans. In this respect, it can be stated that they prepared lesson plans at acceptable and successful levels. The highest-scoring dimensions were local context with concrete events, natural areas, local species, or local practices ($M=3.36$) and integrated the use of technology ($M=3.36$) into their practice. G4 and G7 stood out in this regard. However, the limited reflection of the cultural context in the lesson plans ($M=2.82$) and the lack of explicit identification of misconceptions ($M=3.00$) were aspects that needed improvement in the PSTs' lesson plans.

Pre-service Science Teachers' Perspectives on the CTCA-Based Lesson Planning Process

This section presents the findings obtained from PSTs' perspectives on the CTCA-based lesson planning process (Figure 5). To enhance readability, the analysis results are presented in a summarised form in this section. Detailed codes, categories, themes, and illustrative statements are presented in Appendix Table 5.

Figure 5

Findings on PSTs' perspectives on CTCA-based lesson planning (Summary representation)



According to Figure 5, the PSTs emphasised the importance of identifying appropriate topics during the lesson planning process, highlighted the contribution of the CTCA to active learning, and foregrounded the cultural-technological integration embedded in this approach. They also compared the CTCA with other instructional approaches, reported implementation challenges, and offered suggestions for improvement.

In this process, they identified SSIs ($n=15$), topics related to daily life ($n=7$), and local/cultural topics ($n=7$) as the most suitable topics for CTCA-based lesson planning. The PSTs also stated that the CTCA could contribute to active learning by functioning as a student-centred approach in terms of enabling students to take active roles ($n=19$), enhancing the quality of learning through meaningful and lasting learning ($n=7$), and providing a discussion environment through group discussion ($n=6$). According to them, given its inherent nature, the CTCA can support students in achieving culture-technology integration by fostering cultural awareness ($n=12$) and enhancing the use of digital tools ($n=10$). The PSTs also distinguished this approach from other instructional approaches in terms of its distinctive emphasis on technology integration ($n=9$), student activeness ($n=6$), and its shift away from traditional instruction ($n=6$). Nevertheless, for the PSTs, providing a cultural context related to the topic addressed ($n=7$), creating a discussion environment ($n=8$), developing humour ($n=5$), and their limited familiarity with the CTCA steps ($n=5$) may pose challenges in implementation. To overcome some of these challenges, they suggested that the approach could be improved through structural recommendations, such as strengthening the discussion step ($n=7$) and increasing student participation ($n=7$), as well as technical recommendations, such as placing greater emphasis on technology ($n=5$) and strengthening homework follow-up ($n=3$). The following quotations illustrate the PSTs' perspectives:

"The CTCA can be widely used in science education because socioscientific and environmental issues may vary across regions and cultures." (PST1, Suitable topics)

"In the discussion stage, students actively participate in the lesson and are able to express their ideas freely." (PST5, Active learning)

"I was greatly impressed by the open-ended nature of the 'draw and develop humor' step, as it allows students to use their creativity effectively." (PST22, Active learning)

"Since the topic was related to my own hometown, I was able to make more connections and interpretations." (PST1, Culture–technology integration)

"Cultural approaches and technology are integrated; in this context, our past and future are blended together." (PST30, Culture–technology integration)

"While the 5E model is more related to question–answer activities and preparing presentations, the CTCA values students' own cultures and is more closely associated with technology." (PST8, Comparison with other approaches)

"Throughout my education so far, I have become more aware of how negatively traditional instruction can affect students." (PST21, Comparison with other approaches)

"The discussion section is challenging; because it is difficult to receive feedback from the class, this section may remain insufficient." (PST26, Implementation challenges)

"Since it was an approach, we had not encountered before, I had difficulty understanding its stages." (PST3, Implementation challenges)

"By assigning the homework earlier, a richer discussion environment could have been created; the lesson could also take place outside the classroom." (PST33, Suggestions for improvement)

"Making the misconception step compulsory for every topic implies that there should be misconceptions in every topic." (PST22, Suggestions for improvement)

Pre-service Science Teachers' Performance in Incorporating CTCA into Their Microteaching Practices

The data obtained from the video analysis of PSTs' microteaching practices are presented below (Table 3).

Table 3

PSTs' performance in incorporating CTCA into their microteaching practices

Group	SSI	Score									Evaluation
		C1	C2	C3	C4	C5	C6	C7	C8	M	
G1	Cardiovascular health	2	3	3	3	3	3	2	3	2.75	Acceptable
G2	Biodiversity	4	4	3	3	3	4	3	4	3.50	Successful
G3	Acidic and basic materials	4	4	3	4	3	4	3	4	3.63	Successful
G4	Climate change	4	4	4	4	3	4	3	4	3.75	Successful
G5	Biodiversity	3	4	3	3	3	3	3	3	3.13	Acceptable
G6	Household waste and recycling	3	4	4	3	4	3	3	3	3.38	Successful
G7	Efficient use of resources	3	4	3	4	4	4	3	3	3.50	Successful
G8	Environmental concerns	2	4	3	3	3	3	3	3	3.00	Acceptable
G9	Environmental adaptation	2	3	3	3	3	4	3	4	3.13	Acceptable
G10	Biodiversity	3	4	4	3	3	3	3	4	3.38	Successful
G11	Biodiversity	3	4	3	3	4	3	3	4	3.38	Successful
M		3.00	3.82	3.27	3.27	3.27	3.46	2.91	3.55	3.32	

Note. C1: Cultural Context, C2: Technology Mediation, C3: Local Context, C4: Pre-Lesson Preparation, C5: Group Discussion and Sharing, C6: Drawing–Humour–Concretization, C7: Conceptual Clarification, C8: Digital Summary Message; M: Mean

