Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

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Journal of Turkish Science Education (2025), Volume 22, Issue 4

Journal of Turkish Science Education, 2025, *22*(4), 612-624.
DOI no: 10.36681/tused.2025.031

Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

The development of a reading model in physics teaching for argumentation skills and critical thinking skills: a 'Fuzzy Delphi' method

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ABSTRACT

Reading activities are essential to the physics learning process. Physics teaching has mostly been carried out to foster higher order thinking skills such as critical thinking and argumentation skills. This present study aims to develop a reading model that can be enacted in physics education to facilitate critical thinking and argumentation skills. This study employed the Fuzzy Delphi method. In this study, the Fuzzy Delphi method was divided into two phases. In the first phase, the experts (5 experts) were interviewed to determine the relevance of reading activities to the development of argumentation and critical thinking skills in the physics learning process. Then, in the second phase, we employed 27 experts to determine the stages of the reading model. In this phase, a questionnaire was developed consisting of fourteen questions. The research findings indicate that a consensus was reached on the stages of the reading model aimed at developing argumentation and critical thinking skills. These stages include predicting the purpose and content of the passage, explaining phenomena, reading by critical-argumentation activities, and evaluating predictions of the purpose, content, and explanation of the phenomena.

RESEARCH ARTICLE

ARTICLE INFORMATION
Received: 17.04.2023
Accepted: 29.07.2025
Available Online: 25.10.2025

KEYWORDS: Reading model, critical thinking, scientific argumentation, fuzzy delphi method.

To cite this article: Siswanto, S., Subali, B., Hartono, H., Masturi, M., Wibowo, F.C., Trisnowati, E., Haryati, S., & Sukarno, S. (2025). The development of a reading model in physics teaching for argumentation skills and critical thinking skills: a 'Fuzzy Delphi' method. *Journal of Turkish Science Education, 22*(4), 612-624. http://doi.org/10.36681/tused.2025.031

Introduction

Reading scientific texts is a fundamental activity in the teaching and learning process in science education. It plays a vital role in enhancing students' comprehension (Oliveras, 2013) and can also support laboratory activities by helping students understand scientific information and processes (Rojas, 2019). Reading scientific texts aids in the acquisition of academic and scientific language skills (Anjani, 2022; Duke, 2021). Michalsky (2013) further notes that engaging with scientific texts activates cognitive processes and serves as a bridge to various scientific thinking skills, such as observing, classifying, interpreting, predicting, hypothesising and formulating questions.

Beyond fostering essential skills such as higher-order thinking, reading scientific texts also supports the development of critical thinking and argumentation skills. This is because the activity helps students comprehend scientific information and gather evidence from the text, which can be used to construct well-reasoned arguments. Research has shown that reading activities enhance conceptual understanding (Muhid, 2020; Meneses, 2018; Smith, 2021; Oliveira, 2014; Moats, 2020; Petscher, 2020), providing a foundation for evidence-based argumentation. Processing information from texts often challenges students' preconceived notions about scientific concepts, prompting them to think critically about what they read. Thus, reading activities offer valuable opportunities to develop both critical thinking and argumentation skills (Casado, 2023; Demircioglu, 2023; Anggraeni, 2023; Alsaleh, 2020).

There remains a lack of empirical evidence detailing how a framework or model for such activities can be explicitly designed to achieve these goals. Referring to the general structure of reading activities, which are typically divided into three stages—before, during, and after reading—we aim to integrate critical thinking and argumentation skills into specific activities tailored for physics teaching and learning. To achieve this, we propose using the Fuzzy Delphi method to develop an appropriate reading model. This model will encompass key phases and sub-phases designed to assist students in cultivating their critical thinking and argumentation skills through reading activities in physics learning.

Based on the description above, the research question in this study is how the reading model can be implemented in physics learning to train students' critical thinking and argumentation skills?. In this study, the reading model was developed in stages based on expert consensus.

Methods

We used a fuzzy Delphi Method (FDM) as an analytical method to analyse consensus among experts in developing a reading model for teaching physics.

Fuzzy Delphi Method

FDM combines Fuzzy Theory and the Delphi method (Saido, 2018), a decision-making approach to obtain consensus among experts using a sequence of questionnaires. The use of Delphi method was mainly aimed to attain consensus among experts focused on different opinions of a group decision instead of individual decision (Al-Rikabi, 2024). Practically, using the Delphi method without Fuzzy makes decision-making more difficult, as it requires a longer time to reach a conclusion. In addition, the decision-making process will take even longer.

Blending Fuzzy Theory with the Delphi method can eliminate these difficulties; this was called Fuzzy Delphi Method (FDM). It was an effective tool for obtaining subjective data produced by opinions which engages uncertainty and imprecision and transforms them into quantitative data for a decision making this claim needs a reference. We consider FDM was suitable because it established a decision making of experts' opinions to develop a reading model in physics teaching learning that integrates argumentation and critical thinking activities.

Participants

We employed 32 participants to develop a reading model integrating argumentation and critical thinking activities for physics teaching and learning. The choice of the number of participants aligned with Damigos (2011) who recommended from 10 to 50 experts based on their competency. Because we divided the developments of the reading model into two phases, we employed five experts in the first phase (science education and language experts) to achieve a consensus of relevancy and substance of aspects of reading model to argumentation and critical thinking skills. The experts were associate professors and a professor of science education with 5 years to 20 years of experience. Then, in the second phase, we employed 27 experts to determine the stages of the reading model. The experts were practitioners and a lecturer teaching physics and education in college and they were ever involved in several trainings of professional lecturers by Indonesian Ministry of Education and Culture.

Instruments

We used two sorts of instruments in this present study, namely an interview protocol for a semi-structured interview for the first phase and an FDM questionnaire that referred to themes emerging from analysis of interview data for the second phase.

The first instrument asked respondents to outline their views about a reading model that was suitable for developing argumentation and critical thinking skills. The second instrument involved four phases: predicting the purpose and content of the passage; explaining phenomena; reading by critical-argumentation discussion; and evaluating prediction of purpose, content, and explanation of the phenomena. Finally, the experts were asked to comment on the sub-phases of each phase; it consisted of 14 sub-phases. In the context of the reliability of the questionnaire, we counted Cronbach coefficient by piloting it among 10 experts in science education and we found 0.821 for Cronbach coefficient and this value was categorized as high reliability (Saido, 2018).

Data Analysis

We conducted two data analyses. First analysis was dealing with the interview data and second analysis was related to questionnaire data. In the context of the interview data, we conducted a thematic analysis by transcribing the analysis of the FDM questionnaire was conducted by following some steps:

- Step 1: we determine the linguistic scale. Then, fuzzy numbers were added to the constructed Likert scale (Hsieh, 2004). We then formed a triangular Fuzzy number in order to address the fuzziness among experts by establishing three fuzzy numbers that were m1 (the minimum value), m2 (medium value), and m3 (maximum value). All these numbers are in range 0 and 1. Nevertheless, there will be three values for each response in the Likert scale.
- Step 2: we compute the average fuzzy number and this is conducted by identifying the average responses for every fuzzy number (Benitez, 2007)
- Step 3: we identify threshold value (d) using the formula 1 to determine the consensus level among experts. The specific value of the threshold value that is less than 0.2 shows a consensus achieved by experts and another analysis can be seen from overall group consensus that should be more than 75%. When the condition is not achieved, the FDM should be repeated until a consensus is attained.

$$d(\bar{\boldsymbol{M}},\bar{\boldsymbol{m}}) = \sqrt{1/3 \times (M_1 - \boldsymbol{m}_1)^2 + (\boldsymbol{M}_2 - \boldsymbol{m}_2)^2 + (\boldsymbol{M}_3 - \boldsymbol{m}_3)^2} \qquad (1)$$

Table 1

Linguistic Scale with Fuzzy number

Linguistic scale	Fuzzy number		
	m_1	m_2	m_3
Strongly agree	0.6	0.8	1
agree	0.4	0.6	0.8
Moderately agree	0.2	0.4	0.6
disagree	0	0.2	0.4
Strongly disagree	0	0	0.2

- Step 4: we identify alpha-cut level. In this value, we take 0.5 for alpha-cut level to select elements (sub-phases) for the reading model to train argumentation and critical thinking skills. Nevertheless, the score above and under 0.5 will be omitted; the choice of this score is based on several studies (e.g. Saido, 2018).
- Step 5: we make the defuzzification process in order to justify expert consensus on the element for phase and sub-phases in the reading model. In this process we convert fuzzy number into crips real number (Hsieh, 2004). We can defuzzification value (DV) from this process by using the following equation:

$$DV = 1/3 \times (\boldsymbol{m}_1 + \boldsymbol{m}_2 + \boldsymbol{m}_3) \qquad (2)$$

  The values of m_1, m_2, m_3 are the mean value of fuzzy number for each expert.
- Step 6: we rank phases and sub-phases (elements) of the reading model and use this rank to prioritise the elements based on the DV in the model form implementation in the physic teaching class. The placed on the highest priority ranking that adjust to the highest DV value.

Findings

The result of the thematic analysis of experts' interview data in the first phase can be seen in the Table 2 and Table 3. According to thematic analysis as shown in Table 2 dan Table 3 categorises the two aspects, namely, the relevance and substance of the content. From the interview data, we know that reading activities are relevant to train or bridge aspects of higher-order thinking skills such as critical thinking and argumentation skills. Experts considered that not all reading activities could train argumentation and critical thinking skills; the reading activity that refers to training these skills is advanced reading activities, a reading activity driven by using SQ4R techniques or maximising critical reading techniques.

Table 2

Sample of the thematic analysis about the relevance of reading for argumentation and critical thinking skills

Themes	Coding category	Open coding	Sample of answer by Expert
Reading activity is relevant to train argumentation and critical	Relevance of reading activity for HOTs in science learning process	Reading can build higher order thinking skills (HOTs) and critical thinking	"*…Reading is not only conducted passively; active reading can train students to build their own knowledge. For example, there is the SQ4R technique to train aspects of Higher Thinking Orders Skills (HOTs)...*" (Expert-1) "*…the reading process can be conducted by critical reading. If students are able to read critically, I think*

Themes	Coding category	Open coding	Sample of answer by Expert
thinking activities.			*it can help students construct their knowledge…"* (Expert-2).
		Reading activities are relevant for HOTs	*"…One of the achievements of learning science is facilitating student HOTs, reading activities are relevant to that as long as it is adjusted to the achievements to be achieved…"* (Expert-3).

Table 3

Sample of the thematic analysis about substance of reading activities in science learning

Themes	Coding category	Open coding	Sample of answer by Expert
The substance of reading model in science learning	Predicting purpose of the passage	Critical reading leads to predict the purpose of the texts	*"…Critical reading is usually characterized by the reader being able to predict what the purpose of the text he is reading… a critical reader must be able to find the purpose of his reading…"* (Expert-2)
	Explaining phenomena	Reading content can depict contextual phenomena.	*"…In reading, students are still given some reading content related to contextual phenomena. Students can be asked questions related to these phenomena, then look for explanations by reading…"* (Expert-3)
	Supporting critical thinking	Reading activity can be engaged to critical questions	*"…Presenting critical questions, can use the framework proposed by Tiruneh. Students answer these questions by reading…"* (Expert-3)
	Training argumentation activities	Reading activities can train argumentation activities and patterns	*"…To practice argumentation, students can answer questions by asking argumentation patterns, using Toulmin's formulation as a reference…"* (Expert-4)
	Understanding science concepts/phenomena	Reading activities can be a way for understanding science concepts	*"…but most importantly, students can understand the science content that the text wants to convey…For critical reading, students must understand the message the reading wants to convey…"* (Expert-5)

In addition, based on the Table 2 and Table 3, the experts also viewed that advanced reading activities could be created by innovating the stages of reading activities that are in accordance with the content of the reading material (text) used and the expected learning objectives. Further, we found that reading activities that were suitable for science/physics teaching and learning should contain existence of several elements such as bridging to predict purpose of the passage, explain phenomena, provide critical-argumentation thinking activities, and understand science concepts/phenomena. To follow up what we found in the thematic analysis, we constructed a framework of a reading model that consisted of three main parts: before, during, and after reading. Each part of reading activities leads to several elements obtained from thematic analysis of the interview data. Specifically, the elements emerged in the stages of a reading activity developed aim to support argumentation and critical thinking skills (Figure 1). These elements consisted of four phases: predicting the purpose and content of the reading, explaining the phenomenon, reading by critical-argumentation activities, and evaluating the prediction of the purpose, content, and explanation of the phenomenon. Each phase was elaborated to sub-phases that aims to operationalize the phases in science/physics learning activities. There were 14 sub-phases as presented in the Table 4.

Figure 1

Stages of a reading model for argumentation and critical thinking activities

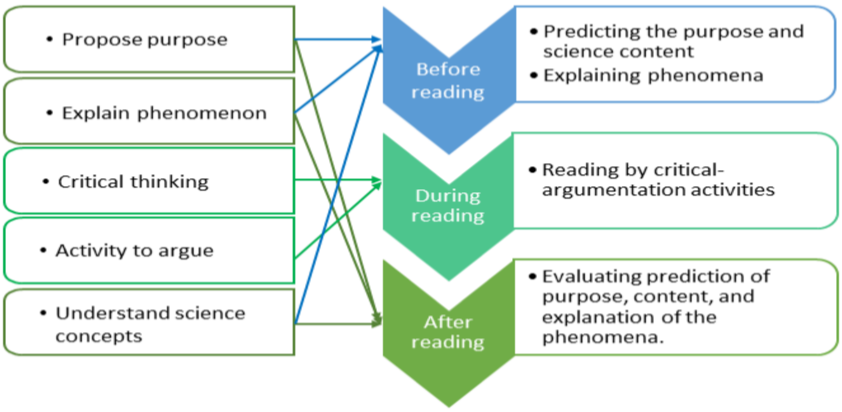


Table 4

Stages of a reading model for argumentation skills and critical thinking skills

Parts of reading activities	Phases	Sub-phases
Before reading	A. Predicting purpose and content of the passage B. Explaining phenomena	• A_1: Predict purpose of the texts • A_2: Predict short description of the content • B_1: Provide an explanation with prior knowledge of a phenomenon related to the texts
During reading	C. Reading by critical-argumentation activities	• C_1: Evaluate validity of the data • C_2: Detect ambiguous concepts and abuse definition • C_3: Explain relationship among variables • C_4: Identify whether a causal relationship claim can/cannot be made • C_5: Predict a possible event • C_6: Evaluate incomplete information in an argument • C_7: Provide a solution to a problem • C_8: Provide a comprehensive scientific argument including to proses claims, evidence/data, explanations, and support
After reading	D. Evaluating prediction of the purpose, purpose, content, and explanation of the phenomena	• D_1: Evaluate purpose of the text predicted in before reading • D_2: Evaluate short descriptions predicted in before reading • D_3: Evaluate the explanation of the phenomena predicted in before reading

After we established stages of a reading model including phases and sub-phases, we tested this reading model by using fuzzy approach. Here, we counted average score of fuzzy number each stage, threshold score, percentage of consensus, alpha cut, and ranking. All scores can be seen in Table 5 and Table 6. Based on data on the Table 6, we found that the threshold value is less than 0.2 and the percentage of agreement is more than 75%. We concluded that sub-phases in the reading model developed have been agreed by all experts. Thus, there is no need for the Delphi test for the next step. Meanwhile, all identified alpha cut values are more than 0.5 that shows an agreement among experts about sub-phases and phases formulated in our reading model. In addition, this value also indicates that the sub-phases created are able to train critical thinking skills, argumentation skills, reading comprehension skills, and motivate students as science teacher candidates.

The Alpha-Cut value shows the ranking in the sub-phases carried out in each main phase. The ranking here refers to an element of priority. A higher ranking indicates that the sub-phase is of higher priority to be carried out than the sub-phase with a lower ranking (Figure 2). In the before-reading stage, the sub-phase explaining the phenomenon becomes the most essential activity. The second order is the activity of predicting the content of the text, and the last order is the activity of predicting the purpose. At the reading stage, the activity that becomes the most important priority is detecting ambiguous concepts and abusive definitions, which are activities in critical thinking. The second place is the activity of providing solutions to a problem. The scientific argumentation activity is also the second priority. The third priority is explaining the relationship between variables and predicting phenomena. The last priority in the stages of reading is the activity of identifying causal claims and evaluating arguments. In the context of the stage of after reading, the priority is assessing the explanation of the phenomenon. The second priority is to evaluate the predictive content of the text, and the third priority is to assess the purpose of the text.

Table 5

Average scores of fuzzy numbers

Reading activity	phase	Sub-phases	Average score of a fuzzy number		
			M_1	M_2	M_3
Before reading	A	A_1	0.46	0.66	0.86
		A_2	0.47	0.67	0.87
	B	B_1	0.49	0.69	0.89
During reading	C	C_1	0.50	0.70	0.90
		C_2	0.53	0.73	0.93
		C_3	0.50	0.70	0.90
		C_4	0.47	0.67	0.87
		C_5	0.50	0.70	0.90
		C_6	0.47	0.67	0.87
		C_7	0.51	0.71	0.91
		C_8	0.51	0.71	0.91
After reading	D	D_1	0.45	0.65	0.85
		D_2	0.48	0.68	0.88
		D_3	0.50	0.70	0.90

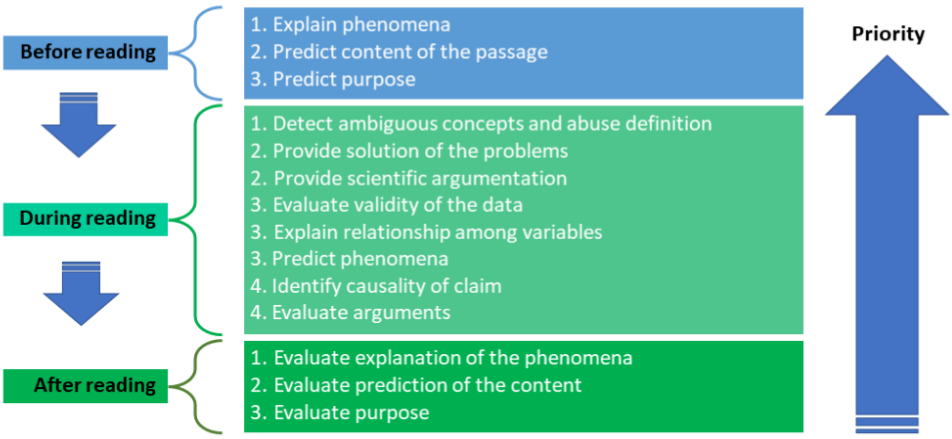
Table 6

Threshold value, percentage of consensus, alpha cut, and ranking of sub-phase

Reading activity	Sub-phase	d	%	Alpha cut	Ranking
Before reading	A_1	0.14	85.90	0.66	3
	A_2	0.13	87.41	0.67	2
	B_1	0.11	88.89	0.69	1
During reading	C_1	0.10	89.63	0.70	3
	C_2	0.07	90.37	0.73	1
	C_3	0.10	89.63	0.70	3
	C_4	0.13	86.67	0.67	4
	C_5	0.10	89.63	0.70	3
	C_6	0.13	86.67	0.67	4
	C_7	0.09	91.11	0.71	2
	C_8	0.09	91.11	0.71	2
After reading	D_1	0.15	85.19	0.65	3
	D_2	0.12	88.15	0.68	2
	D_3	0.10	89.63	0.70	1

Figure 2

Stages of a reading model and its elements for argumentation skills and critical thinking skills



Discussion

The reading model developed in this study emphasises argumentation and critical thinking activities. Critical thinking and scientific argumentation indicators are integrated into the three reading stages: before, during, and after reading. In the interview, science education experts agreed that practising higher-order thinking skills in the science learning process, such as critical thinking skills and scientific argumentation, could be carried out by using reading activities. This is because reading activities involve various kinds of complex cognitive processes, including scientific processes as trained through experimental activities in the laboratory (Siswanto, 2022; Michalsky, 2013). Thus, students can be facilitated to learn how scientific knowledge is developed, formed, and understood in various models of scientific reasoning (Fang, 2010). Based on the study's findings, we discuss what we found in the first and second stages of the development of the reading model.

In the first phase of developing a reading model, we found several activities that should exist in the reading model. These activities include expressing goals, explaining phenomena, critical thinking activities, presenting arguments, and understanding the contents of the reading. These activities aligned with other researchers' arguments about patterns of reading activities (Oliveras, 2013) and elements of critical thinking that should exist in reading activities (Mozaffari, 2021). Further, we used these activities to analyse the stages of the main activity in a reading model developed. The analysis results show that the activities of stating goals, understanding the contents of the reading, and explaining phenomena are in the activity stages before and after reading, whilst critical thinking and argumentation activities are in the activity stages during reading. This aligns with Rojas (2019), who stated that reading has three main stages: before, during, and after reading. Activities before reading are beneficial to activate the initial knowledge possessed by students. Activities during reading then construct new knowledge obtained from a text and relate it to initial knowledge; this can usually be done by proposing some questions. Finally, activities after reading aim to organise the knowledge obtained to become meaningful knowledge.

In the second phase of development of the reading model, the experts agreed that phases and sub-phases in reading activities can develop critical thinking skills, argumentation, reading comprehension skills, and reading motivation for science teacher candidates. Specifically, the experts agreed on all activities in the reading stages. For activities before reading, the experts agreed on the two proposed phases, namely predicting the purpose and content of the reading and explaining the phenomenon. These align with other researchers arguing that activities before reading are related to activities to predict what the text will explain before students start reading (e.g. Patterson, 2018). These activities activate prior knowledge and link it with existing contextual phenomena (Oliveras, 2013; Alshehri, 2024).

We here elaborate and discuss what students do in the context of before reading. In the phase of predicting the purpose and content of the text, students are given a sentence containing the text's title. They can explore their prior knowledge to indicate the purpose and description of the content of the text. This phase is used as the initial stage in practising critical thinking skills, as we know that predicting the text's purpose and content is part of the elements of critical science reading (Archila, 2024). When a reader aims to pass the literal reading stage to the critical reading stage, the reader must be able to interpret the purpose and content of the text presented (Tsai, 2022). In addition, this phase is used to stimulate the initial knowledge stored in the students' memory. Then, in explaining the phenomenon, students are asked questions related to the phenomenon presented in the text. By presenting these questions, students become more motivated to read texts because they aim to restructure the initial knowledge and have built a skill in explaining phenomena (Tseng, 2010). In addition, the phenomena presented have the characteristics of contextual concepts so that students are aware that the concepts studied are closely related to everyday life. This motivates students to learn (Armario, 2022; Mufit, 2024).

Practically, we divided the activities before reading into three sub-phases, namely predicting the purpose of the text, predicting the content of the text, and explaining phenomena. Based on the results of expert consensus, the sub-phase of explaining the phenomenon is the priority; the sub-phase of predicting the content of the text is the second priority; and the sub-phase of predicting the goal is the third priority (Figure 2). This makes a lot of sense because the disclosure of phenomena is very important to be presented in the context of science learning (Lee, 2020). Presenting phenomena at the beginning can lead to cognitive conflicts that create curiosity to learn (Doran, 2021; Tseng, 2010). More importantly, the most important thing in starting learning is to encourage students to have curiosity and activate the knowledge they have (Bybee, 2006). Then, predicting the description of the content and the purpose of the text has a function to complete the sub-phase of explaining the phenomenon. These two sub-phases are beneficial in activating the knowledge possessed by students. This does not mean that the sub-phase of predicting content and purpose should be carried out after the sub-phase of explaining the phenomenon, because we consider that students' prior knowledge in their memory needs to be activated as initial capital to explain phenomena.

In the context of the activities during reading, we found that experts agreed on the proposed phase of a reading model for argumentation skills and critical thinking skills. This phase aims to help students focus on understanding the content of the texts. Here, we integrated several statements/questions to be answered or found in the texts. The importance of providing questions is to focus on the key concepts that must be understood (Siswanto, 2022; Macceca, 2013). The statements/questions in the activities emphasise critical thinking indicators (Anggraeni, 2023) and scientific arguments (Lazarou, 2021). These indicators are then used to develop sub-phases or elements during reading (see Table 4). In this context, reading activities can be designed complexly by involving high-level thinking to process the meaning so that readers are able to connect the content of reading with contextual problems. These activities drove students to understand, assess, and reflect critically on the content of the text (Oliveras, 2013; Macceca, 2013). In addition, we designed this stage to connect students' initial knowledge to what they found in the texts through textual investigations (Saido, 2018). In other words, it involved a variety of complex cognitive processes, including scientific processes and scientific reasoning (Siswanto, 2022; Fang, 2010). For example, the element of evaluating the validity of the data was conducted through textual investigation, in which students will present valid data in the statement. They look for relevant concepts in the texts, and then they will apply them to test the validity of the data presented.

In the following analysis, we view agreement consensus on the priority order of the sub-phases or elements during reading (Figure 2). We found four priorities. The first priority is detecting ambiguous concepts and abuse definitions; the second priority is providing solutions to problems and submitting scientific arguments; the third priority is evaluating the validity of the data, explaining relationships among variables, and predicting phenomena; the fourth priority is identifying causal claims and evaluating arguments. The element of detecting ambiguous concepts and abuse definitions has a position of first priority because they are closely related to the formation of conceptions to strengthen the construction of key concepts in the text. Implementation of these elements aims to drive students to restructure their knowledge by investigating textual evidence in the texts (She, 2004). In the context of providing solutions to problems and making arguments, this phase has a second priority because it naturally trains students to become problem solvers and perform scientific reasoning (Rojas, 2019). These conditions aligned with some examples of science practice that involve students carrying out argumentation and critical thinking activities (Siswanto, 2022; Osborne, 2019; Fathonah, 2023). The other sub-phases or elements have a position on the third and fourth priority because they function as complementary elements for practising science.

Finally, we will discuss the activities after reading. We found that the experts agreed on the proposed phases: evaluate the prediction of the purpose, content, and explanation of the phenomenon. This phase aims to examine accurately students' understanding of the contents of the text and to review the explanations of phenomena presented before reading. The activities after reading are similar to the learning stages based on HOTs at the conclusion and reflection stage (Saido, 2018). They were also similar to the 5E model at the elaboration and evaluation stages (Bybee, 2006). These activities are also an essential part of the learning process to train critical thinking skills (García-Carmona, 2023). Further, we examined sub-phases or elements agreed upon through consensus in the form of the priority order (Figure 2). Evaluating the explanation of the phenomenon is the first priority, while evaluating the description of the content and purpose is the second and third priority, respectively. This consensus result aligned with the consensus result on the before-reading activity. It has been explained previously that the disclosure of phenomena is very prominent in the science learning process because it generates cognitive conflicts that support curiosity to learn (Lee, 2020; Tseng, 2010; Evi, 2024).