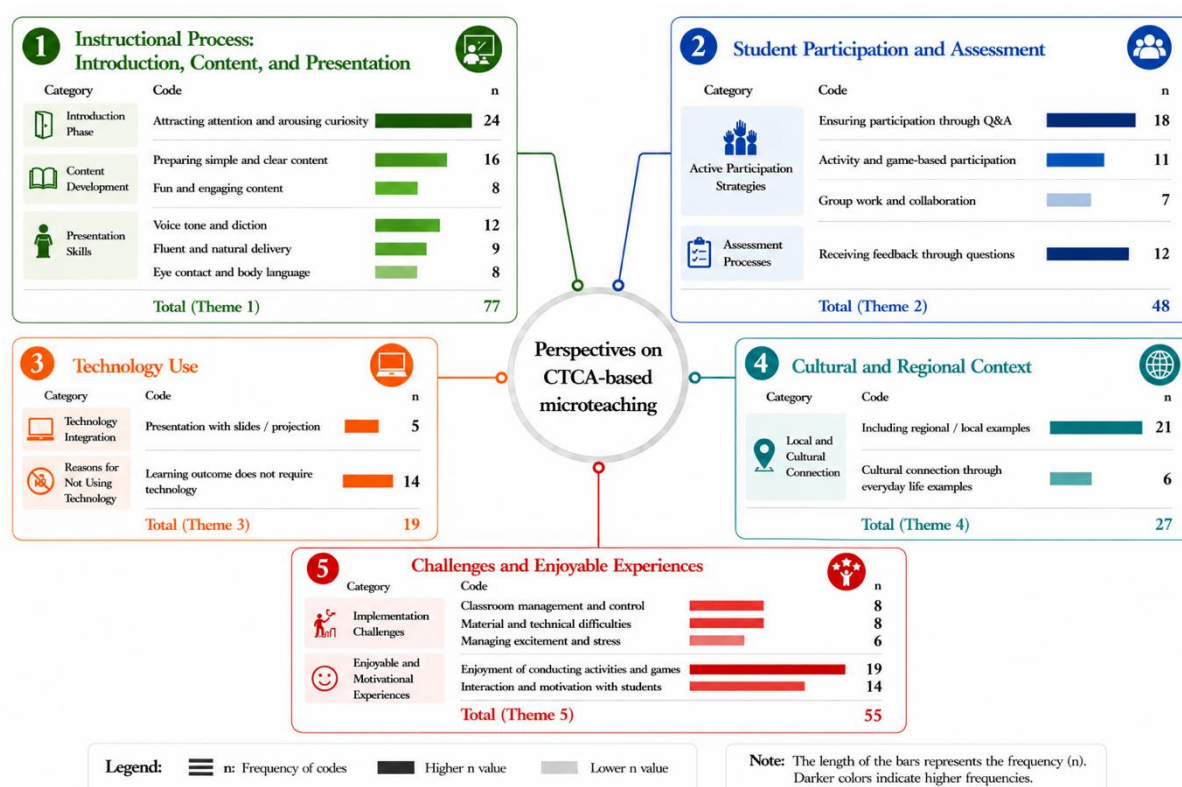
According to Table 3, in general, PSTs incorporated CTCA into their microteaching practices at successful and acceptable levels. The areas in which the PSTs were most successful in their microteaching practices were the use of technology ($M=3.82$) and the delivery of digital summary messages ($M=3.55$). The groups that stood out in the microteaching practices were G4 and G3. However, the PSTs demonstrated an acceptable level of performance in conceptual clarification ($M=2.91$) and establishing a cultural context ($M=3.00$) in their practices.

Pre-service Science Teachers' Perspectives on CTCA-Based Microteaching Practices

This section presents the findings obtained from PSTs' perspectives on CTCA-based microteaching practices (Figure 6). To enhance readability, the analysis results are presented in a summarised form in this section. Detailed codes, categories, themes, and illustrative statements are presented in Appendix Table 6).

Figure 6

Findings on PSTs' perspectives on CTCA-based microteaching practices (Summarized representation)



According to Figure 6, the PSTs evaluated CTCA-based microteaching practices through the themes of instructional process, student participation and assessment, technology use, establishing cultural and regional contexts, and challenges and enjoyable experiences.

The PSTs stated that, during the practices, they experienced the instructional process primarily in terms of the introduction stage, particularly through attracting attention and arousing curiosity ($n=24$); content development, through preparing clear and comprehensible content ($n=16$); and presentation skills, through tone of voice and diction ($n=12$). In addition, during the microteaching process, they experienced student participation by promoting active involvement through question-and-answer techniques ($n=18$) and activity- and game-based practices ($n=11$), as well as assessment by obtaining feedback through questions ($n=12$). The PSTs stated that they achieved technology integration through the technological materials they used, such as slides and videos ($n=9$); however,

they also noted that they did not use technological support when the learning outcome did not require it (n=14). In addition, their emphasis on incorporating regional/local examples into their microteaching practices (n=21) indicates that this approach was the most prominent factor in their use of local and regional contexts. During the practices, difficulties related to classroom control and classroom management (n=8), as well as material preparation and technical issues (n=8), were reported by the pre-service teachers. However, the enjoyment of engaging their classmates in activities and games (n=19), the interaction established with their peers (n=14), and the opportunity to experience the teaching profession (n=2) emerged as motivating factors. The following quotations illustrate the PSTs' perspectives:

"In the introduction, I asked questions that would arouse students' curiosity and checked their readiness." (PST29, Instructional process)

"We paid attention to making it easy, understandable, and clear." (PST6, Instructional process)

"We wanted to design an activity that students would be willing to participate in; there were no passive students." (PST5, Student participation and assessment)

"To make the lesson more engaging, we watched videos related to the topic." (PST34, Technology use)

"Technology was not highly relevant to my learning outcome; I used it only for research purposes." (PST7, Technology use)

"While preparing our slides, we selected visuals from our city so that students could more easily relate to them, as they reflected the environment in which they live." (PST32, Cultural and regional context)

"There were not many aspects that challenged me, but classroom control was difficult." (PST7, Challenges and enjoyable experiences)

"Even though it lasted only 10 minutes, experiencing teaching made me very happy." (PST21, Challenges and enjoyable experiences)

Discussion

Pre-service Science Teachers' Performance in Preparing CTCA-Based Lesson Plans

In this study, PSTs' performance in preparing CTCA-based lesson plans was evaluated, and it was found that most of the groups prepared lesson plans at acceptable and successful levels. Lesson planning is emphasised as one of the fundamental components of teachers' professional competence and draws attention to the integration of pre-service teachers' content knowledge and pedagogical knowledge (Großmann & Krüger, 2024; Kinskey & Zeidler, 2021). Consistent with this, Kinskey and Zeidler (2021) revealed that, in SSI-based lesson plans, PSTs had difficulty simultaneously designing both the subject content and the management of the discussion environment.

The result showing that the strongest performance in the lesson plans was achieved in the dimensions of associating the local context with concrete events, natural areas, or local species, and using technology is noteworthy. Yemini et al. (2025) emphasise the importance of cultural and shared spaces in the context of place-based education. In this context, 'place' does not refer only to a geographical location but also includes the knowledge, skills, and mutual communication of local communities. The locality emphasised in the present study can be evaluated within this framework. In this study, the fact that G4, which focused on climate change, and G7, which focused on the efficient use of resources, stood out as the groups that strongly reflected the local context in their lesson plans may point to a pattern within this sample whereby socioscientific and environment-based topics align more easily with CTCA; given that only two groups addressed such topics, however, this observation should be treated as tentative rather than conclusive. This result is consistent with researchers who argue that SSI teaching can be structured through topics that are most suitable for cultural contexts (Wagner et al., 2026). However, the literature emphasises that technology use should not be limited merely to the diversity of tools and that it is important to integrate technology for pedagogical purposes. Dinçer (2024) states that science teachers may experience shortcomings in technology integration, particularly in terms of design and competence, and that effective integration requires

practice-based, student-centred, technology-supported teacher education. In the present study, the high level of technology-supported implementation in the lesson plans and the fact that these practices were carried out with PSTs are promising in terms of addressing the shortcomings identified in the literature in their future professional lives.

On the other hand, the identification of the reflection of cultural context in lesson plans as the weakest dimension is a result that requires attention. Ellerbrock et al. (2016) emphasize that pre-service teachers are not sufficiently prepared in undergraduate programs to develop cultural awareness and that this deficiency is directly reflected in their lesson plans. Similarly, Halpern and Ozfidan (2024) examined the impact of cultural competence factors in teacher education programs and revealed that the ability to incorporate cultural content into the planning process requires experience and guidance. Wagner et al. (2026), in their study with high school students, investigated how students drew on their cultural repertoires and epistemic science knowledge when responding to a SSI. Their findings showed that integrating biological knowledge with cultural knowledge fosters a critical stance toward knowledge claims, supports the use of pluralistic knowledge among culturally and linguistically diverse students, and promotes critical engagement with SSIs in high school biology. These results, which support the findings of the present study, indicate that the cultural context dimension should be addressed more systematically and sustainably in teacher education programs.

Pre-service Science Teachers' Perspectives on the Process of Preparing CTCA-Based Lesson Plans

The PSTs' views indicate that SSIs and topics connected to daily life were perceived as the most suitable content areas for CTCA. Kinskey and Zeidler (2021) revealed that pre-service teachers' topic selection in SSI-based lessons is directly influenced by their content knowledge and perceptions of pedagogical feasibility. In the present study, PSTs' emphasis on SSIs may stem from the potential of these topics to align with students' cultural and regional experiences. Although the existing literature on CTCA has generally focused on biology achievement, the study by Onowugbeda et al. (2026) presents findings on the effect of CTCA on students' achievement in genetics, a SSI. The study emphasises the value of context-orientated and technology-supported instruction for high school students in the topic of genetics. They recommend that teachers who aim to improve learning outcomes in genetics integrate CTCA into their lessons. Therefore, considering its alignment in terms of both cultural context and content, developing CTCA-based practices that incorporate different SSIs may provide an important integration in science education.

The emphasis on a structure that foregrounds students' active roles indicates that PSTs position CTCA beyond traditional transmission-based models. Minken et al. (2021) emphasise that SSI-based lesson plans strengthen teachers' pedagogical content knowledge and that student-centred activities enhance the quality of learning. In the teaching of SSIs, student involvement, dialogue, and active participation are strongly emphasised (Chen & Xiao, 2021). The systematic review by Högström et al. (2025) shows that group discussions are the most prominent method for teaching SSIs. In the present study, PSTs' strong emphasis on students' active roles during the lesson planning process may be an important indicator of their potential to reflect this experience in their own classrooms.

The emphasis on the potential contribution of CTCA to culture–technology integration is highly consistent with the nature of CTCA. Lee (2018) provided examples through three cases to illustrate how technology, science, and culture can be brought together. According to Lee, culture plays a powerful role in advancing technology and fostering the interaction between technology and science.

Among the difficulties experienced in relation to the CTCA implementation process in lesson plans, creating a discussion environment and establishing a cultural context came to the fore. It is therefore expected that these results align with the finding that the cultural context dimension had the lowest score in PSTs' performance in preparing CTCA-based lesson plans. Zhang and Hsu (2025) emphasise that teachers do not feel sufficiently prepared to manage controversial issues and need

structured professional development support to overcome this difficulty. This emphasis indicates that there is still a need for culture-orientated practices such as CTCA, which may be valuable for PSTs' future professional lives.