Conclusion and Implications

In this study, the phase of a reading model in physics learning has been produced to train critical thinking skills and scientific argumentation based on the consensus among experts. This model was developed based on reading activity as a process, namely before, during, and after reading. The identified stages include predicting the purpose and content of the passage, explaining phenomena, reading by critical-argumentation activities, and evaluating predictions of the purpose, content, and explanation of the phenomena.

The reading model developed in this study has significant implications for physics teaching and learning. Firstly, incorporating scientific reading activities into physics education offers a promising alternative to enhance students' critical thinking and argumentation skills. Since these activities rely on scientific texts, it is essential to ensure that high school physics textbooks are accurate and free from misconceptions that could lead to misunderstandings in students' acquisition of scientific concepts. Secondly, this study has the potential to shift the teaching approach of physics educators. Teachers must actively engage students in both the key phases and sub-phases of the proposed reading model. To do so, they need a thorough understanding of the model and the ability to design worksheets that effectively foster critical thinking and argumentation skills through reading activities. This shift underscores the importance of teacher training programs to equip physics teachers with the necessary competencies. Specifically, teachers must learn how to create statements provided in the worksheet that highlight key concepts, address challenging topics, and identify areas prone to student misconceptions. These skills will enable teachers to guide students effectively in using reading activities to build a deeper understanding that can be a foundation for critical thinking and argumentation skills.

On the other hand, implementing the reading model may face challenges due to the prevalence of mathematical equations in physics textbooks or other scientific texts. To address this issue, the texts should include detailed explanations of the equations, covering their origins and providing examples of their application in real-world physics phenomena. This approach allows students to connect the mathematical models with the contextual phenomena they represent, making it easier for them to grasp the meaning and significance of the equations.

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Journal of Turkish Science Education, 2025, *22*(4), 625-654.
DOI no: 10.36681/tused.2025.032

Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

Research trends and emerging areas of interest from 2004 to 2024 in science education

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ABSTRACT
The purpose of this study was to examine the research papers published in 6 SSCI (Social Sciences Citation Index) Q1 (quartile 1) category journals in the field of science education between 2004-2024 years with regard to the most influential publications, prevailing themes, emerging areas of interest, existing and future relationships between topics, social interactions among authors and their affiliations. In this study, the bibliometric analysis was used for a more rigorous and evolution of the field of large amounts of scientific data. Performance analysis and science mapping analysis were performed using the VOSviewer programme. Publication-related metrics, citation-related metrics, and citation and publication-related metrics were documented for the performance analysis. For the science mapping analysis, citation analysis, co-authorship analysis, co-word analysis, and bibliographic coupling analysis were performed. While there was a sharp decline in the number of science education studies published in 2019, science education studies generally show an increasing trend. Science education studies originate mainly from the USA, Australia and England. Prevailing themes were identified: STEM education, chemistry education, scientific inquiry, teacher education, conceptual change, argumentation, and socio-scientific issues. It was found that the research interest of science researchers has changed from COVID-19 to the present (2019 to 2024). Systems thinking, equity, gender, science identity, engineering education, computational thinking, online education, and systematic reviews were identified as emerging areas of interest. This study provides important implications for multiple stakeholders, including science researchers, curriculum developers, science educators, and education policymakers.

RESEARCH ARTICLE

ARTICLE INFORMATION
Received:
06.12.2024
Accepted:
27.01.2025
Available Online:
27.11.2025

KEYWORDS:
Science education, research trends, literature review, bibliometric analysis.

To cite this article: Budak, U.S., & Yerdelen Damar, S. (2025). Research trends and emerging areas of interest from 2004 to 2024 in science education. *Journal of Turkish Science Education, 22*(4), 625-654. http://doi.org/10.36681/tused.2025.032

Introduction

There is a strong consensus that pupils, who will be the citizens of the future, should be equipped with scientific literacy and scientific process skills, which are 21st-century skills (Turiman et al., 2012), and that these skills can be acquired in science classes (Trna & Trnova, 2015). Scientific literacy is a milestone for individuals to contribute to societal critical thinking on socio-scientific issues (Istyadji & Sauqina, 2023; Sengul, 2019). Therefore, scientific literacy provides a critical perspective for understanding science and society (Rudolph, 2024). When citizens are exposed to scientific ideas and their products daily, they will be better able to cope with these situations as they have scientific knowledge and practices of scientific thinking. Science education can also enable global citizens to participate actively and confidently in decision-making on complex socio-scientific and socio-technical issues (Fensham, 2002). Today, citizens face many complex challenges due to the interaction of human activities and global systems (Salvadó et al., 2013). Science education develops critical thinking skills that help learners tackle complex problems, and it has become even more important in the face of the interconnected challenges of the 21st century (Bayani et al., 2025; Demir, 2022; Maddens et al., 2020).

The increase in science education research has led to the need to analyse these studies and provide a roadmap for future research (Dogan, 2021). Trend analyses can illustrate trends in science education research, research gaps, and, thus, topics that need further research. Trend analyses can provide science educators, policymakers, and practitioners with a framework and insight into the state of science education research (Lee et al., 2009; Lin et al., 2014). While recognising the importance of science education research, it is also acknowledged that there are existing and emerging needs and challenges in science education research that need to be further explored (McFarlane, 2014). For example, there is a need to address climate change from a social and ecological perspective (Henderson et al., 2017), and teachers' science identities and the relationships between those and their scientific, personal, and collective identities (Zhai et al., 2024). Therefore, the motivation and effort of this study are to provide science education researchers with a good map of areas where more research is needed on such needs and challenges in science education.

Aim and Research Questions

This study aims to examine the studies published in SSCI Q1 category journals in the field of science education in the last two decades in terms of the most influential publications, current topics, existing and future relationships between topics, social interactions among authors and their affiliations, using bibliometric analysis. This study seeks to answer the following research questions.

RQ1: What are the trends in publications and citations in science education research?
RQ2: What are the leading authors by number of publications and citations in science education research?
RQ3: What are the most influential documents by number of citations in science education research?
RQ4: What are the prevailing themes and emerging areas of interest in science education research?
RQ5: What are the leading countries by number of publications and citations in science education research?
RQ6: What are the top institutions by number of publications and citations in science education research?
RQ7: What is the social interaction among authors and their affiliations in science education research?

Significance of the Study

Research in science education literature has been periodically analysed to identify prevailing themes. For example, prevailing themes in science education research have been analysed with trend analysis at five-year intervals from 1998 to 2017 (Lee et al., 2009; Lin et al., 2014; Lin et al., 2019; Tsai & Wen, 2005), and by bibliometric analysis from 1982 to 2021 (Tosun, 2022) and from 2001 to 2020 (Wang et al., 2023). However, as a result of the literature review conducted by the researchers of this study, it was found that the trending topics in science education in the post-COVID-19 period have not been investigated. The importance of this study is to show whether the research trends of science education researchers have changed, especially in the period after the pandemic that affected the world, and if so, which topics have increased interest. This bibliometric analysis is unique in that it covers the period when technology impacted the world during COVID-19 and its aftermath, providing researchers with current research gaps and showing the impact of the pandemic on research. This study shed light on prevailing themes and emerging areas of interest in high-impact science education journals and the impact of COVID-19 on research trends in science education. Since the journals indexed by the SSCI publish high-impact research from the international humanities and social sciences, it is important to examine the research trends in these journals (Chen & Du, 2016). The reason for focusing on SSCI Q1 journals in this study is to analyse high-impact research consistent with the goals of identifying influential publications and trends. SSCI Q1 journals are high-quality journals that publish only high-impact research, and articles published in these journals have higher average citations than other journals (Orbay et al., 2021). Therefore, this study aims to examine the studies published in SSCI Q1 category journals in the field of science education in the last two decades. The results of this study will provide policymakers, practitioners, and curriculum makers in the field of science education with information about the global trend in science education and will be useful as empirical research in their educational policymaking.

Literature Review

Systematic Reviews vs. Bibliometric Analyses

Depending on the purpose and research questions of the researchers, systematic review, meta-analysis, or bibliometric analysis can be used in literature review studies. Systematic literature reviews are preferred when the data set is manageable enough to allow for manual analysis when the scope of the review covers specific topics in science education, or for trend analysis over specific time periods (Abdullah, 2022; Donthu et al., 2021; Passas, 2024). While systematic literature reviews have the potential for researchers to make interpretation errors, bibliometric analyses, unlike systematic literature reviews, are based on quantitative techniques and, therefore, minimise researchers' interpretation errors (Donthu et al., 2021). Bibliometric analysis is a systematic method used to identify trends in a research topic, its impact on afield, and potential future directions of the study area by identifying gaps in the field (Abdullah et al., 2023; Passas, 2024). Bibliometric analyses examine huge amounts of scientific data more rigorously and evolutionarily than systematic literature reviews. It provides a good basis for looking holistically at the impact and trends in a particular field and identifying topics needing further research (MacCoun, 1998).

Research Trends Over Time

Research trends in science education have been addressed for specific periods in previous studies. For example, research trends in science education have been examined in five-year periods from 1998 to 2002 (Tsai & Wen, 2005), 2003 to 2007 (Lee et al., 2009), 2008 to 2012 (Lin et al., 2014), and 2013 to 2017 (Lin et al., 2019). Most of the published documents were empirical, with a total of 802 studies published in the *International Journal of Science Education, Science Education, and Journal of Research in Science Teaching* between 1998 and 2002. Conceptual change was reported to be the most studied topic, and there was also a significant increase in research studies on students' learning contexts and social, cultural, and gender issues. Similar to Tsai and Wen’s (2005) study, Lee et al. (2009) reported that the authors from Western counties made significant contributions to science education research in a total of 869 studies published in the same journals between 2003 and 2007 and that most of the published documents were empirical. However, the number of articles by authors from other countries was increasing. It is shown that the interests of science researchers shifted from concept learning and conceptual change to learning contexts, such as the learning environment, between 2003-2007 compared to 1998-2022. It was also found that the interest in learning conceptions, teaching, and goals, policy and curriculum increased between these years.

Lin et al. (2014) examined the trends in science education between 2008 and 2012. They found that 990 studies published in the same journals, in line with previous studies (e.g., Tsai & Wen, 2005) and most of the published documents were empirical. The research trends in these years were identified as learning contexts, science teaching, and conceptual learning. Articles on argumentation, inquiry-based learning, and scientific modelling were also found to be highly cited.

Lin et al. (2018) examined 1,088 studies published in the same journals between 2013 and 2017 for trends in science education research, which has been conducted every five years since 1998. While conceptual change was the prevailing theme from 1998 to 2002, the context of learning, science education, and conceptual learning were the prevailing theme from 2002 to 2017. Lin et al. (2018) noted that studies on inequality in science education, STEM education, and undergraduate research experiences may also be emerging areas of interest.

Tosun (2022) investigated the last 40 years of science education (1982–2021) research with the bibliometric analysis method and found that the number of studies has increased significantly since 2007 and there was a peak in the number of studies in 2020. It was reported that the most used keywords were STEM/STEAM education, nature of science, assessment, professional development, science, scientific literacy, argumentation, gender, and conceptual change. Tosun (2022) found that between 2007-2021, more studies on the nature of science and professional development in science education were revealed. It was also found that the interest in conceptual change, scientific literacy, chemistry education, and attitudes decreased between 2017-2021.

Wang et al. (2023) investigated the prevailing themes of science education research from 2001 to 2020 through bibliometric analysis and found that the interest in science education research has gradually increased. Consistent with previous studies, Tosun (2022) and Wang et al. (2023) found that the countries that produced the highest number of publications were dominated by authors from Western countries. Wang et al. (2023) found that the most influential publications in terms of the number of citations were on standards, methods, practice and reflection in science education. Wang et al. (2023) identified seven prevailing themes from 2001 to 2020: conceptual change, gender, scientific argumentation, professional development, science learning, evolution, and peer review. Although recent studies by Tosun (2022) and Wang et al. (2023) have identified current trends in science education, both studies methodologically selected SSCI journals from all quartiles. Differently, the current study contributes to the science literature by identifying influential publications and trends published only in high-impact SSCI Q1 journals (Orbay et al., 2021). While trends in science education research were examined by Tosun (2022) in the period 1982-2021 and Wang et al. (2023) in the period 2001-2020, it was found that trends in studies conducted post-COVID-19 were not addressed. Therefore, in this bibliometric study, trends post-COVID-19 were revealed by analysing studies conducted in science education in the last two decades (2004-2024) and the impact of COVID-19 on trends in science research was examined.

Methods

Data Collection

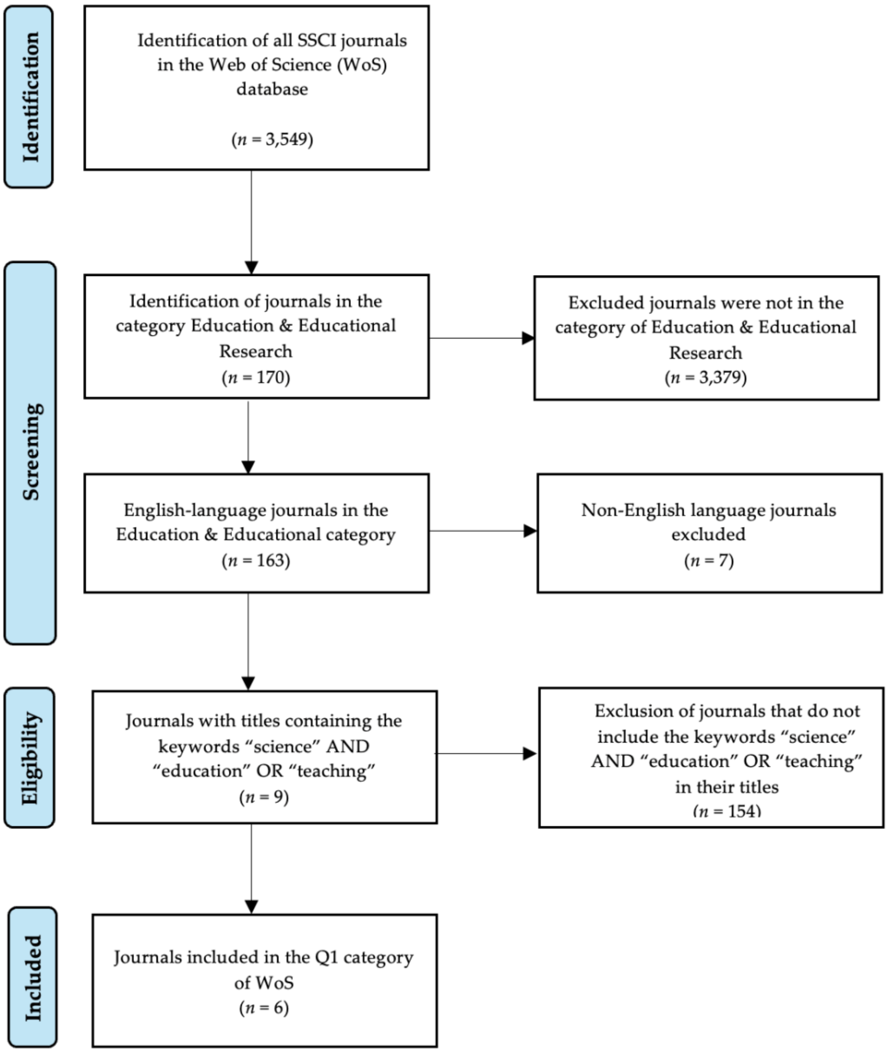
Journal Selection Process

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram was used to identify the journals included in this study. The PRISMA flow diagram is a systematic and rigorous framework for including and excluding studies in the literature according to specific criteria (Moher et al., 2009). In this study, the Web of Science Core Collection (WoS) was chosen as the database to reveal trends in science education because it provides "selective, balanced, and complete coverage of the world's leading research" (Birkle, 2020, p. 363). WoS provides researchers with raw data sets for bibliometric studies (Birkle, 2020). To identify journals from the WoS database, the researchers downloaded a list of all journals indexed in the Social Science Citation Index from the Web of Science Core Collection under the Education & Educational Research (E & ER) category.

The researchers filtered SSCI-indexed journals in English and the Education & Educational Research category in Excel, including “science” and “education” or “teaching” in the journal name. English-language journals were chosen because most international publications are written in English. The analysis of English-language journals is intended to make the bibliometric analysis of science education studies as comprehensive as possible. As a result of filtering the journals, nine journals were identified that met these criteria. From these journals, journals indexed in the SSCI Q1 category in the Web of Science Core Collection were purposively selected according to their Q-rank (quartile rank) categories. The Q1 category journals were selected as the dataset because they are the most prestigious and influential journals (Vijayan & Renjith, 2021). There were six science education journals with “science” and “education” or “teaching” in their titles, and the studies published in these journals constitute the data set of this study. The journals selected for this study are *Studies in Science Education*, *Journal of Research in Science Teaching*, *Journal of Science Education and Technology*, *International Journal of Science Education*, *Research in Science Education*, and *Science Education*.

Figure 1

Journal selection by using PRISMA flow diagram



Note. The figure was prepared according to the Moher et al. (2009) PRISMA flow diagram.

Article Selection Process

The Web of Science Core Collection database was accessed, and the journal name was entered in the "publication titles" section. Inclusion and exclusion criteria were set for selecting articles for this study. As an inclusion criterion, the publication date was set between 2004 and 2024, and articles outside these years were excluded. To examine emerging areas of interest in science education, this study limited the search to the last two decades, 2004-2024, which is the common preference for a great deal of review studies to determine the evolution in a field with a manageable and but also comprehensive examination of both fundamental and contemporary studies (e.g., Amiruddin et al., 2025; Li et al., 2025). Articles published in the selected journals were accessed on October 23, 2024, and articles added after this date were not included in the review. Articles, review articles, and early access studies were then filtered by document type in the WoS database to be included in the analysis.

The reason for including articles and review articles is that while articles present first-hand empirical findings, review articles systematically synthesize articles and provide a close lens on the issues studied in the field. Early access articles are included to provide a broader view of current trends in science education. Early access articles are articles that have been accepted for publication but have not yet been published in the journal. While including early access articles expands the dataset, it may also introduce inconsistencies as these articles may not have been finalized. Other document types such as editorials' letters, commentaries, proceedings, book chapters, book reviews, meta-analyses, working papers, and corrections, were excluded. After inclusion and exclusion criteria filtering, a total of 7,885 articles from *Studies in Science Education* (n = 118), *Journal of Research in Science Teaching* (n = 1,165), *Journal of Science Education and Technology* (n = 1,020), *International Journal of Science Education* (n = 2,397), *Research in Science Education* (n = 1,199), *Science Education* (n = 1,986) were included in this current study. The article selection process for each journal and the number of articles obtained as a result of this process are shown in detail in Table 1.

Table 1

Article selection process for each journal

Journal name	First search (Total number of articles between 2004-2024)	Second search (Journals limited to articles, review articles and early access)	Articles	Review articles
Studies in Science Education	167	118	75	43
Journal of Research in Science Teaching	1,257	1,165	1,139	26
Journal of Science Education and Technology	1,057	1,020	994	26
International Journal of Science Education	2,534	2,397	2,353	44
Research in Science Education	1,250	1,199	1,185	14
Science Education	2,666	1,986	1,940	46
Total	8,925	7,885	7,686	199

Data Analysis

The articles of each selected journal in the WoS database were saved as plain text files. The record content was the full record, and cited references in plain text files. The files of each journal were uploaded to the VOSviewer 1.6.19 (Van Eck & Waltman, 2023) for bibliometric analysis. Performance analysis accounts for the *contributions* of research constituents, whereas science mapping focuses on the *relationships* between research constituents" (Donthu et al., 2021, p. 287). The researchers determined thresholds (i.e., minimum citations) by testing various minimum citation numbers in the program to obtain the best representation of clusters in Vosviewer, which does not demonstrate small and uninteresting clusters (Van Eck & Waltman, 2023). Performance analysis and science mapping analysis metrics were performed with the following metrics (Donthu et al., 2021).

Performance Analysis

Publication-Related Metrics: The total number of publications, number of authors, and co-authored publications were analysed. To determine the number of publications by year for the science education journals selected for this study, the "analyse result" section of the Web of Science (WoS) database was filtered as "publication years" for each journal. The data were transferred into an Excel file. This Excel file was used by the researchers to compile and visualize the number of studies published annually in all journals over the last twenty years

Citation-Related Metrics: The total citations of research and average citations of research were analysed. To determine the number of citations of the science education journals selected for this study by year, the "citation report" was downloaded from the WoS database, and the results were transferred to an Excel file. This Excel file was used by the researchers to collect and visualise the total number of citations and the average number of citations of studies over the last twenty years in all journals by year.

Citation and Publication-Related Metrics: The number of cited articles by the year and the percentage of cited publications were analysed. To reveal the influential research in science education studies, the analysis type was selected as "citation" and the analysis unit was selected as "documents" in the VOSviewer program.

Science Mapping

Citation Analysis*:* Authors, organisations and countries were analysed. The 7,885 articles in the WoS database were published by authors from 3,011 institutions in 107 countries. To identify the leading countries in terms of the number of science education studies and the number of citations, the type of analysis in the VOSviewer program was selected as "citation", and the unit of analysis was selected as "countries". To identify the leading institutions in terms of the number of science education studies and the number of citations, the type of analysis in the VOSviewer program was selected as "citation" and the unit of analysis was selected as "organizations".

Co-Authorship Analysis: Leading authors and distribution of publications by country and institution were analysed. In analysing the collaboration of countries producing science education research, the type of analysis in the VOSviewer program was selected as "co-authorship", and the unit of analysis was selected as "countries". The collaboration of institutes producing studies in science education was analysed by selecting the analysis type as "co-authorship" and "organisations" as the analysis unit in the VOSviewer program. There are 3,011 institutions in the database that have produced publications in science education. To map the co-authorship networks in science education studies, the VOSviewer program selected "co-authorship" as the analysis type and "authors" as the analysis unit. There are 13,073 authors in the database and 675 authors with five or more publications.

Co-Word Analysis: Prevailing themes are defined as current or periodic topics while emerging areas of interest are topics that have been studied recently and may become trending topics in the future. The change in prevailing themes over the years is important in showing how research interests and intensities in science education have evolved (Lin et al., 2014). The frequency of the author's keywords in the articles was used as a criterion to identify prevailing themes and emerging areas of interest. Co-word analysis is a complementary analysis method used to provide supportive and complementary insights on the trending themes derived from bibliographic coupling (Chang et al., 2015). For the co-word analysis, "co-occurrence" is the analysis type and "author keywords" is the analysis unit in the VOSviewer program. For the analysis, only keywords with a minimum frequency of 30 or more were selected to focus on the most representative terms in the field. Thus, 76 out of 10,056 author keywords met this threshold. Prevailing themes provide an insight into major research themes and emerging areas of interest in science education.

Bibliographic Coupling Analysis: A bibliographic coupling analysis was conducted to analyse the prominent topics in science education research over the last two decades. This method is used to understand the current evolution of science education (Donthu et al., 2021). Bibliographic coupling analysis is based on the principle that a reference shared by two studies is a subject link between those studies (Kessler, 1962). For the bibliographic coupling analysis, "bibliographic coupling" was selected as the analysis type and "document" as the analysis unit in the VOSviewer program. For the analysis, only documents with 30 or more citations were included to focus on studies that best represent the field. Thus, 2,052 out of 7,885 science education studies met this threshold.

Reliability and Validity of the Study

Several steps were taken in the present study to ensure the reliability and validity of the analysis. First, the type of analysis- bibliometric analysis- is considered a reliable method employing a transparent, objective, and reproducible review process (Bretas & Alon, 2021; Donthu et al.,2021; Van Raan, 2014). Second, the bibliometric data was obtained from the Web of Science, a reliable database covering high-impact peer-reviewed journals (Zhang et al., 2023). Third, a representative sample of articles in science education was selected by including all articles that met the selection criteria based on PRISMA flow diagram. Fourth, thesaurus files for all science mapping analyses were created to handle erroneous entries and duplicates in the bibliometric data, which negatively influences the validity and reliability of the interpretation of the results (Donthu et al., 2021; Van Eck & Waltman, 2023). Data cleaning while creating the science map is necessary to accurately represent the data because author names, organisation names, country names, and document names may appear in different versions of different documents (Van Eck & Waltman, 2023). For example, "krajcik, j", "krajcik, joe", "krajcik, joseph", and "krajcik, js" are different name combinations of the same author in the database. Fifth, the first author conducted the analyses; the second author checked all analysis results, and any disagreements between the two researchers were resolved until an exact agreement was reached.

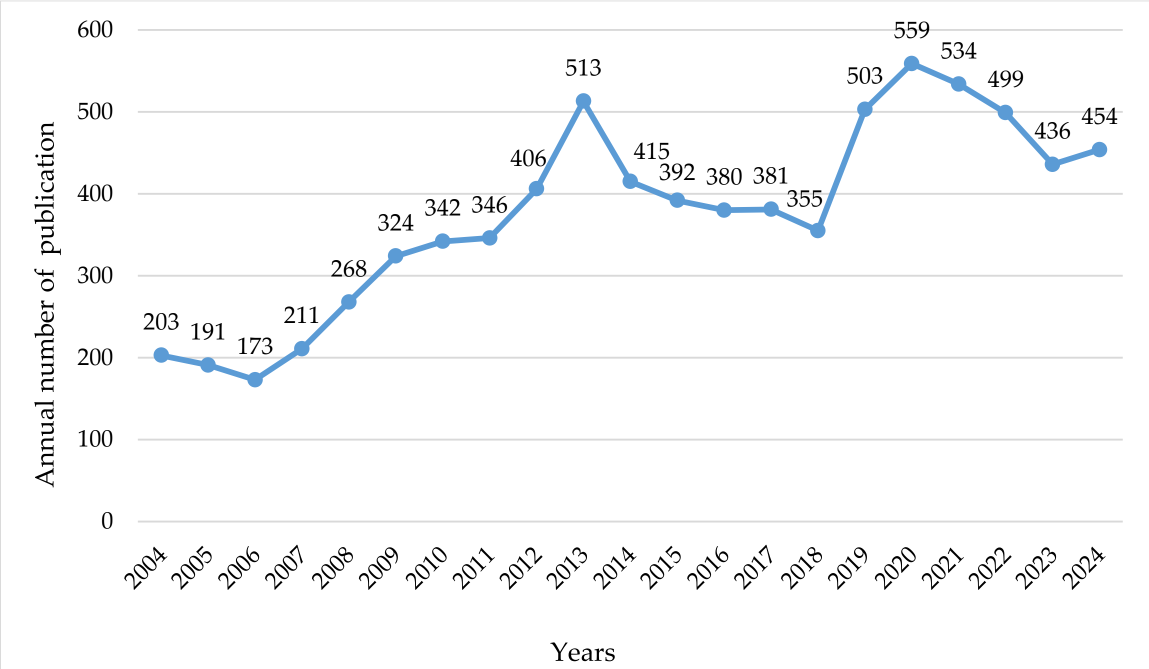
Findings

Publication and Citation Trends

Figure 2 shows the annual number of publications in science education research. In 2004, 203 studies were published, which decreased to 173 in 2006. After 2006, there was an acceleration in the number of publications, while there was a slow increase between 2009 and 2011. In 2013, there was a peak with a total of 513 publications, while there was a sharp decline in the number of publications between 2013 and 2018. In 2020, the second peak in the number of publications was reached, while a sharp decline was observed in 2023. In 2024, the number of science education articles increases again (Figure 2).