PSTs also experienced some difficulties during the lesson plan preparation process. These difficulties included identifying a cultural context, creating a discussion environment, developing humour, and not being sufficiently familiar with the CTCA steps. Cultural context was an important determining factor within the scope of this study. The other difficulties experienced by the PSTs appear to be mostly related to the CTCA implementation process. Since the PSTs were still planning lessons based on theoretical knowledge at this stage and had not yet moved on to implementation, the absence of a clear process for constructing these components may have led to this result.

Pre-service Science Teachers' Performance in Incorporating CTCA into Their Microteaching Practices

The analysis of the microteaching videos revealed that PSTs generally incorporated CTCA into their practices at successful and acceptable levels. When compared with their performance in preparing lesson plans, implementation appears to have slightly exceeded the planning level. This result is consistent with studies arguing that microteaching serves as a strong bridge in transferring theoretical knowledge into practice. Iliasova et al. (2025) showed that microteaching enables teachers to develop multidimensional skills such as classroom management, instructional delivery, and reflective practice together.

It is noteworthy that the strongest performance in microteaching was observed in the dimensions of technology use and digital summary message delivery. The systematic review by Basilotta-Gómez-Pablos et al. (2022) on teachers' digital competence indicates that teachers generally have low to moderate levels of digital competence. The study particularly draws attention to teachers' lack of competence in evaluating educational practices. To address this deficiency, it recommends designing more practical and personalised training programmes that respond to teachers' needs in the digital age. The rapid development of artificial intelligence today also suggests that PSTs may be using these technologies more frequently than in-service teachers. In the present study, the high level of technological competence may stem from PSTs' existing familiarity with technological tools in their daily lives.

The relatively lower performance in the dimensions of conceptual clarification and establishing a cultural context is consistent with the findings on lesson plan preparation. This situation indicates that these skills require not only technical knowledge related to the planning process but also experience and guided practice. Since CTCA is a relatively new approach, it remains an area in which both the researcher and the PSTs have had limited practice. Conducting multiple practices, especially for conceptual clarification, anticipating possible misconceptions in advance, or preparing for misconceptions encountered in previous experiences may be important.

Pre-service Science Teachers' Perspectives on the CTCA-Based Microteaching Process

The PSTs evaluated the microteaching process under the themes of instructional aspects, participation, technology, cultural context, challenges, and enjoyable experiences. The fact that attracting attention and arousing curiosity were the most frequently mentioned instructional experiences indicates that PSTs were aware of the decisive role of an effective introduction phase in motivation. This result is consistent with studies showing that microteaching provides PSTs with opportunities to make their pedagogical choices consciously. Lewis (2024) revealed that microteaching enables PSTs to experience teaching "like a real teacher" and that this experience supports the development of professional identity.

The prominence of the question-and-answer technique and activities/games in the dimension of student participation shows that CTCA's emphasis on active learning was transferred into practice.

Jeon (2025) states that microteaching not only supports individual development but also promotes collaborative learning through structured peer interaction. Therefore, consistent with the participatory design of the microteaching process itself, experiencing CTCA foregrounded student participation for this group of PSTs.

A noteworthy pattern in technology use is that PSTs adopted technological support when required by the learning outcome. Petko et al. (2024), by relating the TPACK framework to contextual factors, show that PSTs' technology choices reflect their pedagogical intentions. In the dimension of cultural and regional context, the inclusion of regional/local examples emerged as the most distinctive feature of the implementation. This result is consistent with studies emphasising that cultural context helps students make sense of science concepts and that local knowledge strengthens learning. Although PSTs demonstrated a relatively low level of cultural context integration during the lesson plan preparation, the level of use of this component increased during implementation. Their increased attention to cultural context during the post-planning implementation process may have contributed to this change in their views.

The difficulties related to classroom management and material preparation may have resulted from PSTs' first experience with the CTCA process. In addition, because the SSIs addressed in the microteaching process can involve dilemmas and conflicting perspectives, they may have caused PSTs to experience challenges in classroom management. Consistent with this, Namdar and Tuskan's (2018) study, which examined science teachers' views on argumentation, also reported that teachers most frequently experienced difficulty in maintaining classroom control during this process. Since CTCA may include argumentation or other discussion-based processes, particularly in the group discussion stage, such difficulties can be expected. In addition, the fact that most PSTs described microteaching as an enjoyable and motivating experience suggests that, for these participants, this process was experienced as relevant not only to technical skill acquisition but also to their sense of professional development.

Taken together, the patterns observed across both lesson planning and microteaching, the finding that technology integration appeared stronger than cultural integration may reflect a difference in what each pillar demands of PSTs, in Heidegger's and Nkrumah's terms respectively. Enacting CTCA's technology pillar largely involves selecting and deploying discrete, visible tools, slides, videos, digital summary messages whose presence or absence is comparatively easy to identify, plan for, and assess. Enacting the cultural pillar, by contrast, requires PSTs to draw on Nkrumah's notion of indigenous knowledge: understanding how a local community makes sense of the world and translating that understanding into instructional content. This is a more interpretive, epistemically demanding task, and one for which PSTs, as digital natives already fluent with technological tools in their daily lives, may simply have had a shorter distance to travel than they did in developing the deeper local knowledge cultural integration requires. Read this way, the pattern may say less about CTCA's inherent structure than about the differing knowledge bases PSTs brought into the course, an institutional and generational factor the present design cannot fully disentangle from CTCA's own demands.

The comparatively weak performance in conceptual clarification is, we suggest, consistent with Shulman's (1987) account of pedagogical content knowledge and pedagogical reasoning. Anticipating and addressing misconceptions is arguably the most demanding component of pedagogical reasoning, requiring not only subject matter knowledge but also an internalised model of how learners are likely to misunderstand a concept, a form of knowledge typically built through repeated classroom experience rather than a single planning cycle. Viewed through Lave and Wenger's (1991) concept of legitimate peripheral participation, PSTs at this stage of their professional trajectory remain peripheral to the practice community of experienced science teachers; the iterative planning–feedback–microteaching–reteaching cycle adopted here, while consistent with Grossman et al.'s (2009) practice-based model of rehearsing core practices under supervision, may simply require more cycles or more targeted feedback specifically on anticipating misconceptions before this particular practice is reliably enacted.

An alternative explanation worth considering is that the CTCA-Based Lesson Evaluation Rubric itself may have made technology integration more visible, and therefore easier to reward, than cultural integration; criteria tied to concrete artefacts (e.g., digital tools used) may be more straightforward to score consistently than criteria requiring judgement about the depth or authenticity of cultural engagement. If so, part of this difference may reflect the operationalisation of the rubric rather than PSTs' underlying capacities, a possibility we could not fully rule out in the present design.

Theoretical and Practical Implications

Theoretically, these interpretations carry two broader implications. For CTCA research, they suggest the approach's three pillars should not be treated as developmentally equivalent when studied with novice implementers: rather than reporting a single aggregate effectiveness score, future CTCA studies would benefit from examining implementation at the level of individual pillars, particularly when the focus shifts from student outcomes to teachers' own enactment. For teacher education research more broadly, these findings suggest that practice-based cycles such as planning, peer feedback, microteaching, and reteaching, may suffice for developing visible, tool-based components of an approach; however, they may not be adequate within a single semester, for fostering more experience-dependent capacities, such as anticipating misconceptions or engaging authentically with cultural knowledge, central to Shulman's (1987) account of pedagogical reasoning.

Practically, these findings point to several concrete considerations for CTCA-based teacher preparation. Programmes may wish to allocate disproportionately more time and iterative practice to cultural integration and conceptual clarification specifically, rather than assuming a single planning–microteaching cycle develops all CTCA components at a similar pace. For cultural integration, the approach could include structured guidance or checklists to help PSTs research and translate local/indigenous knowledge into instructional content, addressing the more interpretive demands this pillar involves. For conceptual clarification, the process could include a dedicated misconception-anticipation step, in which PSTs identify likely student misunderstandings for their specific topic before finalising their lesson plans, rather than leaving this implicit in general planning. Programmes might also consider extending CTCA-based preparation across more than one semester or linking it across multiple courses to allow PSTs more than a single iterative cycle for the components that seem to require more sustained development.

Limitations

Several methodological choices shape how these findings should be interpreted and to what extent they can be transferred beyond the present context. Participants were selected via convenience sampling from a single course, which means those who volunteered may have differed systematically, for instance in motivation or confidence, from PSTs who did not; the reported patterns should therefore be understood as characteristic of this, self-selected group rather than of PSTs in general. The study was further situated within a single institutional context, whose regional culture, curricular structure, and available resources shaped both the SSIs PSTs selected (Table 1) and the forms cultural and technological integration could take; findings regarding, for instance, the relative ease of technology integration may be specific to an institution where PSTs already had strong digital access and fluency, and could differ in contexts with more limited technological infrastructure. The relatively small participant group, 34 PSTs organised into 11 groups, allowed for close, detailed engagement with each group's lesson plans, microteaching performance, and reflections, but also means that patterns observed for one or two standout groups (e.g., G4, G7) cannot be assumed to generalise even within the sample, let alone beyond it. As discussed above, the researcher's multiple roles as course instructor, intervention designer, evaluator, interviewer, and data analyst, while addressed through several procedural safeguards (see Method), remains a source of potential influence that these safeguards may not have fully offset; participants' willingness to voice criticism, for example, may still

have been shaped by their ongoing relationship with the researcher as their instructor. Finally, the qualitative case study design itself was chosen to provide an in-depth, contextually grounded account of an emerging instructional approach, a choice that trades statistical generalisability for interpretive depth; the findings are accordingly best read as an analytic account of how CTCA was taken up in one setting, offering transferable insights for similar contexts rather than claims about CTCA's effectiveness that would require experimental or comparative designs to establish.

These limitations point to several directions for future research. Multi-institutional studies, conducted across universities with differing regional cultures, curricula, and levels of technological infrastructure, would help clarify which of the present findings reflect features of CTCA itself and which reflect this particular institutional context. Comparative designs, contrasting CTCA-based preparation with alternative instructional approaches or with a no-intervention control group, would help isolate the specific contribution of CTCA relative to PSTs' general professional development over the same period. Longitudinal investigations, following PSTs from initial CTCA training into their early in-service teaching, would help determine whether the practice-based competencies observed here, and the gaps identified in conceptual clarification and cultural integration, persist, develop further, or fade once PSTs leave the structured, supervised context of teacher preparation.

Conclusion

The results of the study suggest that, within this educational context, a holistic and practice-based programme design may support the sustainable implementation of CTCA in teacher education. The experiences PSTs reported in relation to local context, technology integration, and active learning suggest that this approach shows considerable potential for engaging PSTs with SSI-based instruction. However, the shortcomings observed in areas such as conceptual clarification and discussion management indicate that CTCA-specific pedagogical skills may require more explicit attention in teacher education at both theoretical and practical levels.

Given that SSIs are directly related to students' daily lives, CTCA appears, based on this study, to offer a promising framework for PSTs to draw on in their future classrooms. The findings suggest that CTCA-based teacher education may support aspects of PSTs' professional development, particularly by encouraging them to relate scientific knowledge to technology and local context and to support students' active participation, patterns that emerged consistently across both planning and enactment. At the same time, cultural context integration and conceptual learning emerged as areas requiring more sustained attention within teacher education programmes, rather than outcomes this single practice cycle appears to have fully achieved. Because it was a qualitative case study conducted with a single cohort at one institution, these conclusions should be understood as context-specific; further research involving comparison groups or longitudinal designs would be needed to establish CTCA's broader effectiveness.