Figure 2

The annual number of publications in science education research

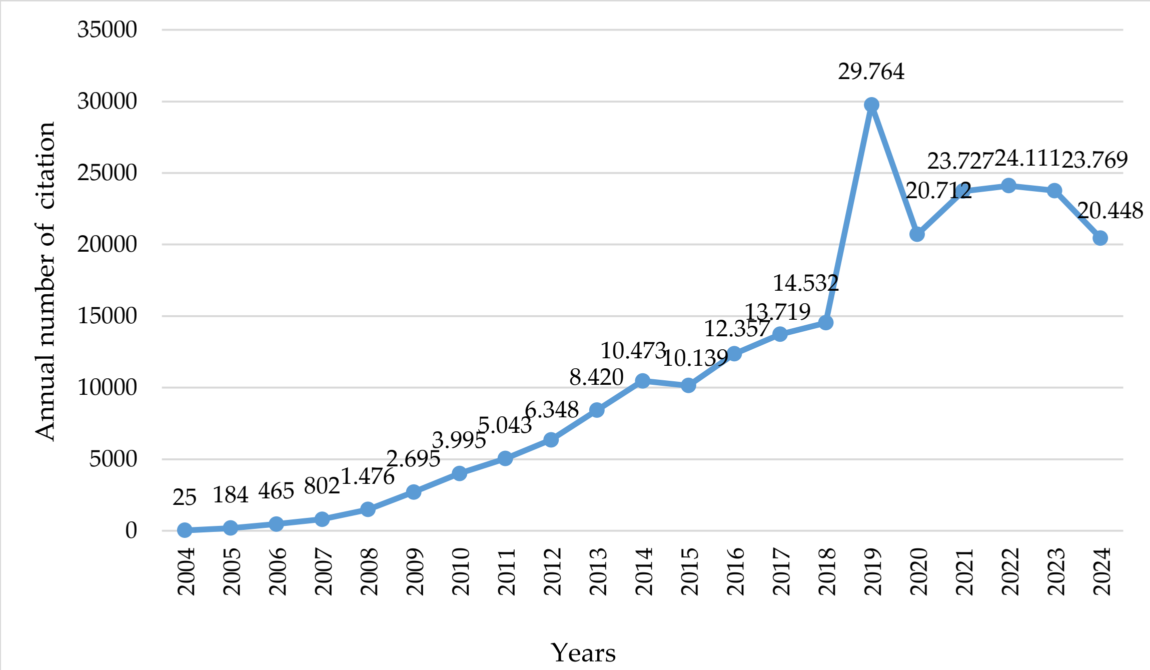


Publication and Citation Trends

Figure 3 presents the annual number of citations in science education research. In 2004, the studies received a total of 25 citations, and the citations received by the studies increased steadily until 2014, with a slight decrease in the number of citations in 2015. Between 2015 and 2018, the number of citations accelerated and reached its first peak in 2019 with 29,764 citations. In 2020, there was a sharp decline in the number of citations, but a slight increase was observed in the following years. In October 2024, the number of citations of science education research is currently 20,444. In summary, Figure 3 shows that there is a growth peak in the number of publications and an upward trend in the number of citations of science education research, except for very short periods.

Figure 3

The annual trend of citations in science education research



Prolific Authors

Influential authors are the backbones that lead academia in terms of their research topics, and the number of publications and citations of the author is an important criterion in evaluating prolific authors (Wang et al., 2023). As shown in Table 2, Tsai Chin-Chung is the most prolific and prominent author in science education in terms of total number of publications. The number of articles published by the top 10 authors accounts for 5.27% (n = 416) of the total articles (n = 7.885).

Table 2

Top 10 most prolific authors

Prolific authors	Total number of publications	Total number of citations
Tsai, Chin-Chung	72	3,381
Krajcik, Joseph S.	48	3,680
Sadler, Troy D.	46	4,959
Mcneill, Katherine L.	38	2,404
Erduran, Sibel	37	2,446
Roth, Wolff-Michael	37	1,319
Treagust, David F.	36	902
Hand, Brian	35	1,059
Jones, Melissa G.	35	748
Abd-el-khalick, Fouad	32	2,011
Total	416	22,909

Most Influential Documents by Total Number of Citations

In this study, there are 384 studies with 100 or more citations out of 7,885 science education studies included in the review. Of these studies, 3.65% belong to *Studies in Science Education* (*n* = 14), 28.64% to *Science Education* (*n* = 110), 4.69% to *Research in Science Education* (*n* = 18), 7.03% to *Journal of Science Education Technology* (*n* = 27), 35.94% to *Journal of Research in Science Teaching* (*n* = 138), 20.05% to *International Journal of Science Education* (*n* = 77).

Figure 4 shows the research networks of science education studies with 100 or more citations. The size of each node represents the number of citations that study has received. The lines between nodes indicate co-citation relationships between studies. Taber (2018), Hofstein and Lunetta (2004), Carlone and Johnson (2007), Seymour (2004), Osborne et al. (2004), Hunter et al. (2007), Minner et al. (2010), Dunleavy et al. (2009), Schwarz et al. (2009), Weintrop et al. (2016) have the most cited studies.

Figure 4

The research networks of science education studies with 100 or more citations

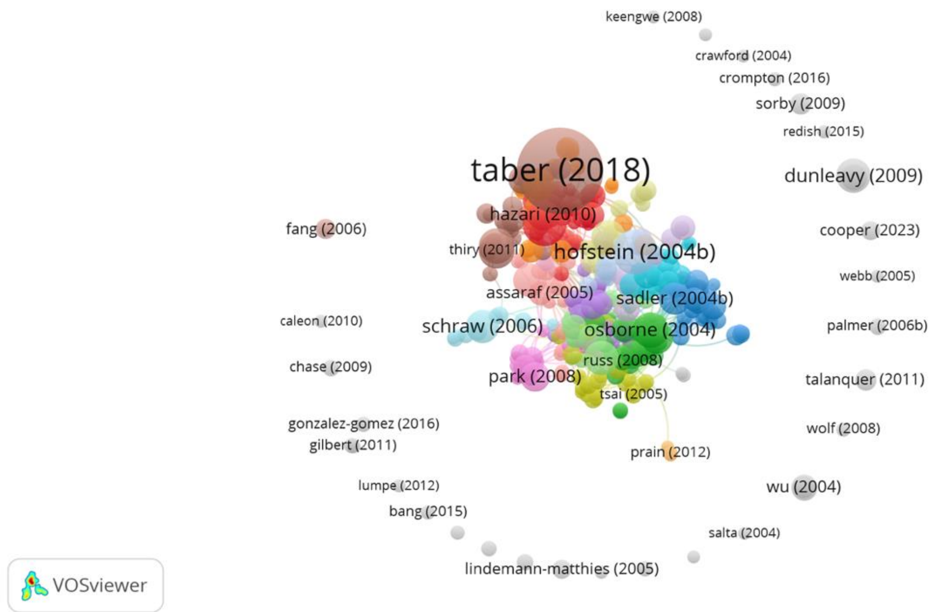


Table 3 shows the 10 most influential documents according to the total number of citations. These studies can be categorised according to their topics as follows: research methodology (Taber, 2018), laboratory in science education (Hofstein & Lunetta, 2004), science identity (Carlone & Johnson, 2007), argumentation in science education (Osborne et al, 2004), undergraduate research experiences (Hunter et al., 2007; Seymour, 2004), inquiry-based science education (Minner et al., 2010), augmented reality (Dunleavy et al., 2009), science modelling (Schwarz et al., 2009), computational thinking (Weintrop et al., 2016).

Table 3

Top 10 most influential documents by total number of citations

Article title	Reference	Journal title	Number of citations	Average citations per year
The use of Cronbach's Alpha when developing and reporting research instruments in science education	Taber, 2018	Research in Science Education	4,345	724.17
The laboratory in science education: Foundations for the twenty-first century	Hofstein & Lunetta, 2004	Science Education	1,194	59.70
Understanding the science experiences of successful women of color: Science identity as an analytic lens	Carlone & Johnson, 2007	Journal of Research in Science Teaching	1,135	66.76
Establishing the benefits of research experiences for undergraduates in the sciences: First findings from a three-year study	Seymour, 2004	Science Education	773	38.65
Enhancing the quality of argumentation in school science	Osborne et al., 2004	Journal of Research in Science Teaching	739	36.95
Becoming a scientist: The role of undergraduate research in students' cognitive, personal, and professional development	Hunter et al., 2007	Science Education	739	43.47
Inquiry-based science instruction-What is it and does it matter? Results from a research synthesis years 1984 to 2002	Minner et al., 2010	Journal of Research in Science Teaching	731	52.21
Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning	Dunleavy et al., 2009	Journal of Science Education and Technology	710	47.33
Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners	Schwarz et al., 2009	Journal of Research in Science Teaching	690	46.00
Defining computational thinking for mathematics and science classrooms	Weintrop et al., 2016	Journal of Science Education and Technology	668	83.50

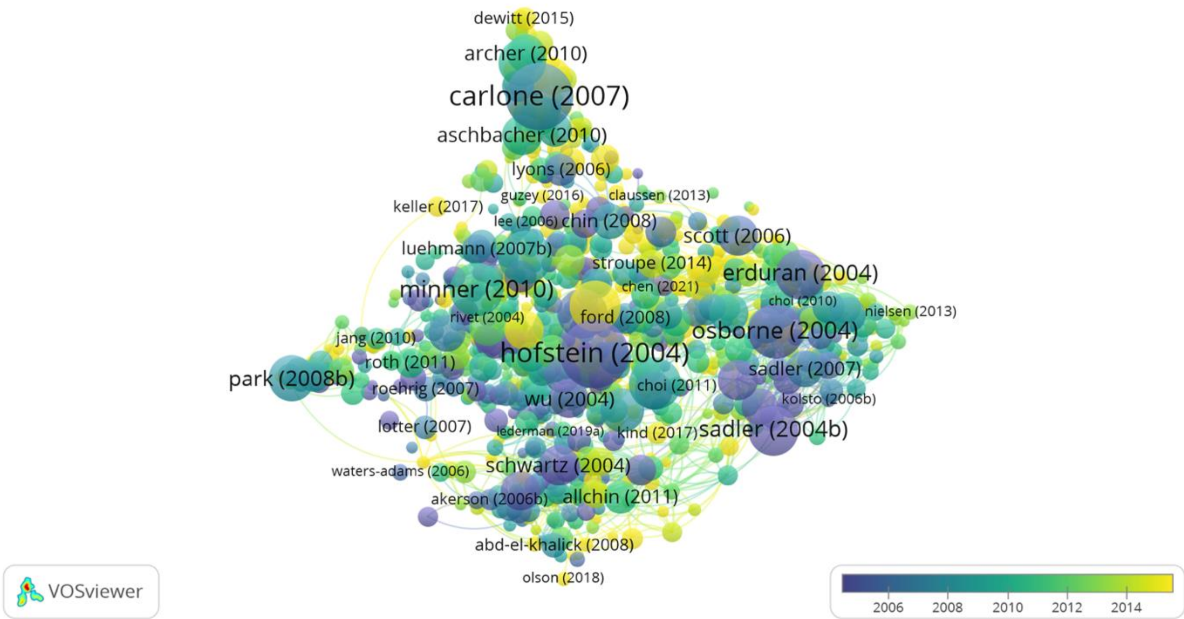
Prevailing Themes and Emerging Areas of Interest in Science Education in the Last Two Decades

Figure 5 shows the bibliographic coupling analysis of documents for present or periodical themes in science education research. An examination of trends in science education research by year revealed that the themes such as laboratory in science education (e.g., Hofstein & Lunetta, 2004), socio-scientific issues in science education (e.g., Sadler, 2004), inquiry in science education (e.g., Abd-El-Khalick et al., 2004), nature of science in science education (e.g., Schwartz et al., 2004), argumentation in science education (e.g., Erduran et al., 2004) were predominantly studied in 2004.

It has been shown that over time, topics such as argumentation (e.g., Berland & Reiser, 2009; Berland & McNeill, 2010), inquiry (e.g., Minner et al., 2010; Ruiz-Primo & Furtak, 2007; Schwarz et al., 2009), and socio-scientific issues (e.g., Zeidler et al., 2009) have continued to be studied, and in addition, new topics such as self-efficacy (e.g., Britner & Pajares, 2006), pedagogical content knowledge (e.g., Park & Oliver, 2008), and augmented reality (e.g., Dunleavy et al., 2009) have begun to be explored. Trends in recent last ten years have shifted toward career aspiration (e.g., DeWitt & Archer, 2015), secondary school students, computational thinking (e.g., Weintrop et al., 2016), new teaching methods (e.g., González-Gómez et al., 2016), STEM education (e.g., Guzey et al., 2016), artificial intelligence (e.g., Cooper, 2023), gender, ethnicity, diversity, equity, minority, and marginalised groups (e.g., Archer et al., 2015; Carpi et al., 2017; Dou et al., 2019; Ong et al., 2018) (see Figure 5).

Figure 5

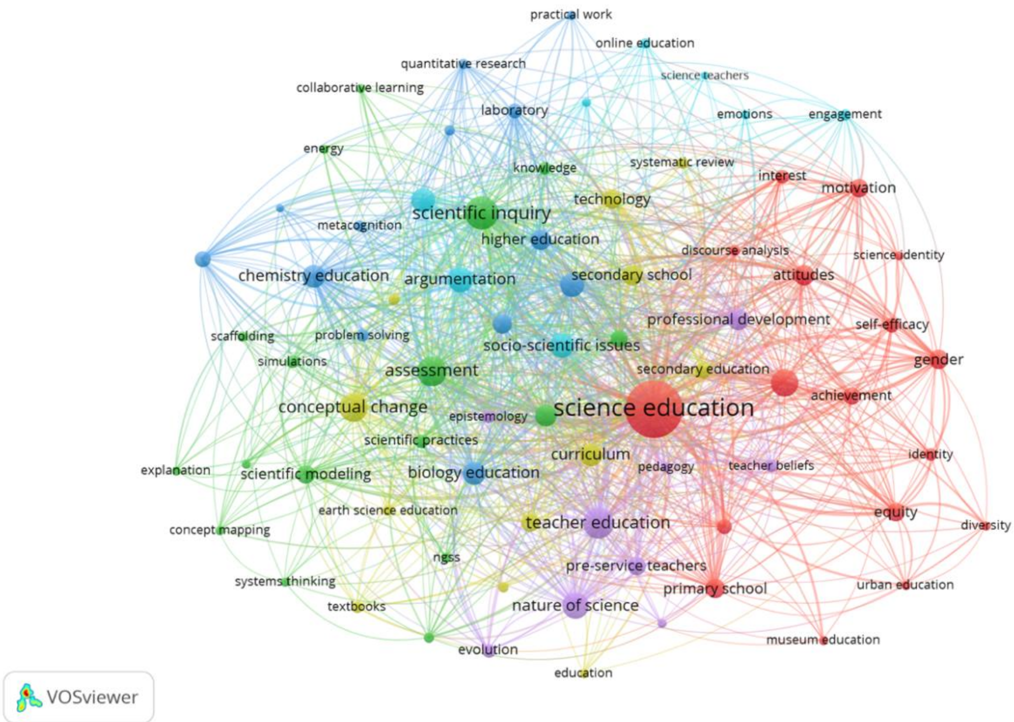
Bibliographic coupling analysis of documents for prevailing themes and emerging areas of interest in science education research



Themes derived from bibliographic coupling analysis may tend to be general, as they are derived from the citation relationships in the references of the studies. As shown in Figure 6, the topics in science education are clustered into six groups. These clusters are shown in blue, green, purple, yellow, turquoise and red colours. The dominant keywords in each cluster are determined by the number of links. Figure 6 shows that the main keyword is “science education”. The dominant keywords in the blue cluster are “chemistry education”, in the green cluster “scientific inquiry”, in the purple cluster “teacher education”, in the yellow cluster “conceptual change”, in the turquoise cluster “argumentation and socio-scientific issues” and in the red cluster “STEM education”. The dominant words in the turquoise cluster are “argumentation and socio-scientific issues” as both argumentation and socio-scientific issues have the same number of links with 59 links.

Figure 6

Relationships among topics in science education research



Note. Although all keywords are included in the analysis, some of them may not be clearly visible in the figure due to overlaps in the science mapping.

Table 4 shows all keywords in each cluster in detail. To be objective, cluster labels were chosen from the highest number of linking words in each cluster.

Table 4

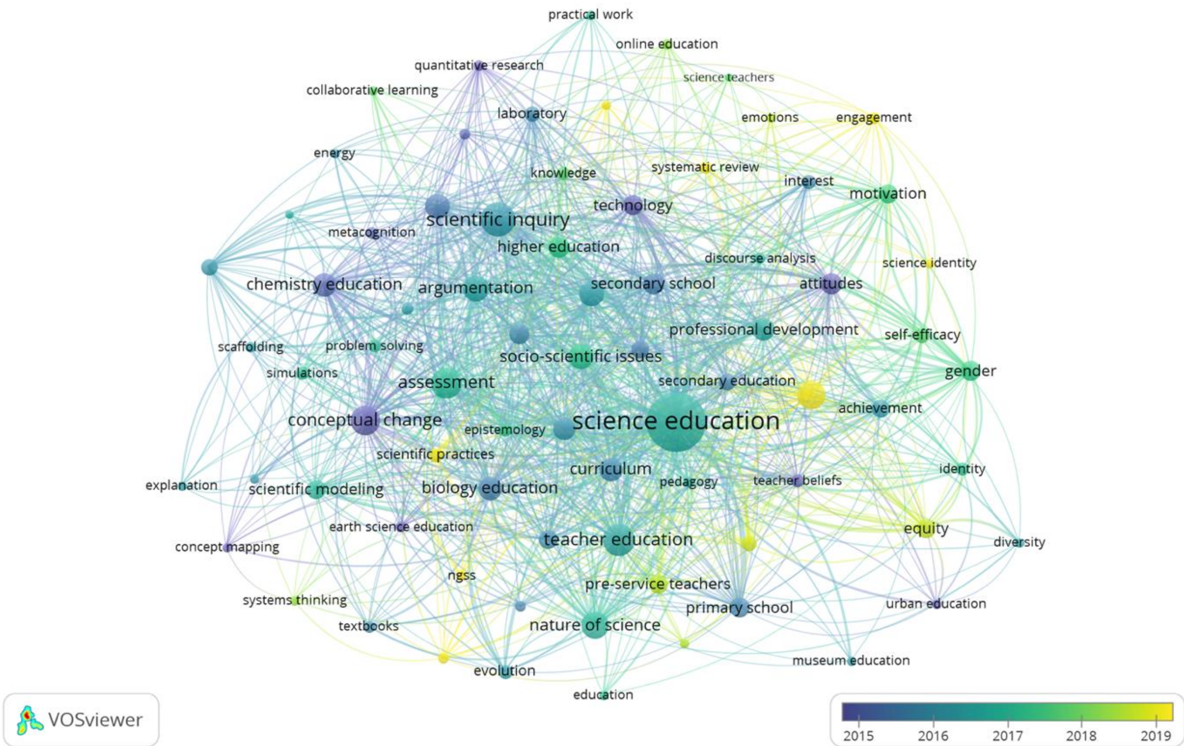
Trending topic clusters and author keywords in science education research

Cluster labels	Author keywords
STEM education	Achievement, attitudes, discourse analysis, diversity, engineering education, equity, gender, identity, interest, motivation, museum education, primary school, science education, science identity, self-efficacy, stem education, urban education
Scientific inquiry	Assessment, collaborative learning, computational thinking, concept mapping, energy, explanation, knowledge, learning, middle school, Next Generation Science Standards (NGSS), representations, scaffolding, scientific inquiry, scientific modelling, scientific practices, simulations, systems thinking
Chemistry education	Biology education, chemistry education, context-based learning, higher education, laboratory, learning environment, metacognition, physics education, practical work, problem solving, qualitative research, quantitate research, scientific reasoning
Conceptual change	Astronomy education, conceptual change, curriculum, earth science education, education, environmental education, secondary education, secondary school, systematic review, technology, textbooks, visualization
Teacher education	Early childhood, epistemology, evolution, nature of science, pedagogy, pre-service teachers, professional development, teacher beliefs, teacher educations
Argumentation and socio-scientific issues	Argumentation, critical thinking, emotions, engagement, online education, science teachers, scientific literacy, socio-scientific issues

Figure 7 shows the evolution of prevailing themes in science education research over the years. It was found that the “conceptual change”, “scientific inquiry”, “professional development”, “argumentation”, “nature of science”, “assessment”, and “metacognition” topics were predominantly studied until 2019. From the years of COVID-19 to the present (2019 to 2024), there is an increasing trend for topics in STEM education (e.g., Anwar et al., 2022), systems thinking (e.g., Budak & Ceyhan, 2024), equity (e.g., Hinojosa et al., 2021), gender (e.g., Chen et al., 2024), science identity (e.g., Chen & Wei, 2022), engineering education (e.g., Chabalengula & Mumba, 2017), computational thinking (e.g., Christensen & Lombardi, 2023), online education (e.g., Saribas, 2023), and systematic reviews (e.g., Ormanci et al., 2015) to be emerging areas of interest.

Figure 7

Emerging areas of interest by years



Note. Although all keywords are included in the analysis, some of them may not be clearly visible in the figure due to overlaps in the science mapping.

Leading Countries

Out of 107 countries, the number of countries publishing more than 20 articles is 39 (36.5%). Table 5 shows the leading countries by total number of publications. Authors in the United States of America (USA), Australia, and England are the top three in terms of the number of articles published, with more than 500 articles. In first place, with a very large gap difference, authors in the USA published 3,445 articles, accounting for 43.69% of the 7,885 articles included in this study. The contribution of the top 10 countries to science education studies is 87.66% (n = 6,912) of all published articles selected in this study (n = 7,885). Authors from the USA, Australia and England are in the top three in terms of number of citations, having published papers with more than 14,000 citations.

Table 5

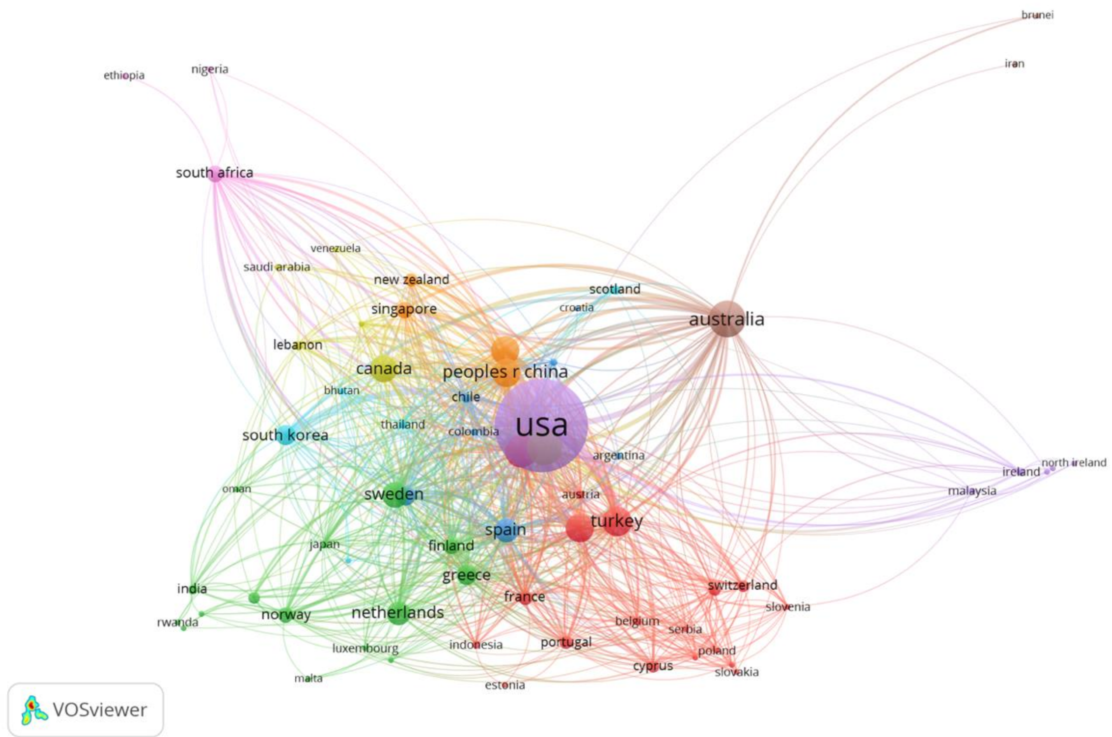
Leading countries by total number of publications

Leading countries	Total number of publications	Total number of citations
USA	3,445	126,107
Australia	561	14,853
England	526	23,685
Germany	410	8,858
Turkey	367	7,571
Peoples R China	344	3,728
Taiwan	340	9,831
Israel	337	11,777
Canada	308	8,345
Sweden	274	4,764
Total	6,912	219,519

Figure 8 shows the scientific network between countries collaborating on five or more publications out of 107 countries (n = 67). In Figure 8, node size positively correlates with the number of co-authored papers, and the link arrows indicate collaborations between countries. The USA has the highest number of partnerships with 59 countries in science education research and collaborates most often with Australia, Turkey, and Ireland. After the USA, England, Australia, Germany, Turkey and the People's Republic of China were the countries that collaborated most with other countries (see Figure 8).

Figure 8

Collaborative research networks between countries that collaborate on 5 or more publications



Leading Institutions

Table 6 shows the top ten institutions by total number of publications. Authors from Michigan State University (USA), National Taiwan Normal University (Taiwan), and Weizmann Institute of Science (Israel) published more than 100 articles, making them the top three most productive institutions. These three institutions accounted for 5.31% of the total number of articles published (*n* = 419), while the contribution of the top 10 institutes in Table 6 to science education studies was 13.58% of the total number of articles published by all the institutions (*n* =1,071) selected in this study.

Table 6

Leading institutions by total number of publications

Leading institutions	Total number of publications	Total number of citations
Michigan State Univ	158	6,867
Natl Taiwan Normal Univ	150	3,778
Weizmann Inst Sci	111	6,234
Purdue Univ	97	2,496
Univ Missouri	96	3,151
Univ Illinois	94	4,257
Nanyang Technol Univ	93	3,292
Univ Michigan	93	6,015
Univ Georgia	92	3,693
Indiana Univ	87	6,534
Total	1,071	46,317

Leading Institutions Social Interaction among Authors and their Affiliations in Science Education Research

Figure 9 shows the collaborative research networks of authors with five or more publications. The size of the nodes in Figure 9 is directly proportional to the number of citations received by the authors. If there are co-authorship relationships, these are also indicated by links. Among the top 10 authors by number of publications, Tsai Chin-Chung, Krajcik Joseph S., Jones Melissa Gail, Sadler Troy D., Mcneill, Katherine L., and Treagust David F. are the most collaborative authors. It was found that Tsai Chin-Chung established a collaboration with Chang, Hsin-Yi, Wu, Hsin-Kai, and Chen, Sufen and worked on technology in education, science education trends, and TPACK (Technological Pedagogical and Content Knowledge) and the nature of science. Krajcik, Joseph S. worked with Mcneill, Katherine L. on learning with science inquiry, Wu, Hsin-Kai on project-based science, and Delgado, S. on pedagogical curriculum. Treagust, David F. worked with Tang, Kok-Sing, and Won, Mihye on conceptual understanding and chemical representations. In general, while there is also collaboration among small groups, the strength of their linkages is weak, and collaborations appear to occur predominantly between specific groups.

Figure 9

Social interaction among authors with five or more publications

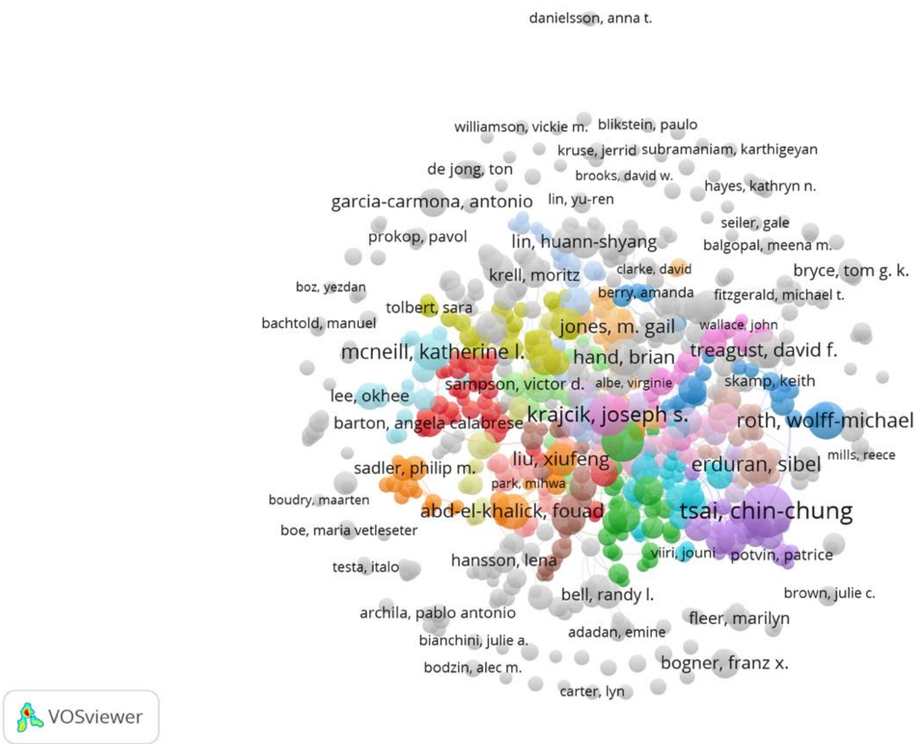
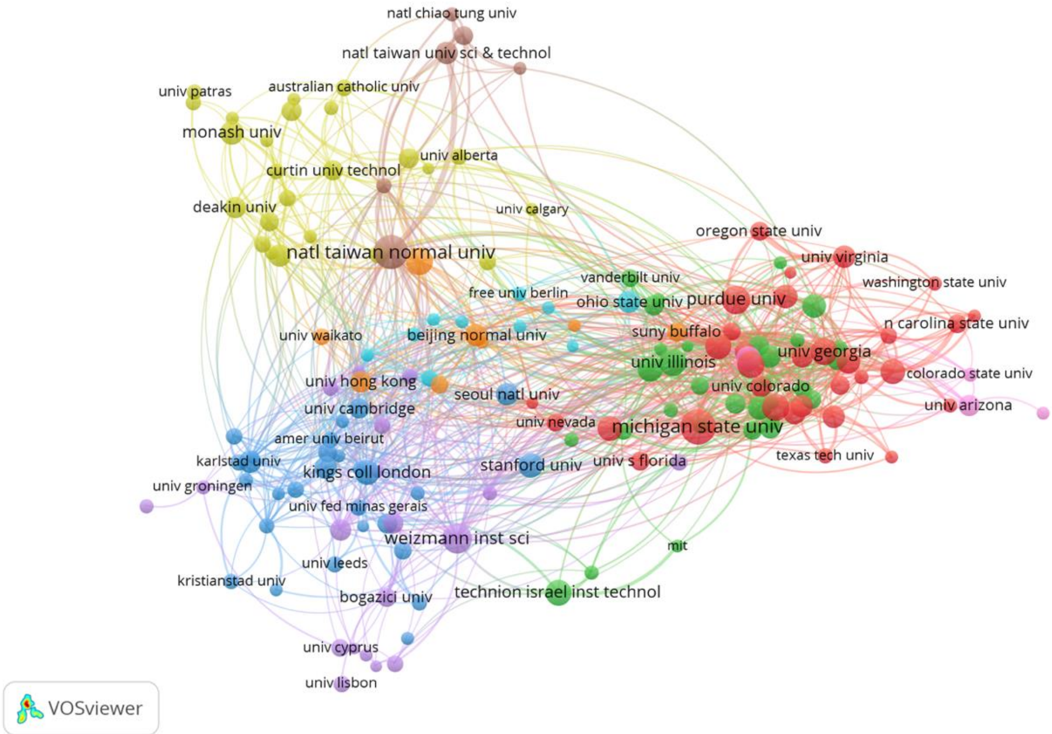


Figure 10 shows the collaborative research networks among these institutions that collaborated on 20 or more publications (n = 162). As shown in Figure 10, Michigan State University (USA), the institution with the most publications, leads as the most collaborating institution with 61 connections. It is followed by Indiana University (USA) with 57 links and National Taiwan Normal University (Taiwan) and Weizmann Institute of Science (Israel) with 51 links each. In summary, while large research institutions tend to collaborate with North America, research institutions in Europe also collaborate with less connected research institutions than in North America.

Figure 10

Social interaction among authors affiliations that have collaborated on 20 or more publications



Discussion

This study provides an overview of prevailing themes and emerging areas of interest in science education research published in the WoS database in six SSCI Q1 index journals over the past two decades (2000 to 2024). This study revealed that although there are fluctuations in the number of science education studies from time to time, there is a general trend of increasing number of publications. These findings are consistent with previous trend studies in science education from 1998 to 2002 (Tsai & Wen, 2005), 2003 to 2007 (Lee et al., 2009), 2008 to 2012 (Lin et al., 2014), and 2013 to 2017 (Lin et al., 2019). This study revealed that the number of citations was low in 2004 year in the WoS database for selected journals. This may be due to the low citation rates in the humanities, which may be due to the low number of linked references citing articles published in the core journals indexed in the WoS database (Marx & Bornmann, 2015). It was also found that the total number of citations of the studies published in all journals in the last twenty years was 233,204, and there were 29.57 citations per article. The results of this study are consistent with the findings of Wang et al. (2023) in the sense that while there was a very slow growth in the number of citations in the first four-year period (2004 to 2008), there was a dynamic growth in the number of citations. However, there were fluctuations in the number of studies published from 2008 to the present. This is one of the important findings in terms of highlighting the increasing interest in science education in recent years (Wang et al., 2023). The underlying factors driving science education research trends may be related to major events, societal, technological, or policy changes, funding changes, or influential special issues in journals. The decline in citations after 2020 could be a global disruption of the COVID-19 pandemic, as published research by science researchers has declined sharply after this period.

Prolific authors are motivated by an unwavering passion to continue their work (Mayrath, 2008) and see it as a "labour of love" (Kiewra & Creswell, 2000, p. 156). Tsai, Chin-Chung, was the most prominent prolific author compared to other researchers, with over seventy articles in 6 science education journals examined. These findings are consistent with the findings of Wang et al. (2023) but inconsistent with the findings of Tosun (2022), as Tosun (2022) found that the most prolific author was Roth, Wolff-Michael. In the present study, Roth, Wolff-Michael ranks sixth in the place of most productive authors. Thus, Tsai, Chin-Chung played an important role in disseminating knowledge to science education research. In terms of the number of citations, Sadler, Troy D., Taber, Keith S., and Osborne, Jonathan F. received over four thousand citations. Thus, the citations of the works of these researchers have shown that they are important sources on which exceptional studies are based. However, the findings regarding the most cited author in this study contradict Tosun's (2022) findings. Tosun (2022) found that the most cited authors were Lederman, Norman G., Treagust, David F., and Abd-el-khalick, Fouad. The reason for this difference may be that this study conducted trend analysis in six science education journals indexed in SSCI Q1, while Tosun (2022) analysed a larger data set by analysing trends in a total of 14 selected journals indexed in SSCI all quartile categories. It was found that some authors received a high number of citations despite a low number of publications. This finding may be due to the fact that people with few publications and high citations may have studied the dominant topics. For example, Tsai, Chin-Chung received 3,381 citations with 72 publications, while Abd-el-khalick, Fouad received 2,011 citations with 32 publications.

The research with high citation counts is highly influential and reflects the most influential topics (Martin-Martin et al., 2017). The most influential document in this study is the study on using Cronbach's alpha in science education, written by Taber (2018). This document has received 4,345 citations in the very short time since it was written. It is a groundbreaking work in terms of science education research methodology because the article examines research that develops and reports on research instruments. This study provides insight into the authors' interpretation of this statistic, as Cronbach's alpha is one of the most common methods used to demonstrate the reliability of scales used in studies. The fact that this study was highly cited may indicate that the use of statistical research methods in science education has increased in recent years. After Taber (2018), the most influential documents are the works of Hofstein and Lunetta (2004) and Carlone and Johnson (2007), which received 1,000 or more citations. Hofstein and Lunetta (2004) addressed the fundamentals of laboratory use in science education in a 21st-century context. In their study, they provided insights into how to improve teachers' laboratory goals in science education and how to assess students' laboratory practice processes and assessments. Carlone and Johnson (2007) developed a science identity model to understand the science experiences of 15 accomplished women. The results of this study reveal striking implications for theoretical concepts of science identity and women of colour’s experience of science culture.

The focus of highly cited studies has changed over time. For example, highly cited studies focused on argumentation in 2003-2007 (Lee et al., 2009), argumentation, inquiry-based learning, and scientific modelling in 2008-2012 (Lin et al., 2014), and inequality in science education, STEM education, and undergraduate research experiences in 2013-2017 (Lin et al., 2019). The highly cited articles in this study are evolutionarily similar in the sense that their research topics bear traces of the most cited studies in previous studies in specific periods. The highly cited articles in this study between 2004 and 2024 include assessment (number 1), laboratory (number 2), science identity (number 3), research experiences (number 4 and 6), argumentation (number 5), scientific inquiry (number 7), augmented reality (number 8), scientific modelling (number 9), and computational thinking (number 10) as topics (see Table 3).

Tsai and Wen (2005) reported that learners’ conceptions and conceptual change were prevailing themes in science education between 1998 and 2002, and the interest shifted slightly to learning contexts and social, cultural and gender issues. It was reported that the prevailing themes in science education between 2003 and 2012 shifted to learning contexts compared to 1998-2002 (Lee et al., 2009; Lin et al., 2014). Lin et al. (2019) emphasized that although students' learning contexts, science teaching, and conceptual learning were the most studied topics in 2013-2017, research on this topic has decreased compared to previous years. As a result of the present study, it was found that past topics such as laboratory, socio-scientific issues, inquiry, nature of science, conceptual change and argumentation are still being studied as found in previous studies (Lee et al., 2009; Lin et al., 2014; Lin et al., 2019; Tosun, 2022; Wang et al., 2023). Similar to the findings of Tosun's (2022) study between 1982 and 2021, the prevailing themes in this study were scientific reasoning, scientific inquiry, teacher education, conceptual change, and STEM education. There is no doubt that the research topics of science education researchers have changed, especially in the studies from COVID-19 to the present (2019 to 2024). In the SSCI Q1 journals and the 2004-2024 timeline, emerging areas of interest include computational thinking, artificial intelligence, systems thinking, engineering education, online education, science identity, and gender issues, as well as ethnicity, diversity, equity, minority, and marginalized groups. STEM education represents a prevailing theme that has been extensively studied in the past and continues to attract scholarly attention.

Undoubtedly, one of the most important findings of this study is that research on online education and technology has increased in the post-COVID-19 period. This finding suggests that the pandemic has shifted priorities in science education toward an increased emphasis on digital tools. This finding may be because technology integration in science education is an emerging area of interest (Stevenson et al., 2017). The shift towards technology in post-COVID-19 science research trends may be due to the obligation for researchers and educators to explore digital learning in depth (Pokhrel & Chhetri, 2021) and to prepare learners for a changing world as technological developments, such as the use of artificial intelligence, accelerate in the 21st century (Pedro et al., 2019). As the use of artificial intelligence (AI) in education is relatively new, it should be considered that it may bring various challenges. Teachers' lack of AI literacy, limited knowledge and experience of AI applications are points that need to be improved. Although the use of artificial intelligence in science education poses various challenges, the use of artificial intelligence in the classroom brings various innovations. For example, AI tools like ChatGPT can provide students with personalized learning experiences.

STEM education is a prevailing theme may be due to the preparation and implementation of curriculum materials for STEM education, as it is constantly evolving (Martín-Páez et al., 2019; Wang et al., 2023). In addition to STEM education, gender and career interest and science identity are emerging areas of interest as low levels of career interest in general and female representation in STEM fields are still the main challenges for STEM researchers, educators and policymakers (NCSES, 2023; WISE, 2023), which leads to researchers to investigate underlying factors for STEM career interest (e.g., Balta et al., 2023; Dabney et al., 2012; Yerdelen-Damar et al., 2024) and to develop interventions aiming equality for minorities (e.g., Todd & Zvoch, 2019; Wade-Jaimes et al., 2021). Science identity is one of the leading factors influencing students' career interests, especially females' (Zhao et al., 2024). Although gender equity in STEM education presents several challenges in practice, it is an important area for orienting underrepresented groups and achieving career goals through various STEM projects.

Another emerging area of interest is systems thinking. Recent systematic literature reviews have reported an increase in the number of publications on systems thinking in science education in recent years (Budak & Ceyhan, 2024). Systems thinking may have influenced an emerging area of interest in science education, as it positively impacts understanding of scientific concepts (Vachliotis et al., 2014) and allows them to take a holistic view of a complex topic such as socio-scientific issues (Delaney et al., 2021).

Wang (2023) found that although scientific argumentation has been studied for years, it has also been studied more extensively in recent years. This finding of Wang (2023) is different from the findings of this study because this study did not find scientific argumentation to be a topic that has been studied in recent years; on the contrary, it found STEM, technology, and systems thinking to be predominantly studied. This difference may be due to methodological differences in the studies, scope of journals, or changing research priorities.

The results of this study, consistent with the findings of other studies (Lee et al., 2009; Lin et al., 2014; Lin et al., 2019; Tsai & Wen, 2005; Tosun, 2022; Wang et al., 2023), showed that the USA contributes the most to scientific knowledge in terms of both the number of publications and citations in science education research. This finding provides clear evidence in the literature that the USA has dominated scientific research for many years. This may be due to government support for researchers, academic collaborations, and the ability to attract international researchers through grants such as the National Science Foundation (NSF) and Fullbright scholarships. However, these findings should be interpreted in the context that the journals selected for this study are all in English and USA, England and Australia are English-speaking.

In this study, Michigan State University, National Taiwan Normal University, and the Weizmann Institute of Science are the leading institutions by total number of publications. Similar to the findings of Tosun (2022) and Wang et al. (2023), the most productive institute was found to be Michigan State University in this study. Tosun (2022) placed the second and third leading institutes as the University of Michigan and the University of Illinois, while Wang et al. (2023) placed the third leading institute as the University of Michigan, which differs from the results of the present study. The result of the study reveals that the leading institutions by number of citations were Michigan State University, Indiana University, and the Weizmann Institute of Science. Similar to the findings of Wang et al. (2023), the most cited institution in this study was Michigan State University. Wang et al. (2023) also ranked the second and third most cited institutions as Kings Coll London and Indiana University, which differs from the results of the present study.

This study found that Tsai Chin-Chung, Krajcik Joseph S., Jones Melissa Gail, Sadler Troy D., and Treagust David F. were the most collaborative authors, consistent with the findings of Wang et al. (2023). International collaborations can influence the quality or focus of science education research. For example, it was found that Tsai Chin-Chung is one of the most collaborative authors, and Chin-Chung established a collaboration with Chang, Hsin-Yi, Wu, Hsin-Kai, and Chen, Sufen, and worked on technology in education. This collaborative network can contribute to the technology as an emerging area of interest. It was also found that Michigan State University (USA), Indiana University (USA), National Taiwan Normal University (Taiwan), and Weizmann Institute of Science (Israel) were the most collaborative institutions. In line with the findings of Tosun (2022) and Wang et al. (2023), this study also revealed that the most collaborative country is the USA, with established research institutions collaborating more with North America and smaller network groups collaborating more with Europe.

Conclusion and Implications

Trends in science education research provide an overview of science education research by illustrating the evolution of topics and allowing them to see the gaps in the field. Unlike previous bibliometric studies (e.g., Tosun, 2022; Wang et al., 2023), this study is unique in that it extends the time period, analyses only research indexed in English-language journals in SSCI Q1, and identifies trends in studies conducted after COVID-19. This study showed trends in the top 6 science education journals indexed in SSCI Q1 over the last two decades (2004-2024), including five-year trends, especially after COVID-19. This study revealed that interests in scientific inquiry, teacher education, conceptual change, argumentation, and socio-scientific issues in the pre-COVID-19 periods shifted to systems thinking, equity, gender, science identity, engineering education, computational thinking, online education after COVID-19.

This study has important implications for science researchers, curriculum developers, science educators, and education policymakers. The first implication of this study is to highlight that the prevailing themes in scientific reasoning, scientific inquiry, teacher education, conceptual change, and STEM education from the COVID-19 era to the present day offer different insights for science researchers. In addition, the emerging areas of interest, such as artificial intelligence, systems thinking, online education, science identity, and gender issues, will provide direction for new scholars and allow them to identify research gaps.

The second implication of this study is for curriculum developers to put research findings into science curricula. This study found that the trending pedagogical approaches are STEM education, scientific inquiry, argumentation, and laboratory, while the emerging pedagogical approaches is systems thinking. The changing interest in pedagogical approaches in science education provides revolutionary insights for curriculum designers. In STEM education, it is important for students to synthesise their knowledge from science, technology, engineering, and mathematics disciplines and to look at things from an interdisciplinary perspective (Bene et al., 2021). Therefore, in light of the findings of this study, curriculum developers should pursue avenues to tailor curricula to student diversity rather than uniform classrooms and provide science educators with possible challenges and potential suggestions. To integrate STEM education into the curriculum, curriculum developers can use the problem-based learning (PBL) approach, which allows students to connect to the real world. In addition, technology integration in science education can provide a more in-depth and experiential approach to science topics through simulations and virtual laboratories.

Systems thinking is a current pedagogical approach that allows students to approach complex problems, such as environmental issues and socio-scientific issues, from a holistic view of the structure and function of the system rather than its parts (e.g., Delaney et al., 2024). Curriculum designers should study these current pedagogical approaches and seek to integrate them into science curricula so that students can become systems literate. To integrate systems thinking into the curriculum, curriculum designers should include conceptual maps that facilitate a holistic view of complex issues such as climate change, allowing students to see the relationships between variables within the system. In addition, incorporating scenario-based learning into the curriculum can enable pupils to analyse multiple systems issues (e.g., economic, social, and environmental dimensions of sustainability) in a single scenario and provide actionable solutions to address them.

The third implication of this study is for science educators to put research findings into practice. Science educators should prepare materials and design lessons in a way that is appropriate for STEM education, considering ethnicity, diversity, equity, minority and marginalised groups. For this reason, science educators should follow current research on STEM education and diversity and educate themselves about the challenges and potential solutions to these challenges. On the other hand, science educators should also strive to educate their students as technologically literate individuals worthy of 21st-century global citizenship. Science educators should look for ways to integrate artificial intelligence into their lessons.

The fourth implication of this study is for educational policy makers to incorporate the research findings into educational policy. Education policymakers should support the practical application of scientific research by providing adequate financial support. For example, classrooms should be equipped with tools and well-trained science teachers to enable STEM and technology-integrated education. Science educators may face difficulties with ethnic and minority groups regarding theoretical knowledge and lack of practice in implementing STEM education in their classrooms. Therefore, education policy makers should not leave science educators alone in this regard and should provide them with professional development programmes in cooperation with universities. The final implication is that science researchers, curriculum developers, science educators, and education policymakers should work collaboratively to improve science education worldwide and seek ways to provide students with scientific inquiry skills, which are the most fundamental goals of science education, while considering classroom diversity.

While this scientific study has significant implications, it should be acknowledged that it has some limitations. The limitations should be considered when interpreting the results of this study. First, the database from which this study was obtained is a single data source, namely WoS. Therefore, we suggest that future studies include databases such as Scopus, ERIC, EBSCO, and Google Scholar for a more comprehensive trend analysis. A second limitation is that the journals included in this study are from the SSCI Q1 category and, non-English journals are excluded. The result of this study should be interpreted in the context of SSCI Q1 and English journals in the WoS database, which limits the generalizability of the results of this study. All SSCI categories can be included in the analysis to provide an overview of science education in future research. In addition, ESCI journals can be included in the analysis because they are also emerging sources. The third limitation is that only English-language journals are included in this study. To see trends in non-English journals, non-English journals can also be included in the analysis, and authors from different countries can collaborate for this purpose. The fourth limitation is that the publication trend analysis is based on the year of publication, which may not accurately reflect the year in which the research was conducted. There can be a considerable delay between a paper being accepted and appearing in a journal, meaning that two papers published in the same year may have been carried out several years apart. The fifth limitation is that the dataset in this study includes studies from the last twenty years (2004-2024), which means that the analysis was conducted with limited data. Therefore, future studies can analyse trends in science education over a more extended period.

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Journal of Turkish Science Education, 2025, 22(4), 655-676.
DOI no: 10.36681/tused.2025.033

Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

Promoting computational and higher-order thinking skills through problem-based learning with digital argumentation in biodiversity

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ABSTRACT
Problem-based learning integrated with Digital Argumentation (PBL-DA) is a learning strategy for optimizing innovative learning in the digital era. This research aimed to investigate whether the application of PBL-DA can foster the Computational Thinking (CT) and Higher Order Thinking Skills (HOTs). A quasi-experimental design measured three aspects: skill (decomposition, algorithm design, evaluation), attitude (confidence, communication, flexibility), and approach (tinkering, creating, collaborating). The students' HOTs were measured through eight aspects: critical thinking, argumentation, problem-solving, problem-identifying, understanding concepts, analysing, making decisions, and creative thinking. The students' CT and HOTs scores of control and experimental classes were analyzed using Hotelling's T^2 test and Tukey's post hoc test. The Hotelling's T^2 test revealed a significant difference between the experimental and control classes for both CT and HOTs ($T^2 = 0.340$, $p < 0.001$ for CT; $T^2 = 0.718$, $p < 0.001$ for HOTs). Tukey's test further showed that PBL-DA significantly impacted the CT skill and attitude aspects ($p < 0.01$), while the approach aspect was not significant ($p > 0.05$). For HOTs, critical thinking, argumentation, problem-identifying and analyzing were significantly improved ($p < 0.01$), but problem-solving, understanding concepts, making decisions, and creative thinking showed no significant improvement ($p > 0.05$). Pearson's correlation analysis indicated a strong positive correlation ($r = 0.651$, $p < 0.001$) between students' CT and HOTs skills. These findings provide evidence of the effectiveness of the PBL-DA model in improving students' CT and HOTs, demonstrating its potential for fostering critical and higher-order thinking skills in the digital era.

RESEARCH ARTICLE

ARTICLE INFORMATION
Received: 18.07.2024
Accepted: 21.02.2025
Available Online: 27.11.2025

KEYWORDS:
Problem-based learning, digital argumentation, computational thinking, HOTs.

To cite this article: Lukitasari, M., Nurhikmawati, A.R., Murtafiah, W., Sukri, A., Urbano, J.M., Tanghal, A.B. & Hasan, R. (2025). Promoting computational and higher-order thinking skills through problem-based learning with digital argumentation in biodiversity. *Journal of Turkish Science Education*, *22*(4), 655-676. http://doi.org/10.36681/tused.2025.033

Introduction

The 21st century requires every country to create a society that can communicate and collaborate to solve problems through critical, creative and innovative thinking. It forces the educational system of many countries to focus on higher order thinking skills (HOTs) to prepare human resources to compete in the global digital era. The idea of incorporating computer thinking into the school curriculum as one of the essential skills for today's children is gaining ground around the world due to the widespread development of information and communication technology (ICT) in education and the skill demands of the 21st-century lifestyle. While the use of ICT in educational practices allows the enhancement of HOTs, thinking skills alone are inadequate to solve complex problems (Gordillo-Tenorio & Cabanillas-Carbonell, 2023). Computational thinking (CT) as a cognitive process involving reasoning is needed to solve problems and better understand processes and systems (Csizmadia et al., 2015).

HOTs are high-level skills that include the domains of analysis, synthesis and evaluation (Anderson et al., 2001; Hill, 2015). Critical thinking processes, analytical skills and creativity are the areas of HOTs that are crucial in developing human intellectuality. Practising HOTs in the learning process is essential because it affects the rate of thinking, problem-solving, and the effectiveness of student learning and will be triggered when someone is given a stimulus in the form of a problem (Liline et al., 2024; Srivastava & Mudholkar, 2001). As to HOTs, CT is a fundamental skill that not only people in the computer field ought to have. CT skills need to be taught in the classroom at the same level as HOTs. The issue is that most lessons in the classroom are not familiar with the practice of CT and HOTs. Therefore, involving CT and HOTs indicators in learning activities is essential in courses including Biology Education.