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Appendices

Table 4

CTCA-based lesson evaluation rubric

Section 1: Inclusion of the Basic Components of CTCA				
Evaluation Criteria	Successful (4)	Acceptable (3)	Needs Improvement (2)	Insufficient (1)
1. Cultural Context (Culture)	Scientific concepts are fully and meaningfully synthesized with local knowledge, traditional practices, or cultural heritage.	Cultural elements are present in the lesson, but they are not fully integrated with the scientific content.	Only superficial or general cultural examples are included.	The cultural context is not included in the lesson.
2. Technology Mediation (Technology)	Digital tools (YouTube, WhatsApp, Web 2.0, etc.) are actively used both for research and as cognitive scaffolding.	Technology use is present, but it is limited to the level of information transmission.	Only a single technological tool is used in a way that does not serve the intended purpose.	The technology component is not included in the lesson.
3. Local Context (Context)	Examples are selected directly from the school's immediate surroundings or from students' everyday living environments.	Regional examples are used, but they are not limited to the environment with which students directly interact.	General and decontextualized case studies are included.	No connection is established with the local/regional context.
Section 2: Alignment with the CTCA Implementation Process				
Implementation Steps	Successful (4)	Acceptable (3)	Needs Improvement (2)	Insufficient (1)
Step 1: Pre-Lesson Preparation	Clear and guiding tasks are given to students for investigating local knowledge and examining web resources.	A task is given, but the research steps (cultural/technological) are not sufficiently detailed.	Only a general research assignment is requested; it is not CTCA-focused.	No pre-lesson preparation is carried out.
Step 2: Group Discussion and Sharing	Data sharing is fully achieved in mixed-ability groups through social interaction during the lesson.	Groups are formed, but the peer learning and cultural data-sharing process remains weak.	The lesson is limited only to forming groups.	There is no group interaction; the lesson is entirely teacher-centered.
Step 3: Drawing, Humor, and Concretization	The topic is concretized through original drawings or humor elements using examples from students' immediate surroundings.	Drawing or humor is present, but it does not fully serve the function of simplifying the scientific concept.	Only ready-made visuals are used; students' creativity is not included.	Enriching materials such as humor or drawing are not included.
Step 4: Conceptual Clarification	Misconceptions arising from cultural beliefs are clarified by comparing them with scientific data and web resources.	Misconceptions are identified, but the synthesis of cultural and scientific data is not fully achieved.	Only scientific definitions are provided; no bridge is established with cultural data.	Conceptual misconceptions and cultural beliefs are not addressed at all.
Step 5: Digital Summary Message	A short and effective digital summary message containing the key information is available at the end of the lesson.	A summary message is available, but it does not fully comply with the CTCA format.	Only a general lesson summary is provided; digital delivery is not carried out.	There is no summarization or digital feedback process.

Table 5*Pre-service Science teachers' perspectives on CTCA-based lesson planning (comprehensive data)*

Category	Code	n	Quotations
Theme 1: Suitable Topics			
Topic scope	Socioscientific issues	15	Because socioscientific and environmental issues may vary across regions and cultures, the CTCA can be widely used in science education. (PST1)
	Topics related to daily life	7	The CTCA is very suitable for topics that can be experimented with or that we encounter in daily life. (PST11)
	Local and cultural topics	7	Relating topics to culture and foregrounding locality reinforce the topic more strongly. (PST26)
	Limitations in theoretical topics	2	It is very difficult to apply this to topics that can be understood entirely theoretically. (PST22)
Theme 2: Active Learning			
Student-centeredness	Students take an active role	19	Students take a more active role and discover their own knowledge throughout the process. (PST25)
	Sense of self-efficacy	3	Being able to figure things out on my own makes me feel good. (PST9)
Discussion environment	Group discussion	6	In the discussion stage, students actively participate in the lesson and are able to express their ideas freely. (PST5)
	Providing feedback	2	Students discuss, reach a conclusion, and find the correct answer together with the teacher. (PST26)
Quality of learning	Lasting/meaningful learning	7	It enables meaningful and lasting learning of the topics. (PST33)
	Addressing misconceptions	2	It facilitates the elimination of misconceptions. (PST25)
Enjoyable learning	Humor and creativity	5	I was greatly impressed by the open-ended nature of the 'draw and develop humor' step, as it allows students to use their creativity effectively. (PST22)
Theme 3: Culture-Technology Integration			
Cultural integration	Providing cultural awareness	12	The biodiversity topic was enriched and addressed with examples specific to Aksaray. (PST21)
	Advantage of local prior knowledge	5	Since the topic was related to my own hometown, I was able to make more connections and interpretations. (PST1)
Technology integration	Web 2.0/digital tools usage	10	It is a good thing to prepare activities for students with the help of technology and enable them to be active. (PST16)
Culture-technology integration	Culture-technology integration	6	Cultural approaches and technology are integrated; in this context, our past and future are blended together. (PST30)
Theme 4: Implementation Challenges			
Cultural difficulty	Finding cultural context	7	It was quite difficult for the drawings to include culture; I still feel as if the drawing did not fully connect with culture. (PST22)
Pedagogical difficulty	Creating a discussion environment	8	The discussion section is challenging; because it is difficult to receive feedback from the class, this section may remain insufficient. (PST26)
Creativity barrier	Difficulty in the humor development step	5	Finding humorous content related to the topic and creating a cartoon about it was challenging. (PST10)
Technical difficulty	Unfamiliarity with the steps	5	Since it was an approach, we had not encountered before, I had difficulty understanding its stages. (PST3)
	Time management (microteaching)	2	Because it was microteaching, we had difficulty keeping to the allotted time. (PST14)
Topic limitation	Limitations in theoretical topics	2	It is very difficult to apply this to topics that can be understood entirely theoretically. (PST22)
Theme 5: Comparison with Other Approaches			
Comparison with the 5E model	Difference in technology integration	9	Compared with the 5E model, the CTCA is a model in which students are more active and more intertwined with technology. (PST16)
	Cultural difference compared with the 5E model	3	While the 5E model is more related to question-answer activities and preparing presentations, the CTCA values students' own cultures and is more closely associated with technology. (PST8)

Comparison of activeness	Difference in student activity	6	In the CTCA, we are more active; in the others, the teacher usually explains and we listen. (PST11)
	Moving beyond traditional instruction	6	Throughout my education so far, I have become more aware of how negatively traditional instruction can affect students. (PST21)
Overall superiority	Well-structured/comprehensive structure	2	I think the CTCA is the most organized and cohesive approach among the other approaches. (PST18)
Theme 6: Suggestions for Improvement			
Structural suggestion	Strengthening the discussion step	7	By assigning the homework earlier, a richer discussion environment could have been created; the lesson could also take place outside the classroom. (PST33)
	Increasing student participation	7	Instead of the teacher preparing everything, students could also be asked to prepare something. (PST8)
	Clarifying the exploration step	3	The exploration part could be a little clearer; it is too open-ended, so there could be small prompts. (PST9)
	Flexibility in the humor step	2	In the draw and develop humor step, I would allow the use of alternative techniques instead of drawing. (PST18)
Technical suggestion	Include ore technology	5	Because it is microteaching, more technology could be used in some steps. (PST14)
	Strengthen homework follow-up	3	In the homework assignment part, whether the student has done the homework should be followed up. (PST28)
	New stage/gamification	2	Gamification could also be added. (PST31)
Critical suggestion	Misconception step should be optional	1	Making the misconception step compulsory for every topic implies that there should be misconceptions in every topic. (PST22)

Table 6

Pre-service science teachers' perspectives on CTCA-based microteaching practices (comprehensive data)

Category	Code	n	Quotations
Theme 1: Instructional Process: Introduction, Content, and Presentation			
Introduction phase	Attracting attention and arousing curiosity	24	In the introduction, I asked questions that would arouse students' curiosity and checked their readiness. (PST29)
Introduction phase	Assessing readiness and prior knowledge	5	I began with the question-answer technique both to attract attention and to examine readiness. (PST10)
Content development	Preparing simple and clear content	16	We paid attention to making it easy, understandable, and clear. (PST6)
Content development	Content supported with visuals and models	4	Supporting it with visuals and models. (PST12)
Content development	Fun and engaging content	8	Making it fun, lasting, and instructive. (PST15)
Content development	Attention to misconceptions	3	I paid attention to misconceptions and the experiment procedure. (PST9)
Presentation skills	Eye contact and body language	8	I paid attention to eye contact, gestures and facial expressions, and proceeding with students through question-answer interaction. (PST10)
Presentation skills	Voice tone and diction	12	I paid attention to teaching the lesson with a tone of voice that every student could hear. (PST21)
Presentation skills	Fluent and natural delivery	9	I paid attention to speaking more fluently and explaining in a way that students could understand. (PST22)
Theme 2: Student Participation and Assessment			
Active participation strategies	Ensuring participation through the question-answer technique	18	I asked students questions and involved them in the activity in groups. (PST3)
Active participation strategies	Activity- and game-based participation	11	We wanted to design an activity that students would be willing to participate in; there were no passive students. (PST5)
Active participation strategies	Group work and collaboration	7	Each student took part in the activity both individually and as part of a group. (PST31)
Assessment processes	Receiving feedback through questions	12	Feedback was received from students through questions. (PST23)

Assessment processes	Ensuring alignment between learning outcomes and assessment	5	Appropriateness for the time and learning outcome. (PST17)
Assessment processes	Self- and peer assessment	2	I would value both self-assessment and peer assessment. (PST34)
Assessment processes	Reinforcement and rewarding	4	Students who answered correctly were rewarded (for reinforcement purposes). (PST31)
Theme 3: Technology Use			
Technology integration	Presentation with slides/projection	5	Using technology in the lesson to make it efficient; it was done with slides and video. (PST11)
Technology integration	Use of video and visual materials	2	To make the lesson more engaging, we watched videos related to the topic. (PST34)
Technology integration	Use of artificial intelligence and internet resources	2	I tried to integrate technology for students by using artificial intelligence models. (PST26)
Reasons for not using technology	Learning outcome does not require technology	14	Technology was not highly relevant to my learning outcome; I used it only for research purposes. (PST7)
Theme 4: Cultural and Regional Context			
Local and cultural connections	Including regional/local examples	21	While preparing our slides, we selected visuals from our city so that students could more easily relate to them, as they reflected the environment in which they live. (PST32)
Local and cultural connections	Cultural connection through everyday life examples	6	I made a season-city connection with the students. (PST33)
Local and cultural connections	Universal content applicable to all regions	4	It was not intended for a single region; I paid attention to choosing universal topics that cover all regions. (PST7)
Theme 5: Challenges and Enjoyable Experiences			
Implementation challenges	Managing excitement and stress	6	I got excited and could not control this excitement. (PST25)
Implementation challenges	Classroom management and control	8	There were not many aspects that challenged me, but classroom control was difficult. (PST7)
Implementation challenges	Material and technical difficulties	8	Preparing the lesson materials was quite difficult. (PST32)
Implementation challenges	Time constraint	3	The shortness of my time was the issue. (PST21)
Enjoyable and motivational experiences	Enjoyment of conducting activities and games	19	I had a lot of fun while having them play the game. (PST32)
Enjoyable and motivational experiences	Interaction and motivation with students	14	Students' active participation in the lesson, both learning and socializing, made the experience enjoyable for me. (PST26)
Enjoyable and motivational experiences	Experiencing the teaching profession	2	Even though it lasted only 10 minutes, experiencing teaching made me very happy. (PST21)