Training students for HOTs requires the integration of ICT to be relevant to the current digital era. Research on ICT-integrated HOTs showed significant results in supporting students' critical thinking skills (S. M. Lee, 2014). The existence of technology in learning drives students to become more independent in their learning activities, such as finding relevant learning resources, stimulating creative questions, and solving problems. Previous research showed that ICT is an appropriate and suitable means to stimulate and build students' understanding of learning materials (Kale et al., 2018; Williams et al., 1994). The process of integrating ICT to support student HOTs certainly cannot be separated from the form of learning in the classroom related to the learning model and learning tools used. However, the CT and HOTs of undergraduate students tend to be low (Giannetto & Vincent, 2014). The educational faculty must prepare their students as prospective teachers to become future professional teachers. Familiarizing students with CT (Hunsaker, 2020) and HOTs is essential for enhancing the quality of human resources. However, in this case, there is no information about the CT abilities of students at Universitas PGRI Madiun (UNIPMA), Indonesia, and Nueva Ecija University of Science and Technology (NEUST), Philippines.

The results of previous studies have shown that the HOTs of prospective biology teachers at UNIPMA still need to be improved (Cantona et al., 2023), specifically in the Biodiversity course. At the Department of Science in NEUST of The Philippines, the students found similar difficulties in this course as the students at the Department of Biology Education of UNIPMA. Most students have not been able to comprehend the classification and benefits of the plants that are found around them. This problem must be overcome so that the quality of graduates meets the standards to become the professional teachers. Improving the quality of learning continuously needs to be improved through the application of various innovative learning models (Montoneri, 2014). The application of the learning model designed to foster HOTs is expected to lead students to comprehend the biodiversity lecture material, find solutions to problems, and evaluate conditions and activities that have been carried out more creatively and dynamically at the same time.

A previous study reported that the PBL model had the potential to increase HOTs. The research that combined problem-based learning activities showed that the implementation of PBL enhanced students' HOTs through concept transfer in new situations, integrating concepts, increasing intrinsic learning interest, and training learning skills (Habók & Nagy, 2016). The application of technology-integrated PBL to support the ability of prospective teacher students to develop professional content knowledge and teaching skills (Kale et al., 2018), improved HOTs (Mubuuke et al., 2016) and problem-solving skills of students (Nantha et al., 2022). Previous studies indicated that the application of ICT-based PBL which prioritizes students' thinking through digital argumentation (DA) increased students' HOTs. The development of arguments from conventional patterns as digital format using ICT showed a significant change in generation in conveying arguments so that they can be traced by identifying, analyzing, and ways of thinking in building their arguments (Pereira et al., 2015). On the one hand, the pattern of argumentation changes made by students in the digitalization era greatly affects critical thinking skills, which are components of HOTs. The existence of ICT was a bridge for students to convey their arguments digitally without being limited by space or time (Tanujaya et al., 2017).

We initially designed PBL-DA as part of the syntax in the modified PBL model that can improve student CT and HOTs. The PBL-DA model allows students to train themselves to convey what they think by writing the argumentation on an ICT-assisted platform. Students with low ability to argue directly can be overcome by digital media. On the other hand, the arguments presented in the e-learning platform can still be observed by students both who write and other students who read the arguments. The quality of students' CT and HOTs and their correlation can be assessed. Therefore, it is necessary to know whether the implementation of PBL-DA can improve CT and HOTs, especially in learning Biodiversity. This study of implementation of PBL-DA was aimed to promote CT and HOTs in learning Biodiversity of students in two universities of Indonesia and The Philippines. By the implementation of PBL DA, students are given the opportunity to convey their thoughts or arguments digitally, especially in the context of problem solving based on the theme of biodiversity. Thus, this study was conducted to answer the research question "How does the implementation of PBL DA affect CT and HOTs abilities in the Biodiversity course?"

Literature Review

Computational Thinking (CT) and Higher Order Thinking Skills (HOTs)

Computational thinking (CT) is currently a trend in education and a cognitive process, a problem-solving process that reflects the ability to think in terms of abstractions, algorithms, decompositions, generalizations and evaluations (Lawshe, 1975). These indicators can be used effectively to improve learning process and its assessment. It can also be described as a focused approach applied by transforming real-world problems into computable parts and applying solutions efficiently (Gao & Hew, 2022; Tosun & Senocak, 2013). There is no single definition of computational thinking, but there are general concepts such as logic, abstraction, generalization, decomposition, and evaluation. Anyone, not just computer scientists, can apply one or a set of computational reasoning skills to these concepts. CT skills emerged around the 1980s era, along with the mainstream use of technology in many areas (Haryani et al., 2014). As one of the important indicators in the mechanism of rational thinking process, CT tends to be rarely used in learning activities. Therefore, it is important to include CT components as indicators as well as their assessment. The integration of technology such as computers, smartphones, and various other types of gadgets is increasing rapidly shows that encouraging CT skills is necessary in the learning process (Hopson et al., 2001). In a broader context, CT abilities with a computational thinking orientation to solve complex problems by finding problem-solving ideas using a computer (Kelly et al., 2016) is very closely affiliated with higher-order thinking skills which were trained with ICT support (Greenbank, 2010).

As with a CT, HOTs represent an advanced cognitive concept on the capacity for effective problem-solving. The HOTs paradigm encompasses four cognitive skills: problem-solving, critical analysis, innovative thought and decision-making (Alkhatib, 2019), which are essential cognitive processes that enable individuals to analyse, evaluate, and create new ideas or solutions. These skills are crucial for students to navigate complex problems and adapt rapidly to the changing demands of the 21st century (Bhaumik et al., 2024). Developing HOTS can equips students with the ability to make better decisions and think independently. It encourages innovation by enabling students to think beyond conventional boundaries and contribute positively to society. The challenge in implementing HOTS for the teacher is the need for deep understanding and preparedness. Therefore, the teachers need to develop effective learning designs and questioning techniques to facilitate HOTS in the classroom.

Problem Base Learning (PBL)

Problem-base learning (PBL) is a learning model that adopts problems encountered in everyday life as its advantage. PBL is a student-centred approach that involves groups solving open-ended problems to learn about a subject. This problem is what motivates and enables learning (Skelin et al., 2008). PBL plays a role in comprehending new situations, integrating concepts, and increasing learning motivation (Habók & Nagy, 2016) and is carried out in the following stages of activity: designing problems, presenting problems to students, discussing with facilitators, and presenting results (Milroy, 2021; Tsortanidou et al., 2019). Through the application of PBL, students will try to solve problems that require a lot of information from various sources. The application of PBL also has the potential to increase students' HOTs through the ability to understand the material better (Habók & Nagy, 2016) and develop content knowledge (Kale et al., 2018). Related to the development of ICT, the application of PBL with the support of these facilities will accommodate the development of education in university, including how students communicate and argue (Andrews, 2015).

A well-designed PBL allows students to develop skills such as teamwork, project management, and leadership roles, oral and written communication, self-awareness and evaluation of group processes, independent work, critical thinking and analysis, explaining concepts, self-directed learning, applying course content to real-world examples, researching and information literacy, and cross-disciplinary problem solving (Nilson, 2010). According to Duch et al., (2001), the general idea of creating PBL problems for classroom learning can be used in the following steps: First, choose a main idea, concept, or principle that is regularly taught in a lesson, and then think of a closed-ended problem, exercise, or task that will be given to students to help them learn that topic. List the learning objectives that students should achieve when solving problems. Second, consider the overall context of the project to motivate students to solve problems by studying real cases where they can develop or apply narrative features to the problems at the end of each chapter. More complex problems require students to solve problems beyond simple plug-and-chug. Third, problems should be included in the sections so that students understand the learning problems that lead them to learn the target topic. Fourth, write a teacher's guide that summarizes the teaching plan for using the problems in the lesson. If the course is a medium to large class, mix small talk, whole class discussions, small group work and regular discussions. The teacher's guide may indicate plans or options for going through pages of problems in different disciplines. Finally, identify key resources for students. Students must learn to identify and use study materials on their own, but instructors may want to point them to some reliable sources to get them started. Many students prefer to limit their research to the internet, so it is also important to direct them to the library.

Digital Argumentation (DA)

Digital argumentation (DA) is the result of the development of communication patterns through ICT-based student logical arguments (Hajj & Harb, 2023; Karami et al., 2013). Students' arguments are conveyed by writing their opinions on the material on a platform that has been prepared. The DA delivered by students can be an indicator of their level of understanding as well as the way they think about the topics discussed. This digital presentation of arguments has the advantage of being more structured in the sentences composed by students. Students will have more time to evaluate each argument that will be presented. Therefore, students will tend to repeat the material before presenting their digital arguments. The weakness that arises with the use of DA is the expression or spontaneity of thoughts that cannot be directly observed. The pre-existing DA track record is also an important part of assisting the evaluation process when needed. Arguments from time to time are shown in digital formats such as cassette tapes and compact discs until now, based on databases such as the Internet. With the advancement of technology, the argumentation format is more concise and has many functions, including helping develop students' HOT skills (Fan et al., 2020).

Theoretical Framework of PBL-DA to Cultivate Students' CT and HOTs

CT and HOTs have connectivity in supporting students as a problem solver as a vital component in modern education. CT provides a structural approach to problem-solving that aligns closely with the development of HOTS, which include analysis, evaluation, and creation. The way CT stages such as decomposition, pattern recognition, abstraction and algorithm design mirror the cognitive processes that involved in HOTs. The PBL-DA design is developed from a problem-based learning model that is integrated with technology through Digital Argumentation (DA). Model development is carried out by modifying and integrating the syntax with other components with a specific purpose, based on the needs analysis and literature review (Viyanti et al., 2020). The PBL-DA model uses basic PBL syntax which are then integrated with information technology to accommodate the DA tasks submitted by students that can be implemented in group or individual learning (Lukitasari et al., 2020). The PBL-DA syntax can be presented as follows: problem orientation; student organization; brainstorming or submitting stimulus questions; data collection through research; shared information and discussion to find solutions to problems; presenting the results of problem-solving; and analysis and evaluation of problem solutions (Lukitasari et al., 2021). By integrating PBL and DA, students are encouraged to engage deeply with content, develop critical and creative thinking, and apply computational strategies effectively. PBL-DA can significantly improve students' CT skills by providing a structured yet flexible framework for dealing with complex problems (Aryan et al., 2022). PBL encourages students to actively participate in their learning process, fostering critical thinking and problem-solving skills, which are important components of CT. Digital Argumentation, on the other hand, supports the development of scientific literacy and reasoning, which further enhances CT skills (Voon et al., 2022). This approach creates a comprehensive learning environment that encourages the development of CT and HOTs skills.

Methods

Research Design

This research is a mixed methods which is a combination of qualitative and quantitative research. This type is carried out by collecting qualitative data which is explored based on the conditions of implementing PBL-DA in the classroom. Then the qualitative data was converted to quantitative data to explain the result comprehensively.

This study was a quasi-experimental research with a counterbalanced design (Hopson et al., 2001). The research involved two groups of students treated with different learning models. The control group was subjected to the conventional learning model that applied with classroom discussion. The experiment classroom used the PBL-DA learning model (Lukitasari et al., 2018). The PBL-DA accommodates PBL syntax with modification by using Learning Management System (LMS) to facilitated arguments presented by students during the learning process.

Population and Sample

The population of this research were students of biological science study program from two universities, Nueva Ecija University of Science and Technology (NEUST) of the Philippines and Universitas PGRI Madiun (UNIPMA) of Indonesia, in total 439 students, consisted of 246 students at NEUST and 193 students at UNIPMA. The research sample were 2 classes at each university to be used as a control and experimental class. Class selection was carried out using purposive random sampling based on classes that in the odd semester of 2022/2023 contained biodiversity courses. The number of students in either control and experimental classes were 25 students so that the total number of sample were 100 students.

Research Procedure

Research activities began with synchronization of Biodiversity course material which was implemented for one semester at NEUST and UNIPMA. Thereafter, PBL-DA learning model applied was carried out by the lectures both universities for the topic of Biodiversity. Detailed course plan is presented in appendix 1, with sample lesson plan and worksheet in appendix 2 and 3, respectively, as shown in Table 1.

Table 1

Control and experiment classes

Unit classes	Condition	
	Experiment	Control
UNIPMA (Indonesia)	PBL-DA	Conventional
NEUST (Philippines)		

The PBL-DA learning method was implemented in the experiment class for one semester. The stages of PBL-DA (Lukitasari et al., 2018) Meanwhile, the control class was taught using discussion and presentation methods following the material.

Instrument

The instrument for measuring CT skills was an essay task that consisted of five components: abstraction, algorithmic reasoning, decomposition, evaluation and generalization (Haryani et al., 2014). Essay task was given on each topic of biodiversity during the lecture period. The CT skills were gathered using the 4 -point marking keys that was developed by Jensen et al. (2014). The development of HOTs and CT instruments were validated by eight experts (Kelly, 2016) using CVI and CVR (Williams et al., 1994). The validation result for the CT instrument shows that the number of CVI and CVR is > 0.79 and = 0.75 consecutively.

The instrument to measure the students' HOTs was given twice to the control and experimental classes, as a pretest and post-test. The pretest was used to determine the students' existing knowledge and homogeneity between the two experimental and control classes about the subject before any intervention. The post-test was used to test the effectiveness of the PBL-DA method in improving students' understanding compared to conventional methods. The HOTs instrument was developed using 30 multiple-answer validated test questions following the lecture material.

Data Analysis

CT and HOTs data in ordinal form were converted into interval scale form through the method of successive intervals (Gilbert & Prion, 2016). The data were then analyzed descriptively to reveal students' CT and HOTs abilities. To determine the effect of the PBL-DA model on CT and HOTs analyzed by Hotteling's T2 test (Nantha et al., 2022; Pereira et al., 2015) continued by Tukey test (Nirbita et al., 2018). The correlation between CT and HOTs of the student was analyzed with the Pearson correlation test. All statistical analyses used IBM SPSS version 26.

Findings

Students' Computational Thinking Skills

Computational thinking skills at Table 2 shows three components of CT skills of the students in both control and PBL-DA classes. The average and each aspect of students' CT skills in the PBL-DA class are relatively higher than control class, with the highest difference is shown in skill aspect.

Table 2

Students' computational thinking in control and PBL-DA classes in biodiversity course (N = 50)

No	Aspects of students' Computational Thinking	Classes		Mean Diff. (Control-PBDL DA)
		Control (Mean±SD)	PBL-DA (Mean±SD)	
1	Skill (Decomposition, Algorithm Design, Evaluation)	59.58±0.73	71.47±0.56	11.89
2	Attitude (Confidence, Communication, Flexibility)	68.35±0.67	73.33±0.58	4.98
3	Approach (Tinkering, Creating, Collaborating)	68.35±0.67	68.99±0.54	0.64
	AVERAGE	65.43±0.69	71.27±0.56	5.84

The effect of PBL-DA on Students' Computational Thinking Ability

To determine the effect of the PBL-DA model on CT and HOTs, the Hotteling's T2 analysis was conducted. Normality and homogeneity tests were carried out as prerequisites for Hotteling's T2 test followed by the Tukey, as the results are shown in Tables 3 and 4.

Table 3

Normality test of students' CT

Variable	Normality Test (Kolmogorov-Smirnov)	
	KS-Z	Sig
CT	0.857	0.455

Table 3 shows that the *p-value* for the normality test on the students' CT variables is 0.455. The *p-value* > 0.05 indicates the variable has normally distributed data.

Table 4

Variance analysis of CT aspects and PBL-DA control group

Box's test of equality of covariance matrices		Levene's test of equality error variances				
Box's M = 1.633		CT Aspect	F	df1	df2	Sig.
df1	= 6	Skill	0.779	1	98	0.380
df2	= 69583.698	Attitude	0.005	1	98	0.942
Sig.	= 0.954	Approach	0.013	1	98	0.911

The results of Box's Test of Equality of Covariance Matrix in Table 4 show that the variance-covariance matrix between the PBL-DA model and the control classes were homogeneous (Sig. = 0.954 >0.05). Table 4 also shows that each aspect of DT has a homogeneous data variance (Sig. = 0.380; 0.942 and 0.911 > 0.05). Based on these results, the Hotelling Test T2 analysis followed by Tukey test can be performed.

Table 5 shows that the Hotelling Trace value is 0.340 with a Sig. 0.000 (Sig. <0.05). This result indicates that there was an influence of the PBL-DA on students' CT abilities. Moreover, Tukey test results show that PBL-DA significantly influences two aspects of students' CT, which were skill and attitude (p-value <0.05), while for the approach aspect, the effect of PBL-DA did not affect it significantly (p-value >0.05).

Table 5

Hotteling's T2 and Tukey test results of students' computation thinking abilities.

Effect (Group)	Value	Sig.	Variable	Tukey HSD Q statistic	Tukey HSD p-value	Tukey HSD inference
Hotelling's Trace	0.340	0.000	Skill	6.0902	0.001	Significant
			Attitude	4.2160	0.003	Significant
			Approach	0.3083	0.833	Insignificant

Students' High-Order Thinking Skills

Table 6 shows the students' high-order thinking which is divided into eight aspects in control and PBL-DA classes.

Table 6

Students' HOTs in control and PBL-DA classes in Biodiversity course (N = 50)

No	Aspects of Students High Order Thinking Skills	Classes		Mean Diff. (Control-PBDL DA)
		Control (Mean±SD)	PBL-DA (Mean±SD)	
1	Critical Thinking	58.65±0.78	85.52±0.52	26.87
2	Argumentation skills	55.06±0.73	71.46±0.64	16.4
3	Problem Solving	61.44±0.69	66.68±0.68	5.24
4	Identifying Problems	63.02±0.65	74.63±0.57	11.61
5	Understanding Concept	68.87±0.67	63.02±0.74	-5.85
6	Analyzing	66.68±0.69	78.86±0.57	12.18
7	Making Decisions	71.46±0.63	74.63±0.61	3.17
8	Creative Thinking	60.00±0.70	64.75±0.68	4.75
	AVERAGE	63.15±0.69	72.44±0.63	9.29

The Effect of PBL-DA on Students' High-Ordered Thinking Skills in Biodiversity

As previously carried out on students' CT data, the Hotteling's T2 analysis was carried out to determine the effect of the PBL-DA model on CT and HOTs. Normality and homogeneity tests were carried out as prerequisites for Hotteling's T2 test followed by the Tukey, as the results are shown in Tables 7 and 8.

Table 7

Normality test of students HOTs data.

Variable	Normality Test (Kolmogorov-Smirnov)	
	KS-Z	Sig
HOTs	0.826	0.503

Table 7 shows that the *p-values* for the normality test on the students' HOTs variables was 0.503. The *p-value* > 0.05 indicates the variable has normally distributed data.

Table 8

Homogeneity analysis of PBL-DA control group and HOTs aspects

Box's test of equality of covariance matrices	Levene's test of equality error variances				
Box's M = 12.978	HOTs Indicator	F	df1	df2	Sig.
df1 = 36	Critical Thinking	0.749	1	98	0.389
df2 = 32316.056	Argumentation	1.481	1	98	0.226
Sig. = 0.060	Problem-Solving	0.763	1	98	0.385
	Identifying Problem	0.373	1	98	0.543
	Understanding concept	0.000	1	98	1.000
	Analyzing	0.428	1	98	0.515
	Making decision	0.053	1	98	0.818
	Creative thinking	0.476	1	98	0.492

The results of Box's Test of Equality of Covariance Matrix in Table 9 show that the variance-covariance matrix between the PBL-DA model and the control is homogeneous (Sig. = 0.060>0.05). Table 8 also shows that each HOTs aspect has a homogeneous data variance (Sig.>0.05). Based on these results, the Hotelling Test T2 analysis followed by Tukey test was carried out (Table 9).

The results of the analysis in Table 9 show that the Hotelling Trace value is 0.718 with a Sig. 0.000 (Sig. <0.05). This result indicates that there was an influence of the PBL-DA treatment group on students' HOTs abilities in general. Moreover, the Tukey test results show that PBL-DA influenced four aspects of HOTs, that were critical thinking, argumentation, identifying problems, and analyzing (p-value < 0.05). Meanwhile, PBL-DA did not affect significantly (p-value >0.050 on the other four aspects of HOTs, including problem-solving, understanding concepts, making decisions, and creative thinking aspects.

Table 9

Hotelling T2 and Tukey tests of students' HOTs.

Effect (Group)	Value	Sig.	Variable	Tukey HSD Q statistic	Tukey HSD p-value	Tukey HSD inference
Hotelling's Trace	0.718	0.000	Critical Thinking	8.9544	0.001	Significant
			Argumentation	5.1970	0.001	Significant
			Identifying Problem	3.7409	0.009	Significant
			Analyzing	4.0342	0.005	Significant
			Problem-Solving	1.6547	0.244	Insignificant
			Understanding concept	1.8904	0.184	Insignificant
			Making decision	1.0316	0.467	Insignificant
			Creative thinking	1.5153	0.286	Insignificant

The Correlation Between Students' CT and HOTs

Pearson correlation analysis has Sig value < 0.05. The result of this study indicates a positive correlation between students' CT and HOTs abilities with a strong correlation level (0.651) as shown in table 10.

Table 10

Correlations analysis between student' CT and HOTs

		HOTs	CT
HOTs	Pearson Correlation	1	0.651**
	Sig. (2-tailed)		0.000
	N	100	100
CT	Pearson Correlation	0.651**	1
	Sig. (2-tailed)	0.000	
	N	100	100

Note. Correlation is significant at the 0.01 level (2-tailed).

Discussion

The implementation of the PBL model that developed into PBL-DA through technology integration in this study showed a significant increase in HOTs and CT skills in several aspects. PBL encourage students to be involved and seek their learning through problem-solving (Allchin, 2013; Greenbank, 2010). In practice, the problems raised and resolved by student groups were based on the theme or sub-theme of the biology course, that were integrated science and Biodiversity. The lecture process, with the support of technology, encourages students to be able to convey arguments both in writing and in person.

The result shows that CT and HOTs abilities significantly difference between experiment and control classes. These results indicated that the PBL-DA learning model (Lukitasari et al., 2018) that was used can encourage an increase the students' CT and HOTs abilities. The submission of problems based on narratives from many sources to be resolved in groups provides facilities for developing the capabilities of CT and HOTs. Discussions to accommodate opinions as well as possible alternative solutions to problems (Milroy, 2021) are an important part of implementing PBL-DA. During lectures and when practicing CT skills, especially when solving problems, students use a lot of computer support. Then, with their groups, they hold discussions and then sort out the material obtained to analyze the possibilities of solving the problems presented. Technically, student groups optimize resources starting with computers, mobile phones, supporting software programs, and internet networks. In this process, it is consistent that learning conditions using many technological sources were part of CT capabilities, especially from a computational perspective (Lukitasari et al., 2021) nurturing students' CT of pattern recognition and decomposition concepts (Jawawi et al., 2022). On the other hand, students' HOTs abilities also experienced significant differences between the experimental and control classes. The PBL-DA combination trains students in solving problems that have an impact on increasing HOTs. With the clear stages of PBL, students can think critically, present arguments online and offline, identify problems, carry out analysis, and find possible solutions to problems with the help of technology. Connectivity between individuals in social interactions, both directly and indirectly, was a determining factor in the growth of student HOTs (S. M. Lee, 2014).

The interesting results on this study were obtained after Hotteling’s test carried out on the two variables, CT and HOTs. Based on the aspects measured on CT, the approach was the only aspect that is not significant compared to the other two aspects: skill and attitude. The approach aspects, which consists of the sub-aspects of tinkering, creating and collaborating, were possible because the communication process has not been optimal in the groups that have been formed, although, on the other hand, the existence of groups should be in line with optimizing collaboration within the group. In this case, it was very important to pay attention to the approach aspect when the learning process is carried out, both between lecturers and students and between students who were members of groups. The approach process was an important part to be maintained as a way of providing a sense of comfort for students to express the ideas they get. It was because the ideas conveyed in the form of computational-based work as a form of CT are a form of communication that requires complex skills such as thinking, being creative (Fields et al., 2021), and collaboration in groups. It can be further explained that group collaboration plays an important role in developing students' HOTs abilities.

The Hotteling’s test measures HOTs ability, which was the dependent variable of this study, based on eight aspects, showing four aspects (critical thinking, argumentation, identifying problems, and analyzing) were significant, while four other aspects (problem-solving, understanding concepts, making decisions, and creative thinking) were not significantly affected by the implementing PBL-DA. Many factors, such as mindset, background understanding, and the ability to overcome obstacles (Green, 2017), can influence and explain why the four aspects of HOTs were not significant. Practicing HOTs in learning activities simultaneously in many forms, such as getting used to working on HOTs-based questions and the process of working on assignments to solve problems, was an important part of learning. Therefore, the role of educators as interventions to encourage students' thinking levels is an important part that needs to be pursued (Labak et al., 2024; K. Lee & Cho, 2021). The habituation factor in practicing HOTs in the learning process was very significant for increasing aspects of understanding concepts (Jazuli et al., 2020). These interesting results demonstrate the complexity of HOTs capabilities, which have the potential to be developed specifically in many ways (Lye & Koh, 2014).

Conclusion and Implications

In conclusion, the results of this study indicate that there was a significant difference in CT and HOTs performance between the experimental and control classes after applying the PBL-DA learning model. The PBL-DA model, with most of the lecture time being conducted online, is motivated using technology to support the learning process. Even though the overall test results showed significant results, when additional tests were carried out to determine the results of CT and HOTs in each aspect, several aspects were found to be not significant. Thus, it can be concluded that the successful application of PBL-DA for CT and HOTs does not only require technology as the main foundation but also requires habituation and active communication in the form of collaboration between students and other students and also between students and lecturers. Furthermore, the results of this study suggest a wider and more diverse sampling to facilitate and encourage more comprehensive results from the CT and HOTs.

Acknowledgments

We thank The Ministry of Education and Culture for joint research funding through the Merdeka Campus Competition Program (PKKM) grant in the Biology Education Study Program Universitas PGRI Madiun (UNIPMA). Thanks to research partners from PHINMA Rizal College of Laguna and Nueva Ecija University of Science and Technology (NEUST), Philippines for the research collaboration that was carried out.

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Appendix 1

Course Plan Outline

COURSE OUTLINE OF PLANT BIODIVERSITY	
What is this course about?	
In this course you investigate diversity of the plant: Plant biodiversity & Biodiversity levels, Genetic, species and ecosystem biodiversity, Biodiversity & Ecological distribution of Chryptogamae, Biodiversity & Ecological Distribution of Angiosperm, and Biodiversity & Ecological Distribution of Gymnosperm	
How will this course be delivered?	
Learning activities are carried out using blended learning by utilizing the existing learning management system (LMS), as e-learning UNIPMA (eLMA). Apart from that, the implementation of learning is framed using problem based learning (PBL) and encourages active student communication online or digital argumentation (DA) in the (eLMA).	
Learning materials	The learning material will introduce and invite the students to carry out investigations and observations about plant diversity. Students will carry out activities in groups by working on assignments that have been designed according to the material. Students will explore plant biodiversity of Chryptogamae, Angiosperm and Gymnosperm. Students also learn how the ecological distribution plans and the interaction each other.
Observation/ Practicum	Practical activities are carried out in groups which are useful for expanding knowledge and understanding of the material. Students make observations and describe plant types according to their anatomical and morphological characteristics. Students also directly improve their ability to make detailed drawings of plants, from roots, stems, leaves and even their reproductive organs. For a wider range, students have the skills to identify and classify the types of plants observed.
Tutorial/Mentoring	This mentoring and tutorial help students develop critical thinking skills, use of scientific vocabulary, and scientific writing in the form of activity reports. Students are trained to convey arguments well using LMS facilities in hybrid learning.
Course Topic	
Plant biodiversity & Biodiversity levels. Anatomy, morphology and characteristics of major taxon of the plant. Laboratory skills (identification, botany, microbiology). Scientific drawing and writing skills (laboratory report) Field investigation skills	
Schedule	
Period	Activities
Week 1	**Pretest** Learning material; Course introduction; Origins and patterns of global plant biodiversity. Tutorial; Evolution and biodiversity levels
Week 2	Learning material; plant diversity at genetic, species and ecosystem levels Tutorial; analysis of genetic, species and ecosystem diversity problems

Week 3	Learning material; Biodiversity & Ecological distribution of Chryptogamae (Thallophyta, Bryophyta) Practicum; observation anatomy and morphology, microscopes and scientific drawing
Week 4	Learning material; Biodiversity & Ecological distribution of Chryptogamae (Bryophyta, & Fungi) Practicum; observation anatomy and morphology, microscopes and scientific drawing
Week 5	Learning material; Biodiversity & Ecological distribution of Chryptogamae (Pteridophyte) Tutorial/Mentoring; discussion, problem solving and presentation
Week 6	Learning material; Biodiversity & Ecological Distribution of Angiosperm (*Ranunculaceae, Caryophyllaceae* dan *Rosacea)* Practicum; observation anatomy and morphology, microscopes and scientific drawing
Week 7	Learning material; Biodiversity & Ecological Distribution of Angiosperm (*Solanaceae, Acanthaceae* dan *Lamiaceae)* Practicum; observation anatomy and morphology, microscopes and scientific drawing
Week 8	**Midterm test** Tutorial/Mentoring; discussion, problem solving and presentation practicum report.
Week 9	Learning material; Biodiversity & Ecological Distribution of Angiosperm (*Orchidaceae, Liliaceae* dan *Poaceae)* Practicum; observation anatomy and morphology, microscopes and scientific drawing.
Week 10	Learning material; Biodiversity & Ecological Distribution of Gymnosperm. Tutorial/Mentoring; discussion, problem solving and presentation
Week 11	Learning material; Biodiversity & Ecological Distribution of Gymnosperm. (Cycadidae, Konifer) Practicum; observation anatomy and morphology, microscopes and scientific drawing.
Week 12	Learning material; Biodiversity & Ecological Distribution of Gymnosperm. (Ginkodidae, Gnetophyta) Practicum; observation anatomy and morphology, microscopes and scientific drawing.
Week 13	Learning material; Biodiversity & Ecological Distribution of Gymnosperm. (Reproduction System of Gymnospermae) Tutorial/Mentoring; discussion, problem solving and presentation
Week 14	Learning material; Biodiversity & Ecological Distribution of Gymnosperm. Tutorial/Mentoring; discussion, problem solving and presentation
Week 15	Learning material; Refreshing all material of plant biodiversity Tutorial/Mentoring; reflection, discussion and presentation
Week 16	**Final exams (Posttest)**

Assessment tasks
Delivery mode: ALL

Task No	Product	Process	Weighting (%)	Condition
1	Pretest	Individual	0	Online
2	Written laboratory report	Group	25	Online and Offline

				submission
3	Digital argumentation	Individual	20	Online submission
4	Practical/ Laboratory skills	Group	25	Offline
5	Final exam	Individual	30	Online submission

Appendix 2

Simple Lesson Plan

<table>
<tr><td colspan="2">Semester: Second semester
Subject: Bryophyta
Topis: Moss (Bryophyta)</td></tr>
<tr><td colspan="2">Objective
At the end of the lesson, the students will be able to
1. After working on the worksheet, students are able to convey arguments to solve problems
2. After working on the worksheet, students are able to prepare problem solving in stages regarding bryophytes using CT stages</td></tr>
<tr><th>Syntax of PBL-DA</th><th>Activity</th></tr>
<tr><td>1. Problem orientation</td><td>Students pay attention to the presentation of material about bryophytes. Answering several questions asked by the lecturer:
1) How can we differentiate between the types of plants we encounter?
2) Have you ever observed moss plants?
3) Describe mosses and their role in life.</td></tr>
<tr><td>4) Student organization</td><td>Students are grouped according to regulations. Start a discussion to provide responses to apperception questions. Students also group according to regulations.
Start a discussion to provide responses to apperception questions. Students also open the material provided in the LMS, eLearning UNIPMA (eLMA).</td></tr>
<tr><td>5) Brainstorming</td><td>In groups, students pay attention to the worksheet about bryophytes presented by the lecturer. Based on the problems presented, each group looks for relevant supporting references.
Students work on worksheets with computational thinking (CT) stages for moss material.
The abstraction stage is carried out by identifying factors that influence the diversity of bryophyte.
The discussion continued by decomposing the main problem regarding the decline in bryophyte diversity (for general).</td></tr>
<tr><td>6) Data collection through investigations</td><td>The student group worked out a way to solve the problem based on the decomposition of moss plants and developed a problem-solving algorithm in the form of a flowchart.</td></tr>
<tr><td>7) Sharing information and discussion to find a solution of problem</td><td>The student group submitted a flowchart (algorithm) for solving the problem about current moss populations and environmental conditions. The evaluation stage is carried out with a presentation of the flowchart to get suggestions for improvements.</td></tr>
</table>

8)	Presenting troubleshooting results	The results of the evaluation stage are presented again to obtain strengthening of the best problem solving for issues regarding moss populations and environmental conditions.
9)	Analysing and evaluating problem solutions	The results of the worksheet are a planned as problem-solving effort to overcome the low diversity of moss populations, environmental conditions and Bryophyta diversity. Each stage in CT is completed sequentially by groups of students.

Assessment

No	Type of assessment	Assessment form
1	Diagnostic	Trigger questions during apperception
2	Assessment for learning (AfL)	The results of worksheet work according to the CT stages Presentation of arguments during presentations Submission of digital arguments (DA) in discussion forums in LMS

Reflection

1. How effective was the lecture process using the PBL-DA learning model?
2. Were the CT-based worksheets that have been prepared able to help students' understanding of the bryophyte material?
3. Have all students carried out their lectures well?
4. How did students utilize the discussion forums in the LMS?

Appendix 3

Worksheet

Worksheet - (Week 3 & 4)
Bryophyta Biodiversity and Conservation

Instruction:
1. Complete the tasks in group discussion and send it to the 'discussion forum' on the LMS provided.
2. Every argument presented in the discussion forum should be accompanied by supporting data as evidence.
3. Follow the steps in the table to complete the task.
4. To investigate the decline in Bryophyta biodiversity in a specific ecosystem and propose solutions using computational thinking (CT) skills with each step.

Case study about moss

A local forest ecosystem has experienced a significant decline in Bryophyta (moss) biodiversity over the past decade. Scientists have observed that moss populations, which once thrived in the area, are now scarce. In Indonesia, particularly in Sumatra and Borneo, deforestation for palm oil plantations and logging is leading to the loss of epiphytic mosses and liverworts. Moss has an important role in the ecosystem, such as providing habitat for microfauna which is important in the litter decomposition process and as a bioindicator plant because it is sensitive to air pollution, especially heavy metals. Several types of moss which can be indicators of air quality can be seen in the following image.

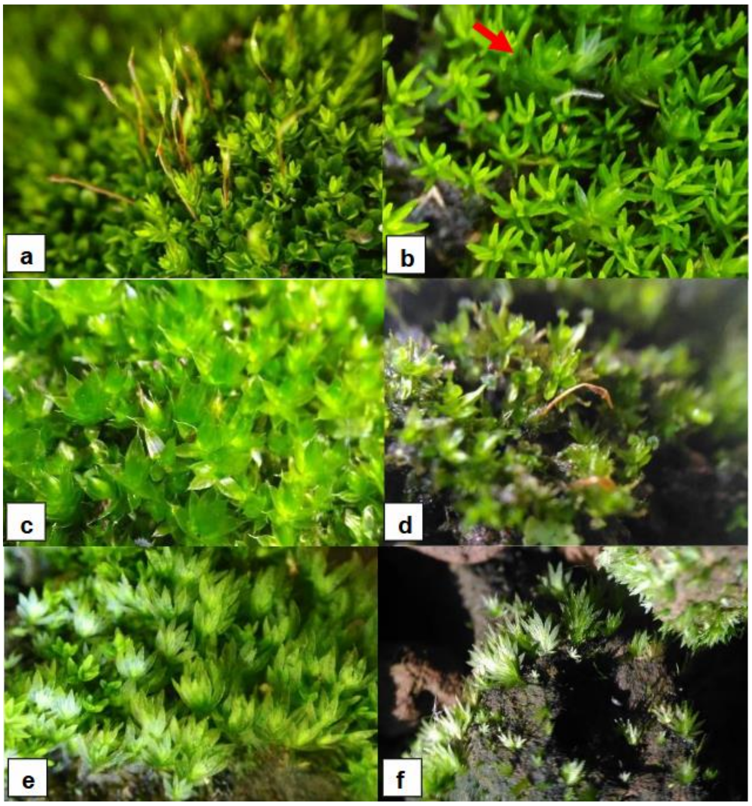

Figure 1. a. Barbulla indica, b.Gemmabryum apiculatum(panah merah), c. Bryum coronatum, d. Calymperes tenerum, e. Fissidens atroviridis,f. Fissidens biformis.abcdef
Source; Fastanti, Wulansari (2021), https://jurnalbiologi.fmipa.unila.ac.id/index.php/jbekh/article/view/194/158

These Bryophytes, which grow on trees, are critical for maintaining humidity and supporting biodiversity in tropical rainforests.

- Indonesia has lost over 25% of its forest cover since 2000.
- Epiphytic Bryophyte diversity has declined by 50% in deforested areas.

This decline is affecting the ecosystem's ability to retain water, support microorganisms, and stabilize soil.

Your task is to investigate the causes of this decline and propose actionable solutions to restore Bryophyta biodiversity.		
CT Skills	**Task/ Activity**	**Questions**
Abstraction	Identify the key factors affecting Bryophyta biodiversity in the forest ecosystem. 1. Research the environmental conditions required for moss growth (e.g., moisture, shade, soil pH). 2. List the key factors that could contribute to the decline (e.g., deforestation, pollution, climate change). 3. Ignore irrelevant details (e.g., specific moss species names unless critical).	- What are the most critical factors influencing Bryophyta biodiversity? - Why is it important to focus on these factors when addressing the problem?
Decomposition	Break down the problem into smaller, manageable parts. 1. Divide the problem into smaller components: - Environmental factors: How have changes in moisture, temperature, or soil quality affected mosses? - Human activities: What role do deforestation, pollution, or urbanization play? - Biological factors: Are there invasive species or diseases impacting moss populations? 2. Assign each component to a group or individual for further investigation.	- How does breaking down the problem help you understand it better? - Which component do you think is the most critical to address?
Algorithmic Reasoning	Develop a step-by-step plan to investigate and address the decline in Bryophyta biodiversity. 1. Create an algorithm (step-by-step plan) to solve the problem: - Collect data on current moss populations and environmental conditions. - Analyses the data to identify the primary causes of decline. - Propose solutions (e.g., reforestation, reducing pollution, creating protected areas).	- Why is it important to follow a structured plan when solving environmental problems? - How can you ensure your plan is realistic and actionable?

	- Implement and monitor the solutions. 2. Use a flowchart to visualize your plan.	
Evaluation	Evaluate the effectiveness of potential solutions for the problem. 1. Propose 2-3 solutions to restore Bryophyta biodiversity (e.g., creating moss-friendly habitats, reducing air pollution, educating the public). 2. Evaluate each solution based on: - Feasibility (cost, resources, time) - Impact (how effectively it addresses the problem) - Sustainability (long-term benefits) 3. Rank the solutions and justify your choice.	- Which solution do you think is the most effective, and give reason argumentation? - What challenges might you face when implementing these solutions?
Generalization	Apply your findings to other ecosystems facing similar biodiversity issues. 1. Research another ecosystem where Bryophyta or other non-vascular plants are declining. 2. Compare the causes and solutions to those in the forest ecosystem. 3. Write a generalization about conserving biodiversity in fragile ecosystems.	- How can the lessons learned from this case be applied to other ecosystems? - Why is it important to generalize solutions for biodiversity conservation? - Use visuals (e.g., graphs, flowcharts, images) to support your arguments.

Journal of Turkish Science Education, 2025, *22*(4), 677-702.
DOI no: 10.36681/tused.2025.034

Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

Supporting eighth-grade pupils' understanding of hydrostatic pressure with inquiry-based activities

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ABSTRACT
This study aims to facilitate and implement inquiry-based exercises in the domain of hydrostatic pressure within the subject of physics education. The design research method was used to support eighth-grade pupils at Palembang State Middle School by developing inquiry-based activities on hydrostatic pressure. Three stages–experimental preparation, classroom experiments (pilot experiments and teaching experiments, and retrospective analysis–were carried out to formulate pupil learning trajectories. Pupils were expected to form the hypothesis that the dam walls are designed to increase the thickness of deeper wall or dam. They then created and conducted an experiment using appropriate tools and materials. The data collected were graphed and the graph was used to determine whether the hypothesis had been proven true. Finally, pupils applied their understanding of hydrostatic pressure and to given problems. Findings demonstrated significant improvements in pupils' conceptual understanding, experimental skills, and problem-solving abilities. Generally, students were able to accurately describe the relationship between hydrostatic pressure and the depth and density of the liquid, as evidenced by their correct interpretation of experimental data and graphical representations. The results also can be used to implement inquiry-based activities with a broader planned learning trajectory, and as a pioneer of further research across different learning contexts.

RESEARCH ARTICLE

ARTICLE INFORMATION
Received:
31.12.2024
Accepted:
01.05.2025
Available Online:
27.11.2025

KEYWORDS:
Educational design research, hydrostatic pressure, inquiry-based activities, learning trajectory.

To cite this article: Siahaan, S. M., Ismet, I., Soeharto, S., & Patriot, E. A. (2025). Supporting eighth-grade pupils' understanding of hydrostatic pressure with inquiry-based activities. *Journal of Turkish Science Education, 22*(4), 677-702. http://doi.org/10.36681/tused.2025.034

Introduction

Hydrostatic pressure is one of the topics in junior high school physics. Learners study the concept of pressure on liquids and the factors influencing it. Many have difficulty understanding this concept (Donkor Taale, 2011; Susman et al., 2008; Loverude et al., 2003; Zhou et al., 2019). Many attempts have been made to help pupils understand this topic centred on the teacher explaining the factors that affect the pressure in liquids, including the deeper the funnel entering the water inside the breaker, the different fluids are used differs from h1 for funnel-to-breaker depth, depending on the density, pressure increasing with depth, and pressure at any depth being the same in all directions, but increasing with density.

Previous studies have shown that hydrostatic pressure and buoyancy are difficult for learners at all levels, and many have misconceptions (Çepni et al., 2010; Chen et al., 2013; Radovanović & Sliško, 2013; Saputra et al., 2019; Soeharto, 2021). These misconceptions include objects floating in water because they are lighter than water, or objects sinking in water because they are heavier than water, the shape of the container and the amount of liquid affecting hydrostatic pressure, and fluid pressure only applying downwards (Pratiwi, 2013; Ramirez, et al., 2021;Saputra et al., 2019). Misconceptions occur because pupils obtain the wrong initial concept from the community, misunderstanding the teacher's explanation, and not being trained to find the concept of pressure directly and actively (A. C. & S. S., Edie, 2015; Syaiful, 2017; Wen et al., 2020).

Experiments or direct observations have been used to help pupils gain a deeper understanding of the concept of hydrostatic pressure and reduce their misconceptions (Keselman, 2003; Wenning, C.J., 2011; Jauhariyah et al., 2018). Using an experiment or mini project can enhance understanding in learning science (Hakim et al., 2016). Inquiry-based learning has been proven to improve understanding in science learning (Antonio & Prudente, 2021). Inquiry-based learning is a learning strategy in which learners follow inquiry methods and practices similar to those of professional scientists to construct knowledge (Shanmugavelu et al., 2020). This can be defined as the process of constructing some hypotheses, and testing them by conducting experiments and making observations (Bell et al., 2010). In the literature, the investigative process generally begins with asking questions and generating hypotheses, followed by an investigative process that ends with conclusions and evaluations (Hmelo-Silver et al., 2007; Murphy et al., 2018; Said et al., 2021). Making predictions is reformulating the hypothesised relationships between variables in such a way that it becomes clear how changes in the independent variable affect the dependent variable, for example using 'if- then' statements (De Jong & Van Joolingen, 1998). In this study, it is hoped that there will be an inquiry phase, making hypotheses, making experimental designs, conducting experiments, analysing data and explaining the results as an indication of following the inquiry approach.

Writing clear learning objectives is essential for effective teaching (Marzano, R.J., 1998). The success of a science lesson is inseparable from a teacher’s ability to plan lessons before teaching (Ramadhanti. P., 2015). This is consistent with what Hmelo-silver et al. started with Rutten et al., (2016) that the importance of this learning objective is to prevent a shift of inquiry learning away from the teaching discipline as a body of knowledge. Both the learning process and the content require adequate consideration. Combining an inquiry approach with concrete goals related to learning content implies that the environment in which learning occurs resembles the context in which it is likely to be used. One of the main obstacles to applying the inquiry learning model is that teachers need to adapt their role appropriately, and that the learning objectives associated with Bloom's taxonomy level require teachers to take on a less directive and more supportive role (Urhahne et al., 2010; Pietarinen et al., 2021). In this study, we used the learning trajectory to help school learners learn about liquid pressure using an inquiry-based learning model. The purpose of this research was to produce a learning trajectory that can assist pupils in learning about the pressure of liquids using an inquiry-based learning model.

Problems in Understanding Hydrostatic Pressure Concepts in Science Education

The majority of junior high school pupils struggle with comprehending abstract scientific concepts and solving related problems. Hydrostatic pressure as physics concept is a particularly challenging topic for pupils to grasp. To effectively learn the concept of hydrostatic pressure, they require assistance in constructing the foundational knowledge that underpins the idea (Berek et al., 2016). But many still have alternative conceptions or misconceptions (Pratiwi et al., 2019; Maknun, 2020).

Misconceptions can be owned by students when they gain knowledge about an event based on that knowledge; they formulate a naïve theory about the mechanisms of natural processes (McDermott, 1984). Some of the difficulties in understanding physics concepts are caused by several things, including difficulty interpreting mathematical equations and tending to use theories in explaining physical phenomena tend to use naïve theories in explaining physical phenomena (Loverude et al., 2003; Goszewski et al., 2013).

The understanding obtained is limited to the pressure that exists in a liquid is the same without considering the density of the liquid. The application of the hydrostatic pressure equation related to atmospheric pressure is still poorly understood; learners experience problems in the concepts of vacuum space and having air. Most assume that hydrostatic pressure is inversely proportional to the area of the fluid container; therefore, the larger the container area, the smaller the hydrostatic pressure. In many contexts they equate pressure with density (Tuada et al., 2023).

Inquiry-based Activities in Physics Learning

A learning model that is based on the nature of physics and provides opportunities for students to conduct investigations/experiments to form knowledge/physics concepts is needed. A guided inquiry learning model is one of the learning models that emphasises the science process skills, thinking skills, and scientific inquiry. The syntax of inquiry- based activities learning, according to Tekin and Muştu (2021), is orientation, formulation of problems, formulation of hypotheses, collecting data, testing hypotheses, and formulating conclusions. The advantage of the model is that the teacher does not just let go of the activities carried out by the pupils, so that pupils who think slowly can still follow the activities being carried out. Learning using inquiry-based activities can build learners into individuals who can access information and understand where the information is obtained. The worksheet used an inquiry- based learning model which is one of the factors that can achieve the expected learning goals.

The inquiry learning model can help students find and use various types of information and ideas to increase their knowledge of a problem or issue (Santosa, 2014; Frågåt et al., 2021). In other words, the inquiry learning model is a learning model involves learners fully in the learning process, can investigate existing problems, and find their own solutions to these problems. The advantages of implementing the inquiry-based learning model are as follows: (1) Can form and develop "self-concept" in students, so that they can better understand basic concepts and ideas. (2) Helps in using memory and transferring to new learning process situations. (3) Encourage learners to think and work on their own initiative, and be objective, honest, and open. (4) Encourage learners to think intuitively and formulate their own hypotheses. (5) Giving intrinsic satisfaction. The learning process was stimulating. (6) Can develop individual talents or skills. (7) Gives learners freedom to learn on their own. (8) Learners can avoid traditional learning methods (9) Can give learners enough time. Meanwhile, the disadvantages of applying the inquiry-based learning model are as follows: (1) It is difficult to control student activities and success. (2) It is difficult to plan learning because it collides with students' learning habits. (3) Sometimes, in implementing it, it takes a long time to make it difficult for teachers to adjust it to the predetermined time. (4) As long as the criteria for learning success are determined by students' ability to master the subject matter, this strategy is likely difficult to implement.

Relevant Studies in Indonesia

Several relevant studies have been conducted by Verawahyuni (2022), who reported on teacher performance in implementing laboratory-based guided inquiry with the main goal of reducing the number of misconceptions about static fluid material. Data on implementation, learning quality, and pupil activities were collected using observation and documentation techniques. The number of MK ? students was determined on the basis of the results of the conception test on static fluid material before and after the action. CAR ? was conducted at the junior high school level in Samarinda with the source of teacher observations, the learning process in class, and eighth grade pupils. The data were analysed descriptively. Rahmawati et al. (2018) know that students' concept understanding is taught by guided inquiry-based learning and conventional learning. The results of the study showed that the average number of classes that used guided inquiry-based learning was 78.44, while the number of classes that used conventional learning was 65.16, Based on this data, the guided inquiry model is an effective learning model used to improve pupils' concept understanding. Wardani et al. (2017) investigated the effect of inquiry-based laboratory activity by comparing the inquiry and non-inquiry laboratory activity in terms of conceptual understanding among junior high school pupils in the topic of lights and optics. The effectiveness of this method was also investigated for both male and female students. The method used in this research was a quasi-experiment that used two classes, where one class was randomly selected as the experimental class and the other as the control class. Dewi et al. (2019) had research result that student repeatedly have difficulties in understanding complex physics concepts, such as fluid dynamic concept. This occurred because the students' conceptual understanding was low, indicating a poor student mental model.

Research Questions and Study Significance

The main purpose of this study is to facilitate and implement inquiry-based exercises in the domain of hydrostatic pressure within the subject of physics education To achieve this purpose, we formulated two research questions as below:

1. How does the inquiry-based learning trajectory support eighth-grade pupils in understanding hydrostatic pressure and addressing common misconceptions?
2. What are the challenges and improvements observed in pupils' conceptual understanding, experimental skills, and problem-solving abilities through the implementation of inquiry-based activities?

The significance of this study lies in its contribution to enhancing pupils' conceptual understanding of hydrostatic pressure through an inquiry-based learning approach. By designing and implementing a structured learning trajectory, this study provides a framework for fostering scientific reasoning, critical thinking, and problem-solving skills among eighth-grade students The findings offer valuable insights into how inquiry-based activities can effectively address common misconceptions and improve pupils' ability to relate theoretical concepts to real-world applications, such as dam construction. Additionally, this study serves as a reference for educators in developing more engaging and student-centred instructional strategies, ultimately supporting the advancement of physics education. Moreover, the research contributes to the broader field of science education by demonstrating the impact of inquiry-based learning on learners' experimental skills and conceptual development, offering potential for adaptation across different learning contexts.

Methods

Research Design

This study is qualitative research that uses educational design research. Design research is a systematic and iterative methodology commonly used in education and other fields to develop and improve educational interventions, instructional materials, and learning environments. There were three stages: experimental preparation, classroom experiments (pilot experiments and teaching experiments), and retrospective analysis.Five activities were observed in performing learning trajectories using an inquiry-based learning model: understanding and constructing the concept, making the experimental design, conducting the experiment, making graphs, and solving related problems.

Participants

The participants in this study were purposefully selected to evaluate the impact of the educational intervention on a diverse cohort of eighth-grade pupils from a selected school in Palembang. Initially, the study involved five groups comprising a total of 30 students. Following the completion of the learning process, a rigorous selection process was undertaken to identify participants for data analysis. This process ensured balanced representation across gender and academic backgrounds, resulting in the selection of six pupils for the study. Prior to their participation, informed consent was obtained, and strict adherence to ethical standards was maintained, including the protection of participant privacy and data confidentiality.

Instrument

The developed supports the inquiry-based activities developed in this study and the instruments used to evaluate student activity sheets (SAS), interview sheets, field notes, Hypothetical Learning Trajectory (HLT), and digital books. The SAS are structured instructional materials designed to guide students through the inquiry-based learning process. These sheets serve as a framework for engaging learners in various learning activities, including hypothesizing, designing experiments, conducting investigations, collecting and analysing data, and drawing conclusions. The SAS are developed to facilitate step-by-step exploration of hydrostatic pressure concepts, helping learners actively construct knowledge through hands-on experiments and problem-solving tasks. Content validity of all instruments was assessed by two physics education lecturers to ensure the credibility, accuracy and quality of the content. This validation process aimed to confirm that the instruments effectively measure the intended constructs and align with the objectives of the study.

Data Analysis

In a design study employing a qualitative research approach, data analysis was centred on qualitative data collected throughout the research process. The data analysis involved a systematic examination focusing on open-ended survey responses and observational notes. The interpretation of qualitative data was constructed based on the activities in the Results and Discussion section. This analysis is carried out in alignment with the research questions or objectives, allowing for the exploration of complex, context-specific issues and providing rich, nuanced insights that inform the design and refinement of educational interventions or innovations in response to research findings. The iterative process in learning activities analysis supports ongoing reflection, refinement, and in-depth exploration of participants' experiences and perspectives, contributing to the enhancement of educational practices and the body of knowledge in the field.