An Example of a Lesson Plan Prepared by Pre-Service Teachers

CTCA Implementation Steps (*The original Turkish text is provided in parentheses*)

Group (PSTs): G5 (PST13-PST15)

SSI: Biodiversity

Learning outcome: FB.6.7.1.1 Being able to question the importance of biodiversity for wildlife

Step 1: Get the assignment and research (15 minutes)

(a) Students are informed in advance that the lesson will address questioning the importance of biodiversity for natural life. (b) Students are asked to reflect on the local aspects of biodiversity in natural life, cultural practices, or their ideas about natural life related to biodiversity. They are informed that they will share the ideas developed through this activity with their classmates. (c) Students are asked to investigate places in Aksaray that host different species by consulting artificial intelligence tools, older family or community members, magazines, and academic articles.

((a) Öğrencilere sınıfta biyoçeşitliliğin doğal yaşam için önemini sorgulayabilme konusunun ele alınacağı hakkında önceden bilgi verilir. (b) Öğrencilerin biyoçeşitliliğin doğal yaşamdaki yerel yönleri, kültürel uygulamaları veya biyoçeşitlilikle ilgili doğal yaşama yönelik düşünceleri istenir. Öğrenciler bu çalışmalarını sonucunda oluşacak düşüncelerini sınıfta arkadaşları ile paylaşacakları konusunda bilgilendirilir. (c) Aksaray'da bulunan ve farklı canlı türlerine ev sahipliği yapan yerler hakkında yapay zekadan, büyüklerinden, dergi ve makalelerden araştırmaları istenir.))

Step 2: Discuss with the group and share the result (25 minutes)

To ensure diversity in the information obtained from artificial intelligence tools, older family or community members, magazines, and academic articles, students with mixed abilities are assigned to different groups. Each group is asked to select a group leader. A brainstorming process is then initiated within the groups, and the cultural/web-based reflections are documented and presented by the group leader. The teacher concludes the topic by sharing local and cultural practices related to biodiversity.

(Yapay zekadan, büyüklerinden, dergi ve makalelerden edinilen bilgilerin çeşitliliği için karma yetenekli öğrenciler farklı gruplarda toplanır. Grup lideri belirlemeleri istenir. Grup içinde beyin fırtınası süreci başlatılır ve kültürel/web tabanlı yansımalar grup lideri tarafından belgelenerek sunulur. Öğretmen biyoçeşitliliğe yönelik yerel/kültürel uygulamaları paylaşarak konuyu tamamlar.)

Step 3: Draw and develop sense of humour (15 minutes)

The teacher continues the lesson using information, images, videos, and audio recordings obtained by researching areas in Aksaray that host biodiversity. A concept cartoon is created by the teacher using Canva and left incomplete so that students can contribute to and further develop the drawings. The drawings may also be created using paper and pencil. Humorous elements may be incorporated into this section. An example of a drawing that can be developed at this stage is presented below.

(Öğretmen Aksaray'da bulunan biyoçeşitliliğe ev sahipliği yapan bölgeleri araştırarak bulduğu; görsel, video, ses kayıtları ile ilgili bilgilerle dersi iletir. Öğretmen tarafından Canva uygulaması kullanılarak kavram karikatürü oluşturulur ve yarım bırakılır, öğrencilerin de katılımı ile çizimlerin geliştirilmesini sağlayabilir. Çizimler kâğıt-kalem kullanılarak oluşturulabilir. Bu bölüm mizah içerebilir. Bu bölümde oluşturulabilecek bir çizim örneği aşağıda sunulmuştur.)

Step 4: Make sense of the concepts and clear the misconception (10-15 minutes)

To facilitate conceptual understanding, the importance of local/cultural practices and research is revisited in the classroom. If students hold any misconceptions, the teacher addresses and corrects them. When necessary, tools such as artificial intelligence, textbooks, and conceptual change texts may be used to resolve these misconceptions. An incomplete example of a conceptual change text is presented below.

(Kavramları anlamlandırmak için yerel/kültürel uygulama ve araştırmanın önemi sınıfta hatırlatılır. Eğer öğrencilerde kavram yanlışlığı varsa öğretmen tarafından giderilir. Gerekli görülürse, yapay zeka, ders kitabı kullanılarak kavramsal değişim metinleri gibi araçlara yer vererek kavram yanlışlıkları giderilir. Tamamlanmamış örnek bir kavramsal değişim metni aşağıda sunulmuştur.)

Step 5: Summarize and send a message (10-15 minutes)

At the end of the lesson, the teacher shares an infographic summary on biodiversity, created using Canva and containing visuals and a specified character limit, with the students via text message/email, EBA, or a web-based application. A QR code system may also be used to help students become familiar with technology. An example is provided below.

(Dersin sonunda öğretmen biyoçeşitlilik ile ilgili belirli karakter sayısı içeren görseller de bulunan Canva uygulaması yardımıyla oluşturulmuş infografik özeti öğrencilere kısa mesaj/mail, EBA veya web tabanlı bir uygulama aracılığıyla iletir. Burada öğrencilerin teknolojiye aşina olmaları için karekod sistemi kullanılabilir. Buna bir örnek aşağıda verilmiştir.)

Example Drawing for the “Draw and Develop Sense of Humour” Step (Turkish)



Example Conceptual Change Text for the “Make Sense of Concepts and Clear the Misconception” Step

“The coexistence of different species within biodiversity negatively affects the continuity of the food chain and threatens ecosystem stability...”

(“Biyçeşitlilikte farklı türlerin bir arada olması, besin zincirinin devamlılığını olumsuz etkilemekte ve ekosistemin güvencesini tehdit etmektedir...”)

Example Infographic for the “Summarize and Send a Message” Step (Turkish)