Procedure and Data Collection

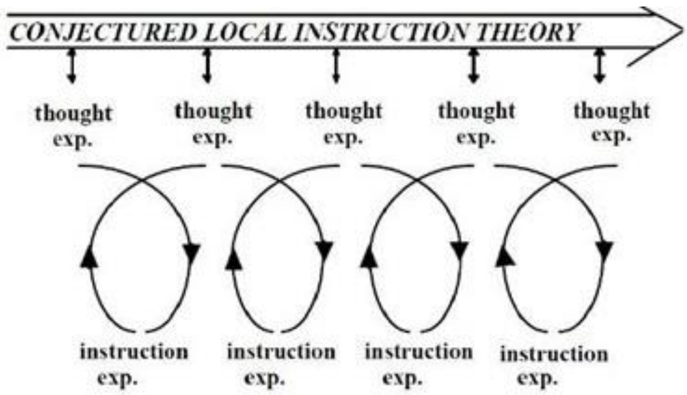
There were three stages: experimental preparation, classroom experiments (pilot experiments and teaching experiments), and retrospective analysis. In experimental preparation, researchers conducted problem identification, literature review, and design of the educational intervention and evaluation. Inquiry-based activities were developed in this study, and the instruments used to evaluate student activity sheets (SAS), interview sheets, field notes, Hypothetical Learning Trajectory (HLT), and digital books to collect initial qualitative data. In classroom experiments, teaching experiments were carried out. According to Gravemeijer (2004), the purpose of a teaching experiment is to test and raise suspicions about the Local Instructional Theory (LIT) developed at an early stage and to develop an understanding of how it works.the sequence of activities that were conducted in the early stages was carried out in the classroom in two cycles. The first cycle was conducted as a pilot study.

A pilot was conducted mainly to adjust the content and sequence of activities and improve them to obtain a better design for the next cycle, namely, the teaching experiment. The second cycle was carried out as the actual teaching process in which the sequence of activities was carried out in the classroom. The science content in the teaching trial stage in these two cycles remained the same, and in the second cycle, a revision was made from the first cycle. During the teaching experiment, the conjecture (guessing) of students' strategies and thinking can be developed for further learning in accordance with the characteristics of interventionist design research.

Retrospective analysis entailed gathering, scrutinising, and pondering data acquired from classroom experiments. Scholars have scrutinized these data to gauge the efficacy and influence of educational interventions within authentic learning environments. By meticulously assessing the data, they pinpointed recurring themes, tendencies, and valuable insights that shed light on the effectiveness of the intervention and potential areas for enhancement. Additionally, this phase encourages self-reflection within the research process, aiding researchers in making informed choices for future rounds of research and simplifying the process of documenting and disseminating discoveries to the community.

Figure 1

Argumentation skills score of PSTs



*Note.** (Gravemeijer, K. et al., 2006)

Findings

This research produced a learning trajectory on learning material on pressure on liquids in eighth-grade students by using the inquiry learning model and a scientific approach. In this chapter, the researcher describes all data obtained from each stage of the research. Three stages were used in this study: (1) preliminary design, (2) teaching experiment, and (3) retrospective analysis. The preliminary design is the first stage in this research, which is the research preparation stage (preparing for the experiment). The purpose of this initial design was to design an initial hydrostatic pressure HLT material for an eighth-grade state middle school even semester, which was then tested in the second stage of the teaching experiment to answer first research question in this study. In the teaching experiment, there were two stages: the teaching experiment (cycle 1) and the teaching experiment (cycle 2). Teaching experiment design was used to deliver teaching material and to observe students' conceptual understanding, experimental skills, and problem-solving abilities. After the experimental teaching phase was completed, the researcher conducted a retrospective analysis of what had been obtained in the previous stages of the discussion section.

Activities in Preliminary Design in Understanding Hydrostatic Pressure Using the Inquiry-Based Learning Trajectory

Activity 1. Understand and Construct the Concept of Hydrostatic Pressure

Activity 1 was designed to construct the concept of hydrostatic pressure, train pupils' reasoning, and visualise hydrostatic pressure. The following describes the initial knowledge of pupils in this first activity to understand the concept of hydrostatic pressure and the characteristics of the walls of the dam building. The goal is to understand and construct the concept of hydrostatic pressure using dam-wall drawings. We formulate a hypothesis based on the problem and initial observations. In the initial description of learning, the teacher first conditioned the pupils to sit in the groups. Next, the teacher asked them to perform Activity 1 and look for answers as to why the dam walls were getting lower and thicker (Figure 2). The teacher then conveys the learning objectives and distributes student activity sheets (SAS) 1.

Figure 2

(a) Water dam (b) Bottle filled with water

(a) (b)

The teacher guided the students to observe and answer the problems in SAS 1. The activities in SAS 1 are as follows: (1a) Making a hypothesis, is there a relationship between hydrostatic pressure and the design of a dam wall? To answer this question, students must first answer the following questions: (1b) What factors affect the amount of hydrostatic pressure? What is the value of hydrostatic pressure at each point from the surface to the bottom of the dam? Is it smaller or bigger? (1c), see Figure 3, and describe the results of the observations. Then, (1d) students were asked to formulate hypotheses based on the problems and observations that had been made. When completing SAS 1, students were allowed to discuss with their group members. The teacher guides students in discussing the conjecture of students' thinking in Activity 1, which is presented in the following table.

Table 1

Pupil thoughts in activity 1

Learning activity	Observing the dam wall drawings Make a hypothesis
	Allegations of students' thoughts on the activities carried out
	Pupils visualise what they think the thickness of the dam wall is.
	Why are dam walls getting lower and thicker? They answered this problem in their own way and ability
	Pupils are asked to make a hypothesis, whether there is a relationship between hydrostatic pressure and the design of the dam wall
	What factors affect the amount of hydrostatic pressure?

	What is the value of hydrostatic pressure at each point from the surface to the bottom of the dam? Is it smaller or bigger? Why are dam walls getting lower and thicker? They answered this problem in their own way and ability

Another stage of this activity is reflection. The teacher guides students to formulate hypotheses according to the achievable goals. After students follow the learning process, they can formulate hypotheses related to hydrostatic pressure, namely hydrostatic pressure which depends on the depth of the liquid. The deeper the liquid, the greater the hydrostatic pressure. This was formulated by students from the observations in Figure 2(b), which show different water jet distances. The deeper the hole in the bottle, the greater the water emissions. This indicates that the hydrostatic pressure increased.

Activity 2. Make an Experimental Design from the Available Tools and Materials

Activity 2 was designed to give pupils the opportunity to design experiments using the tools and materials provided. Starting with the lesson, the teacher conditioned the students to sit in. Next, the teacher asks students to carry out Activity 2 and design an experiment that will be carried out with the tools and materials available. Then, the teacher presents the learning objectives and distributes SAS 2. The teacher asks students to write their names on the SAS they have been given, and then asks students to read the SAS given first together and discuss what needs to be done. The teacher guided students in carrying out experimental design activities using the tools and materials available. When completing SAS 2, students were allowed to discuss with their group members. The teacher guided the students in discussions.

Activity 3. Conduct an Experiment Based on the Experimental Design That Has Been Made

At the beginning of the learning process, the teacher first conditioned the students so that they could do experiments. This experiment required cooperation between the students in the groups. There were students holding bottles, students who opened the water faucet and bottle caps, students who measured the spray of water, and students who filled the data in the table. The teacher then asked the students to perform the experiment outside the classroom.

Activity 4. Drawing Graphs

Students created graphs that showed the relationship between the variables measured in the experiment and analysed the experimental results whether they were in accordance with the proposed hypothesis. The students' initial knowledge of this fourth activity is their ability to make and read graphs. Create and read graphs of the experimental results: Starting with the lesson, the teacher first conditioned the students to sit in groups. The teacher then asked the students to draw a graph from the experimental data outside the class.

Activity 5. Solving Some Problems Related to Hydrostatic Pressure

The teacher instructed pupils to analyse the conclusions from the experimental data graphs carried out with the hypotheses that have been made before. Then, students solved several problems related to hydrostatic pressure, including by looking at the experimental results obtained, whether they were in accordance with the hypothesis previously proposed. From the graphs obtained, students can find a relationship with the hypothesis at the beginning of Activity 1. Students found reasons for the unequal thickness of the dam walls. At the bottom of the dam, the dam wall must be thicker so that it does not break. In other words, the dam can withstand water pressure. The teacher found that from the results of the experiments conducted, students easily found answers to the problem of why dam walls have different thicknesses. Students are looking for thicker dam walls down to the bottom of the dam to be able to withstand water pressure.

Experiment Design to observe students’ conceptual understanding, experimental skills, and problem-solving abilities.

1. Pilot Experiment (Cycle 1)

Cycle 1 of the research experiment was to try a hydrostatic pressure learning design with HLT 1 on six students of state middle school in Palembang with different abilities, namely, medium high and low. The student names and abilities are MFAR (high), AF (average), AJA (average), and MZA (low). The selection of the six students was based on discussions with a science teacher teaching at school. In cycle 1, the researcher acts as a model teacher; besides that, the researcher also observes and analyses things that happen when a series of activities are carried out. The pilot experiment consisted of five parts.

Activity 1: Understand and Construct the Concept of Hydrostatic Pressure Using Images of Dams and Formulate Hypotheses Based on Problems and Preliminary Observations That Have Been Made

At this meeting, the teacher opened the lesson by asking students about their readiness to learn, then explained the learning objectives, and made perceptions about the context to be taught. The teacher then asked the students to sit with their group mates. Students were given student activity sheets (SAS 1), after which they were asked to discuss completing the SAS 1. Some of the initial questions from the teacher "Is there a relationship between hydrostatic pressure and the design of a dam wall?". “Yes, there is,” said the student. "What factors affect the amount of hydrostatic pressure?" Some students answered "Weight and depth of water". bigger? "Asked the teacher. "The bigger it is, because the liquid that drops will be more and more", answered the student.

Results. of student observations Figure 3, following excerpts of student notes: "The water in the bottle gushes out through 2 holes in the bottle. But the water under the hole will not come out because the depth of the water does not allow water to escape through the two holes." A summary note of the student's observations is that water at a height below the hole will not gush out because the water level does not allow it. The following is the formulation of the hypothesis based on the problems and observations made.

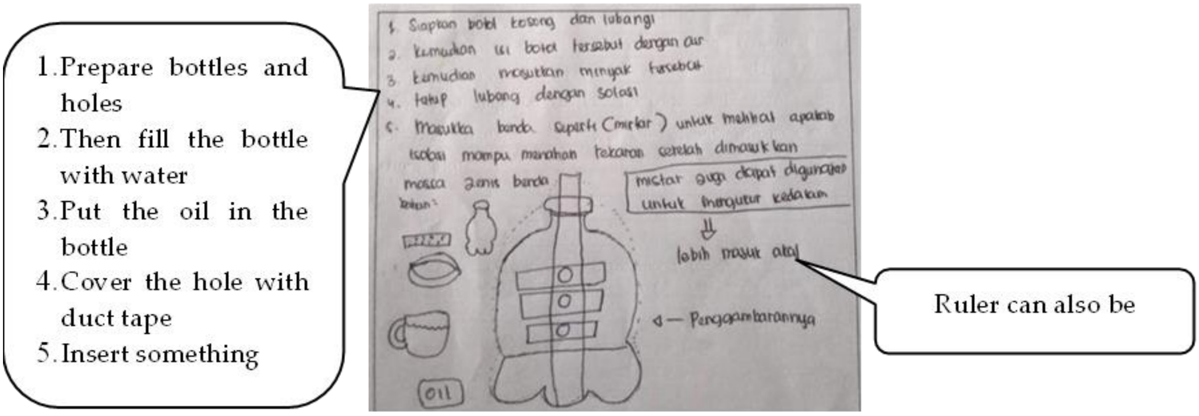
Hypothesis 1: The pressure on the dam is getting higher.
Therefore, an increasing water volume inside the dam wall will become thicker.
Hypothesis 2: Water that is below the level of the hole will not come out.

Activity 2: Make a Trial Design of Available Tools and Materials

Activity 2 aimed to enable students to design experiments to test the hypotheses. In SAS 2, the following tools and materials are provided: water, cooking oil, empty bottle (1000 ml), ruler, and screen. The students were then asked to draw an experimental design with the tools and materials. The following is a picture of students’ experimental design.

Figure 3

Image of the experimental design that will be carried out by students

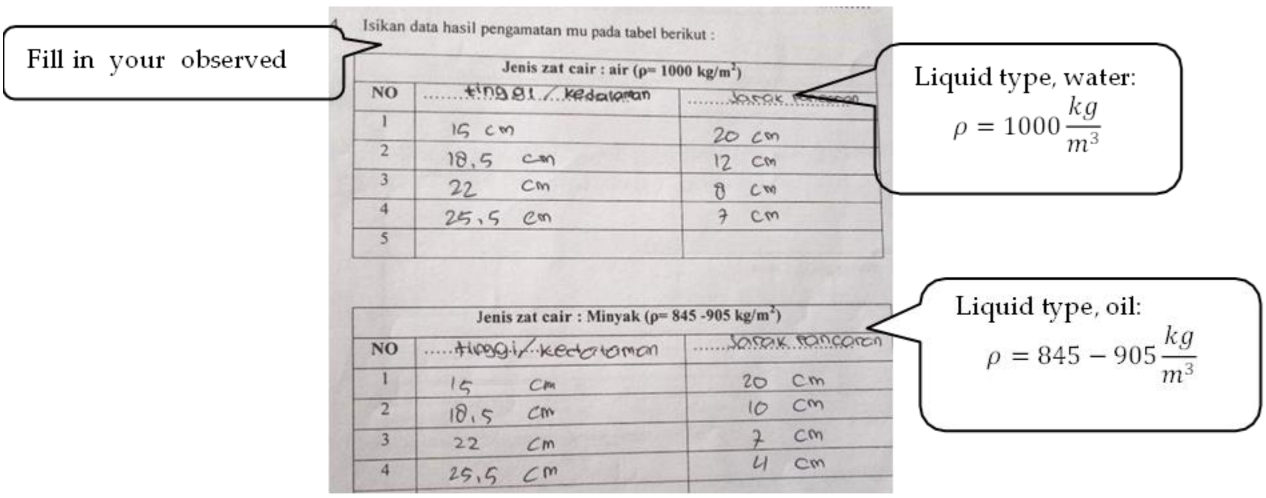


Activity 3: Conduct an Experiment Based on the Experimental Design that Has Been Made, Collect Observation Data, and Fill in the Observation Table

On the student activity sheet (SAS) 3, students were given two tables. The first table for liquid types is water, whereas the second table for liquid types is cooking oil. There are three columns in each table. The first column number and the second and third columns are the observed variables. Variable names are left blank, with the hope that students will write them according to the previous experimental design. From Figure 6, it can be seen that the second column variable is the height or depth of the hole, whereas the third column is the variable distance of the water jet or oil jet distance. The table shows the four different bottle-hole depths. Students find data on the distance of the water spray and the distance of the oil jet through the hole in the bottle that was made. The data are presented in the table shown in the following figure.

Figure 4

Water and oil experiment data obtained by students

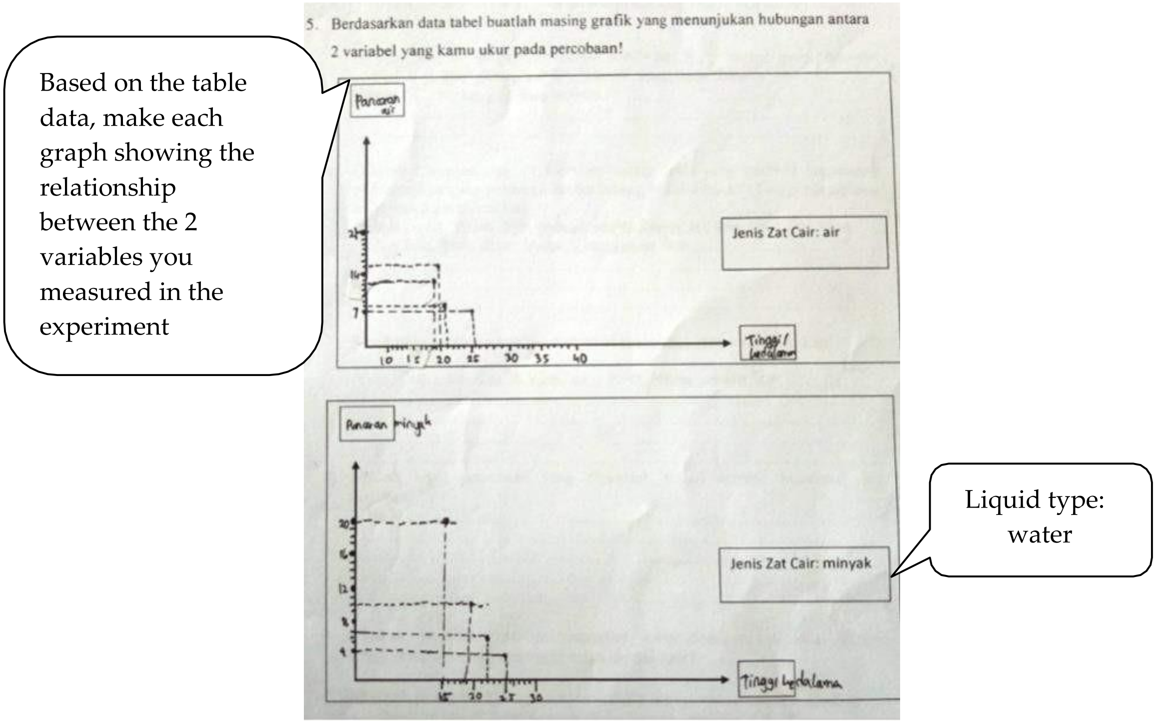


Activity 4: Create a Graph Showing the Relationship Between the Variables Measured in the Experiment and Analyze the Experimental Results to Determine whether They Support the Proposed Hypothesis

In Activity 4, students are expected to be able to work on SAS 4, which aims to move the table data into graphs. In SAS 4, there are two diagrams consisting of an x-axis and a y-axis for two different types of fluid data, namely, water and oil. In the diagram, students were expected to write variable names for the x- and y-axes. The following is a graphic image of the students' work.

Figure 4

Graph of the results of experiments with water and oil obtained by students



Activity 5: Solving Several Problems Related to Hydrostatic Pressure, Including Looking at the Experimental Results to See whether They Are in accordance with the Hypothesis Previously Proposed

Activity 5 aims to train students to analyze various problems at the beginning of learning, including connecting experimental results with hypotheses that have been made before. The following are the results of the analysis and students' answers to these questions. "Why is the jet of fluid so different for different orifices". The student answered, "Because each hole can release water with a different pressure." How much does the area of the liquid jet change when the depth changes? The teacher asked. Some students answered "On the surface of the liquid, the pressure is small, and the lower the pressure, the greater the pressure. Therefore, there is a difference in water emissions." "As it is known that oil and water have different densities. What is the difference in the beam distance when the bottle hole is opened? The student answered, "which is farthest from the surface because the pressure is small and closest to the base because the pressure is large." Furthermore, the teacher's question, 'Write conclusions based on the results of the experiment you did!'. Students answered, "In conclusion, the more water you get, the greater the pressure." "Are the experimental results obtained in accordance with the proposed hypothesis?", asked the teacher. Students answer "According."

"Based on the answers to the problems presented at the beginning using the conclusions that have been obtained. Can the experiment you design answer this, and why are dam walls designed to become thicker? Student has answered, "Because the lower you go, the greater the pressure, so to withstand the water pressure, the walls are made thicker."

The purpose of learning Activity 5 is for students to be able to solve several problems related to hydrostatic pressure, including seeing whether the experimental results obtained are in accordance with the hypothesis previously proposed. However, from the students' answers to question 6c, it appears that they cannot see the relationship between density and hydrostatic pressure. Students could only see the relationship between depth and hydrostatic pressure. Interestingly, when connected with equations (1) and (3) above, which were formulated by students, it can be concluded that students were not able to relate the weight of objects to the density of objects.

2. Experimental Learning (Cycle 2)

After repairing the HLT in the experimental pilot, a teaching experiment was conducted (cycle 2). The researcher acted as the model teacher. Cycle 2 was held in eighth grade with 32 students. For the implementation of learning, students were divided into seven groups. The four groups consisted of five students, and the other three groups consisted of four students. The division of fixed groups is based on a combination of high-, medium-, and low-ability groups. At this experimental teaching stage, there were no observers, with the hope that observations would be made by observing the learning videos.

a) Activity 1: Understanding and Constructing the Concept of Hydrostatic Pressure Using Pictures of Dams and Formulating Hypotheses based on the Problems and Initial Observations that Have Been Made

At the first meeting, the teacher opened the lesson by asking the students about their readiness for learning. Next, the teacher conveys the learning objectives and creates perceptions of the context to be used. The teacher then asked the students to sit with their group friends, each consisting of four or five people. Group 1 is DCS, GRT, MAZ, NK, CMEP. Group 2, namely MRF, MFAR, MZ, and RK. Group 3, namely MRM, AK, MRK and AF. Group 4 is FAW, NRF, HPK, and HA. Group 5 is AH, ARF, AJA, AH and MRF. Group 6, namely TMP, NFA, FAT, MAF and MDA. Group 7, namely ANP, GAM, NRP, NR and TNA.

In Activity 1, the activities aimed to train students to formulate the hypotheses of a problem. The formulation of this hypothesis is in accordance with the steps in the inquiry learning model and the scientific approach. What was interesting about the students' answers to the initial questions was that the students had guessed correctly that hydrostatic pressure depended on the liquid, and when asked about factors other than water depth, they mentioned the density of the liquid. Student answers in experimental learning were different from student answers during cycle 1 (piloting). During the trial, according to the students, another factor besides depth is the weight of the liquid (i.e., the product of mass and gravity). If formulated mathematically, the student's answer can be formulated as.

$$P_h \propto \rho . h \qquad (1)$$

This shows that hydrostatic pressure is proportional to the density and depth of the liquid. This formulation is better than the formula in Cycle 1 (piloting).

b) Activity 2: Create an Experimental Design using Available Tools and Materials

Activity 2 has the goal of allowing students to design experiments to test the hypotheses that have been made. In SAS 2, the following tools and materials are provided: water, cooking oil, an empty bottle (1000 ml), a ruler, and tape. The students were then asked to draw an experimental design with the tools and materials. The following is a picture of the students' experimental design. Students wrote that the distance between the bottle holes was the same. However, there are no instructions on how to measure the depth of the bottle hole, whether measured from the bottom or surface of the water. In addition, there are no instructions on how to punch holes into bottles. Could the big watering hole be any different? Not explained. In addition, the observation table form was not required. Cooking oil was not used during the experimental stage. Experimental steps: 1) Prepare tools and media materials; 2) Drill the bottle first with four holes; 3) Ensure that the distance between the holes is sparse; 4) Cover the holes withDuct tape; 5) Put water in the bottle; 6) Open the bottle holes one by one; and 7) Measure the distance of the water jet using a ruler.

c) *Activity 3 Conducted an Experiment Based on Experimental Design, Collected Observational Data, and Filled It into the Observation Table*

Students were given two tables on a Student Activity Sheet (SAS) 3. The first table for liquid types is water, whereas the second table for liquid types is cooking oil. There are three columns in each table. The first, second, and third columns are the observed variables. Variable names are left blank, with the hope that students will write them according to the previous experimental design. Students find data on the distance of the water spray and the distance of the oil jet through the hole in the bottle that was made. However, the students did not conduct any experiments using cooking oil.

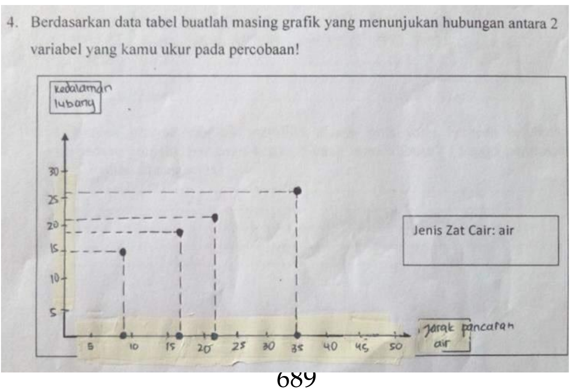
In Activity 3, students were expected to find ways to measure and collect data correctly. Students were expected to work conscientiously and carefully. In addition, students are expected to work well with all group members. Students must understand the variables to be measured and observed. Students must understand how to measure them to avoid errors from occurring. If students do not understand or are still unsure, they should ask the teacher how to measure it. As shown in Figure 4.10, there was a student error in measuring the depth of the bottle hole. The deepest hole was located at the farthest distance. In fact, in the data obtained by students, the farthest beam distance is at the shortest hole, or the shortest beam distance is at the farthest hole. This is against the truth. This is because students measured the depth of the bottle hole from the bottom of the water, not from the surface of the water.

d) *Activity 4: Make a Graph Showing the Relationship Between the Variables Measured in the Experiment and Analyze the Experimental Results, whether They Are in accordance with the Proposed Hypothesis*

In Activity 4, students are expected to be able to work on SAS 4, which aims to move the table data into graphs. In SAS 4, there are two diagrams consisting of an x-axis and a y-axis for two different types of fluid data, namely, water and oil. In the diagram, students were expected to write variable names for the x- and y-axes. The following is a graphic image of the students' work.

Figure 5

Experimental graph obtained by students



The purpose of learning in Activity 4 was for students to be able to make and read graphs from the results of the experiments. In Figure 6, it appears that students determined the variable depth of the hole on the y-axis and the variable distance of the liquid jet on the x-axis. Students seemed to be trying to make a fixed scale on the x- and y-axes. Students seemed to understand how to read graphs. The students read the chart as follows: the deeper the hole in the bottle filled with liquid, the farther the water jets. This is in accordance with the experimental observations.

e) Activity 5: Resolving Several Problems Related to Hydrostatic Pressure, Including Looking at the Experimental Results and whether They Are in accordance with the Hypothesis Previously Proposed

Activity 5 aims for students to analyse problems at the beginning of learning, including connecting experimental results with the hypotheses made. The following are the results of the analysis and students' answers to these questions. "Why are the jets of fluid so different for different orifices?". The student answered, "Because of the difference in the depth of each hole." "How much does the level of fluid jets change as the depth changes?". The student answered, "If the depth of the water increases, the length of the jet also increases." The teacher asked,' As you know, oil and water have different densities. What is the difference in the beam distance when the bottle hole is opened? Write a conclusion based on the results of the experiment you did!". Students answered, "The deeper the water, the farther the water and the greater the hydrostatic pressure." "Are the experimental results obtained in accordance with the proposed hypothesis?". Students answered, "Yes, appropriate". The teacher asked again, "Explain the answers to the problems presented at the beginning using the conclusions that were obtained. Can the experiment you design answer this, and why are dam walls designed to become thicker? "Yes, because the deeper the hydrostatic pressure, the greater," said the student.

Figure 5a

Answered students' numbers 6 to 8

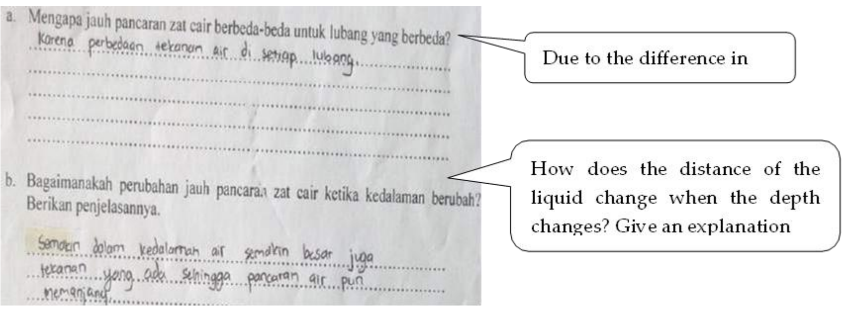
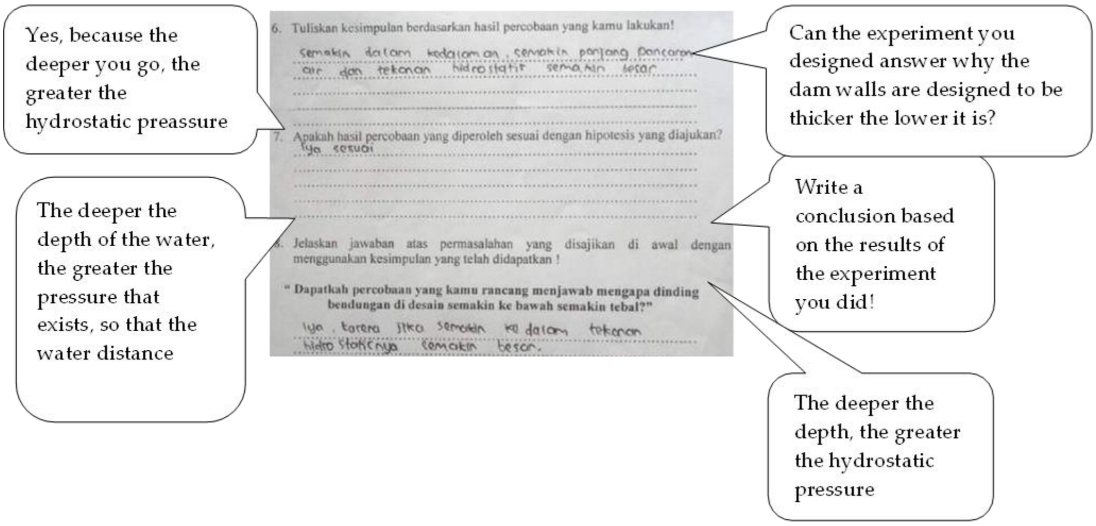


Figure 5b

Answered students' numbers 6 to 8



Discussion

Based on the results of the research and retrospective analysis that have been done, the problem formulation in this study will be answered. The primary focus of this research is to investigate the learning trajectory of middle school students in Palembang using the Hypothetical Learning Trajectory (HLT) framework. The learning trajectory is designed to explore contextual factors that support students' conceptual understanding and engagement with hydrostatic pressure concepts. The causes of student learning difficulties can come from the students themselves or from outside the students, for example the way the subject matter is presented, or the learning atmosphere is carried out (Kempa, R.F., 1991).

At the initial design stage, researchers designed student learning trajectories to understand hydrostatic pressure materials through five activities. The five activities are : (1) understanding and constructing the concept of hydrostatic pressure using pictures of dams, and formulating hypotheses based on the problems and initial observations that have been made; (2) making a trial design of available tools and materials; (3) conducting experiments based on the experimental design that has been made, then collecting observational data and filling it into the observation table; (4) making a graph showing the relationship between the variables measured in the experiment and analyzing and concluding the results of the experiment; and (5) solving several problems related to hydrostatic pressure, among others, to see whether the experimental results are in accordance with the previously proposed hypothesis. In this stage, we try to train and observe student conceptual understanding.

In the experimental pilot stage, students will be engaged to the learning process and to develop their skills such as making hypothesis, understanding the graph and data, seeking information and conducting investigation. the students experienced errors in measuring the depth of bottle holes. In addition, students experience difficulties reading and understanding graphs. Most students' answers were in accordance with the expectations of the researchers. Another difficulty experienced by the students was reading and understanding the graphs in SAS 4. However, students could describe these graphs. The difficulty is observed when the experimental data depicted in the graph differ from the facts. Supposedly, if students can understand the graph well, they can realize that there has been an error in measuring the depth of the bottle hole (Berhanu and Sheferaw 2020). At the teaching experiment stage, the learning process was carried out after the researcher revised the HLT that had been carried out in the experimental pilot. Learning during the teaching experiment went well according to the HLT that had been designed. It is just that when working on SAS 3, it takes quite a long time, namely, conducting experiments based on experimental designs made to collect data. This was because the experiment had to be conducted outside the classroom. In addition, there are students who are willing to get their pants wet as long as experimental data can be obtained. Because it was done outside the class by all groups, the situation became rowdy and a little disturbing to the other classes who were studying.

In this study, hydrostatic pressure learning was conducted using inquiry learning models and scientific approaches. An investigation refers to conducting a research. Inquiry strategy refers to a series of learning activities that maximally involve all students' abilities to seek and investigate systematically, critically, logically, and analytically, so that they can formulate their own findings with confidence (Kim et al., 2021).

The inquiry learning model used in this study requires students to be more active in asking questions, seeking information, and conducting investigations to find out for themselves a concept in which the teacher guides students in carrying out activities by giving initial questions and directing them to a discussion activity. Inquiry provides students with a real and active learning experience. Students learn to become scientists where they are given the opportunity to investigate and find their own answers (Wenning, C.J., 2011). Students were also can be supported using feedback from teachers during the learning process (Ole & Gallos, 2023).

However, it seems that it is still difficult for eighth-grade students of state middle school to apply this model purely and purely. The teacher's help is still needed to correct student misconceptions, such as an incorrect understanding of how to measure the depth of the bottle hole in this learning activity. After implementing the HLT designed with the inquiry learning model and scientific approach, it can be concluded that this research can produce a learning trajectory that can help students understand the concept of hydrostatic pressure from the informal to the formal stage.

Each activity within the design research framework is strategically structured to foster students' skill development. To evaluate this progression, we have elaborated on the assessment methods employed throughout the study. These assessments include Student Activity Sheets (SAS), which systematically document students' ability to formulate hypotheses, design experiments, and analyze data; observational field notes, which capture students' engagement, problem-solving strategies, and collaborative discussions; and graph interpretation tasks, which assess their ability to derive meaningful insights from experimental results. Furthermore, we have emphasized the observed progression in students' skills from the pilot experiment (Cycle 1) to the teaching experiment (Cycle 2), highlighting notable improvements in their reasoning abilities, capacity to analyze relationships between variables, and overall scientific inquiry competencies.

Conclusion and Implications

In this study, a learning trajectory was produced that can help students understand the concept of hydrostatic pressure, whose magnitude depends on the depth of the liquid, mass of the liquid, and gravity field. The learning trajectory can support the students' understanding of the concepts in the five activities. First, students looked at a dam drawing in SAS 1 and hypothesized that the dam wall was designed to increase the thickness of deeper walls. Second, the students created an experimental design based on the tools and materials in SAS 2. Third, students conducted an experiment based on the design that has been made. Fourth, the students described a graph of the experimental data. Then, students analyze the graph to find answers, and determine whether the hypothesis that has been made is proven true. Finally, students answered several questions to build their understanding of hydrostatic pressure and related the experimental findings to the problem formulation in SAS 1, namely: why is the dam wall designed to be deeper and thicker? Furthermore, the results can be used to implement inquiry-based activities using a broader-designed learning trajectory. This can also be used as a reference for further research in different learning contexts.

This research is expected to be useful (1) for students to train to develop natural knowledge, improve reasoning abilities, and express ideas in studying liquid pressure material through simple experiments; (2) for teachers, it can be used as an example and information in the learning process can especially help teachers in presenting learning for liquid pressure material using an inquiry-based learning model; (3) for other researchers, it can be used as reference material for further research or studies on other science learning topics using an inquiry-based learning model.

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Appendix

Appendix 1a
Sample of Lesson Plan

Lesson Plan 1 – Hydrostatic Preassure

A. Identity

Educational Institution	SMP Negeri 9 Palembang
Subject	Integrated Science
Class/Semester	VIII / II
Main Material	Pressure in Matter
Time Allocation	5 Lesson Hours (1st Meeting: 3 Hours, 2nd Meeting: 2 Hours)
Note	This lesson plan is specifically for the 2nd meeting.
Educational Institution	SMP Negeri 9 Palembang
Subject	Integrated Science
Class/Semester	VIII / II

B. Core Competencies (KI)

1. KI.3: Understand and apply knowledge (factual, conceptual, and procedural) based on curiosity about science, technology, art, and culture related to observable phenomena and events.
2. KI.4: Process, present, and reason in concrete domains (using, analyzing, assembling, modifying, and creating) and abstract domains (writing, reading, calculating, drawing, and composing) according to what is learned at school and other sources from similar perspectives/theories.

C. Basic Competencies and Indicators of Competency Achievement (IPK)

Basic Competencies	Indicators of Competency Achievement (IPK)	Description
3.8 Explain the pressure of matter and its applications in daily life, including blood pressure, osmosis, and capillarity in plant transport tissues.	3.8.1 Explain the concept of pressure. 3.8.2 Compare the relationship between force and surface area in relation to pressure.	Understanding pressure concepts and their applications.
4.8 Present experimental data to investigate the pressure of liquids at certain depths, buoyant force, and capillarity, for example, in plant stems.	4.8.1 Present experimental data on liquid pressure at certain depths. 4.8.2 Present experimental data on the application of pressure principles in the capillarity process for substance transport in plants.	Conducting and presenting experiments related to pressure.

D. Learning Objectives

After studying Hydrostatic Pressure, students are expected to:

1. Predict (hypothesize) the factors affecting hydrostatic pressure experienced by objects.
2. Analyze the effect of depth on hydrostatic pressure.
3. Analyze the effect of density on hydrostatic pressure.
4. Present experimental results of hydrostatic pressure.
5. Conclude the concept of hydrostatic pressure.
6. Apply the concept of hydrostatic pressure in daily life.

E. *Learning Materials*

Pressure in matter (especially liquid):

F. *Learning Methods*

a) Approach: Scientific
b) Learning Model: Inquiry
c) Learning Methods: Practicum, Discussion, Q&A.

G. *Learning Media*

1. Media: LCD projector, screen, laptop, PPT media, school environment.
2. Tools and Materials: Spring balance, beakers, weights, water, cooking oil, mineral bottles, tape, and Hydrostatic KIT.

H. *Learning Resources*

1. Ministry of Education and Culture. 2017. Science for Junior High School/MTs Class VIII Semester 2. Jakarta: Ministry of Education and Culture (pp. 1-33).
2. Ministry of Education and Culture. 2017. Teacher's Book _Science for Class VIII_. Jakarta: Ministry of Education and Culture (pp. 320-318).
3. Tim Abdi Guru. Integrated Science for SMP/MTs Class VIII. Jakarta: Erlangga (pp. 228-243).
4. School environment.

İ. *Learning Step*

Learning Steps	Inquiry Model Syntax	Activity Description	Time Allocation
Introduction	-	• The teacher prepares the students for learning. • The teacher establishes a pleasant learning environment. • The teacher engages in an apperception exercise and motivates the students by asking: – Have you ever gone diving? What sensations did you experience in your ears while diving? – Did you feel that your ears were under pressure? – As you dived deeper, did you experience greater pressure? – Why might this phenomenon occur?	5′
Core Activities	Orientation Stage	• The teacher communicates the learning objectives and their relevance in everyday life. • The teacher outlines the scope of the material and the activities to be undertaken. • The teacher details the learning activities that will be conducted.	70′

		• The teacher directs the students' attention by providing a stimulus through the presentation of the following image. 	
	Formulating the Problem	• The teacher gives the students the opportunity to formulate as many questions as possible that have been identified through observation, for example: 1. What is the relationship between the pressure of a liquid, the density of the substance, the height of an object, and the Earth's gravitational force? 2. How can the pressure in a liquid be determined?	
	Formulating the Hypothesis	• The teacher divides the students into several groups consisting of 4–6 students. • The teacher distributes the worksheet to each group. • The teacher guides the students in reading and scrutinizing the worksheet. • The teacher guides the students in carrying out the activity as outlined in the worksheet, namely: **"Conduct an experiment on the pressure of a liquid at a specific depth."**	
	Collecting Data	• The students discuss the results of the experiment. • The teacher asks the students to engage in group discussions to answer the questions in the worksheet, supervising and guiding them throughout the discussion.	
	Testing the Hypothesis	• Students verify whether the formulated hypothesis is correct by comparing it to the conducted experiment and other learning resources.	
	Formulating the Conclusion	• The students draw conclusions from the experiment, for example: The pressure of a liquid is influenced by the density of the liquid and the depth of the object. $Ph = \rho.g.h$ The students communicate the results of their group work.	
Closing		• The teacher clarifies and communicates the correct	5′

answers from the discussion:

a) The pressure exerted by a stationary liquid is called hydrostatic pressure. The pressure of a liquid is influenced by its density and the depth of the object. $Ph = \rho.g.h$

b) This hydrostatic pressure is important for designing various structures, such as dams for hydroelectric power plants and submarines.

- The teacher, together with the students, reflects on the learning process that has taken place.
- The teacher concludes the lesson while offering a closing salutation.

Appendix 1b

Sample of Student Activity Sheets (SAS)

Student Activity Sheets (SAS) - Hydrostatic Pressure

Learning Objective: Investigate hydrostatic pressure

What do you need?

The following materials are required for the experiments:

For Experiment 1:

1. Two beakers
2. U-shaped pipe and U-shaped hose
3. Funnel
4. Colored water
5. Coconut oil or cooking oil
6. Balloon to cover the funnel

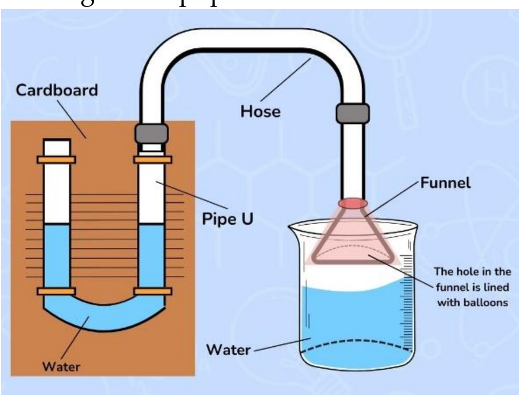
For Experiment 2:

1. Mineral water bottle
2. Cutter or hole punch for the bottle
3. Colored water
4. Coconut oil or cooking oil
5. Tape to cover the holes in the mineral water bottle.

What Should You Do?

Experiment 1

1. Arrange the equipment as shown in the following image.



2. Fill the beaker with water.
3. Insert the funnel into the beaker and vary the depth of the funnel.
4. Observe the difference in water levels in the U-shaped pipe.
5. Repeat the experiment by replacing the water with cooking oil.
6. Record your observations in the table below.

Table 1. Experimental Data of Liquid Pressure in a U-Shaped Pipe

No	Depth (h) (cm)	Difference in Height (Δh) (cm)	
		Water	Coconut Oil
1			
2			
3			
4			
5			

Experiment 2

1. Arrange the equipment as shown in the following image.

2. Make holes in the mineral water bottle at several points with different heights.
3. Seal all the holes in the bottle using tape.
4. Fill the mineral water bottle with water.
5. Remove the tape from the holes.
6. Observe the difference in the water spray distance from each hole in the mineral water bottle.
7. Repeat the experiment by replacing the water with cooking oil.
8. Record your observations in the table below.

Tabel 2. Table 2. Experimental Data of Liquid Pressure in a Mineral Water Bottle

No	Hole Depth in the Bottle (h) (cm)	Spray Distance (cm)	
		Water	Coconut Oil
1			
2			

3			
4			
5			

What Should You Discuss?

1. In your opinion, which is greater: the density of water or the density of cooking oil?
2. How does the difference in water height in the U-shaped pipe change when the funnel is inserted deeper into the beaker?
3. Compare the difference in water height in the U-shaped pipe at each funnel depth when inserted into the beaker filled with water and when filled with cooking oil.
4. How does the spray distance of water and cooking oil from the holes in the mineral water bottle compare?
5. Compare the spray distance of water and cooking oil from the mineral water bottle when the hole covers are removed.
6. The difference in height and spray distance is caused by the pressure of the liquid (water and oil) transmitted through the funnel and hose in Experiment 1 or through the holes in the mineral water bottle in Experiment 2. What factors affect the magnitude of pressure in this experiment?

What Should You Conclude?

Based on the experiments and discussions you conducted, what can you conclude?

1. The density of water … the density of cooking oil (fill in with the symbol >, =, or <).
2. Calculate the difference for each experiment!
3. Compare the water height in the U-shaped pipe and the water level in the beaker.
4. Mention the factors that influence the results.

Journal of Turkish Science Education, 2025, *22*(4), 703-723.
DOI no: 10.36681/tused.2025.035

Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

Coordinating multiple representations in a hybrid real–virtual laboratory: Students' strategies in learning light reflection and refraction

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ABSTRACT
This study investigates how middle school students coordinate multiple representations while learning about reflection and refraction of light in a hybrid laboratory environment that combines real and virtual settings. Conducted as a qualitative case study, the research involved a group of 48 students enrolled in a public school. The dataset comprised video and screen recordings from real and virtual experiment sessions, student worksheets, drawings, semi-structured interviews, and findings from a concept test administered prior to the implementation. The data were coded with respect to representation use, patterns of transitions and correspondences among representations, and levels of abstraction (concrete–intermediate–general). After establishing inter-coder reliability, the data were analyzed through descriptive and content analysis methods. The findings indicate that students transitioned between real experiments, simulations, schematic drawings, and mathematical expressions using specific strategies, such as verification, re-representation, and elaboration of explanations. However, these representations were not always fully integrated. Levels of abstraction were found to be predominantly concrete during the exploration phase, while shifting toward more general principles during the modeling and discussion phases. The results from this two-session implementation suggest that hybrid laboratories may not fully realize their pedagogical potential for supporting multiple representations unless representational transitions are intentionally structured and guided by the teacher.

RESEARCH ARTICLE

ARTICLE INFORMATION
Received:
05.01.2025
Accepted:
07.05.2025
Available Online:
27.11.2025

KEYWORDS:
Multiple representations; hybrid real–virtual laboratory; simulation-based learning; light reflection and refraction.

To cite this article: Dinçer, S. (2025). Coordinating multiple representations in a hybrid real–virtual laboratory: Students' strategies in learning light reflection and refraction. *Journal of Turkish Science Education, 22*(4), 703-723. https://doi.org/10.36681/tused.2025.035

Introduction

In science education, conceptual learning demands an understanding of the underlying principles of phenomena, rather than the rote memorization of formulas and definitions (Bessas et al., 2024; Jaakkola & Veermans, 2020; Wang et al., 2025). Instruction that relies on single, predominantly abstract representations does not consistently support students' ability to transfer what they have learned to new situations (Jaakkola & Veermans, 2020; Lore et al., 2024; Ulger, & Çepni, 2020). Consequently, presenting scientific topics through multiple representations (graphs, diagrams, physical models, verbal descriptions, and equations) allows learners to relate different aspects of a phenomenon and construct a deeper, more integrated understanding. The benefits of multiple representations do not emerge automatically; in the absence of appropriate pedagogical design, they may in fact increase distraction and cognitive load (Becker et al., 2020; Lore et al., 2024).

In effective designs, how the representations complement one another must be made explicit, and students should be supported through strategies for transitioning between, matching across, and integrating different representations (Ainsworth, 1999; Lore et al., 2024). In this way, simplified abstract representations can foreground generalizable principles, while concrete representations and experiences can serve as a bridge to everyday life (Fyfe et al., 2014; Jaakkola & Veermans, 2020; Rau et al., 2017). In this context, the combined use of real (physical apparatus–based) and virtual (simulation-based) laboratories is particularly noteworthy. Simulations make complex processes visible by idealizing them, whereas real laboratories provide opportunities for direct observation and tactile feedback. An appropriately designed hybrid configuration can integrate the complementary advantages of both approaches (Bousquet et al., 2024; de Jong et al., 2013; Manyilizu, 2023).

Although the international literature has made substantial progress in these areas, detailed findings remain limited in the Turkish context, particularly at the middle school level, regarding how students coordinate multiple representations in real and virtual environments (Ardac & Akaygun, 2004; Tüysüz, 2010). Existing classroom-based interventions in Turkey have largely focused on improving students' conceptual understanding or views of the nature of science through structured inquiry models, rather than on fine-grained analyses of representational coordination in hybrid laboratory settings (Bakırcı, Çalık, & Çepni, 2017).

In light of this, the present study aims to examine in detail how middle school students coordinate multiple representations, observations from real experiments, simulation screens/outputs, drawings and diagrams, mathematical relations/formulas, and verbal explanations, within the "reflection and refraction of light" unit in a learning environment where real (physical-apparatus-based) and virtual (computer-simulation-based) experiments are used in combination. The study aimed to reveal students' strategies for transitioning between representations, matching or associating different representational forms, and integrating them effectively. It also sought to describe how the levels of abstraction observed in this process, ranging from concrete descriptions to intermediate explanations and general principles, varied across different phases of learning, namely exploration, modeling, and discussion. In doing so, the study intended to generate evidence on how real–virtual laboratory combinations either facilitate or hinder inter-representational coordination, thereby offering design principles and practical implications for the integration of real and virtual laboratory activities in science education. In line with this aim, the following research questions were addressed:

- What strategies do participants use to coordinate multiple representations in a learning environment where real and virtual experiments are integrated?
- What are the frequencies with which participants transition between different representations and attempt to match them?
- What levels of abstraction are observed in participants' expressions, and how do these levels vary across different phases of the learning process (exploration, modeling, and discussion)?

Literature Review

The integration of digital technologies and the use of multiple representations in science education have gained increasing prominence. Recent research in this area emphasizes that students' ability to represent scientific concepts in diverse ways is a natural and necessary part of the learning process (Flores-Camacho & Gallegos-Cázares, 2025; Irwanto et al., 2025; Nielsen et al., 2022). From the perspective of representational pluralism, students' sense making of science topics through various mental models or representational forms is viewed not as an error or deviation, but as a natural process in the construction of knowledge. Flores-Camacho and Gallegos-Cázares (2025) reinforce this perspective by advocating the design of learning environments in science education that deliberately encourage students to debate multiple representations instead of imposing a single "correct" one. In school settings, however, a recurring tension between plurality and uniformity is evident. While students tend to depict a scientific phenomenon through diverse alternative conceptions, teachers, constrained by the curriculum, often favor the adoption of a singular, standardized representation (Cheung & Erduran, 2025; Nielsen et al., 2022). Hence, the instructional process must strike a balance between fostering representational pluralism and ensuring conceptual coherence.

Research shows that working with multiple representations (text, visuals, graphs, symbols, etc.) plays a central role in scientific understanding (Lore et al., 2024; Nielsen et al., 2022; Stöger & Nerdel, 2024). Because different representations highlight different facets of scientific understanding, engaging students with these multiple representational forms can deepen their conceptual learning. For example, expressing a phenomenon both verbally and visually helps students construct a richer mental model of the topic. Studies further demonstrate that instructional activities designed to develop representational competence can simultaneously enhance students' representational skills and their subject-matter knowledge (Rau, 2017). A study conducted by Lore et al. (2024) elaborates on this issue in detail. The researchers reported that, in a multi-representational learning environment modeling the earthquake cycle, although the majority of students exhibited representational skills to some extent, only a small subset demonstrated advanced proficiency in coordinating and making sense of representations. Moreover, the study concluded that specific representational competencies, such as the ability to interpret simulations represented through code blocks, were significantly associated with overall achievement. These findings highlight the necessity of structuring and scaffolding representational competence in science education.

In addition, new analytical frameworks are being developed to better understand how students represent scientific concepts. For example, Cheung and Erduran (2025) designed a framework capable of analyzing students' understandings of the nature of science as expressed through both drawing and written modalities. Because previous assessment instruments generally evaluated students' views only through written responses, this study provided a more comprehensive account of their thinking about scientific methods and practices by also incorporating multiple modes such as drawings. In their study, Nielsen et al. (2022), investigated how a preservice science teacher employed multiple representations while producing a digital explanation. The teacher candidate created a multimedia product; including images, text, and animations; to explain the concept of transparency to 11- to 12-year-old students. Observations and interviews conducted throughout the process showed that the candidate built understanding by seamlessly transitioning among representations and interweaving them. This creative process enhanced both the candidate's conceptual understanding of the topic and their facility in mobilizing diverse semiotic resources. This finding suggests that having students or preservice teachers produce their own digital content and representational examples can make substantial contributions to learning through iterative reflection and revision.

In a study conducted in the context of limited laboratory resources in Tanzanian chemistry classes, Manyilizu (2023) reported that students who first engaged in experiments using a virtual chemistry laboratory performed significantly better in the real laboratory compared to those who started directly with the real laboratory. It was particularly emphasized that starting with the virtual laboratory improved learning outcomes by providing students with prior experience before the hands-on experiment. Similarly, in Indonesia, Lestari et al. (2023) conducted a study with students with low levels of scientific literacy, testing an instructional model that combined the use of virtual laboratories with teacher demonstrations. They reported that this blended approach led to the greatest gains in students' scientific literacy scores compared to using either virtual laboratories alone or demonstrations alone. This finding suggests that virtual tools can play a complementary role, supporting real laboratory experiences by addressing students' conceptual gaps.

In another study, Wang et al. (2025) conducted a meta-analysis of 27 studies published between 2001 and 2021 to examine the effects of combining real and virtual experiments in physics education. This comprehensive analysis revealed that the integrated use of real and virtual experiments had a positive and statistically significant effect on students' learning outcomes compared to using real experiments alone. It has been found that hybrid experiments are particularly beneficial in more abstract and complex areas of physics, highlighting the advantage of visualization provided by virtual environments in facilitating the understanding of abstract concepts. Moreover, the meta-analysis emphasized that factors such as class size and the sequencing of experimental activities can influence outcomes; the most effective learning results were observed in small-group settings with virtual–real experiment sequences designed according to a specific pedagogical framework.

Virtual reality (VR) applications offer considerable pedagogical potential in science education, as they can immerse learners in interactive three-dimensional environments that foster high levels of cognitive and affective engagement. A recent study by Irwanto et al. (2025) illustrated this potential. In this study, the topic of chemical reaction rates was taught to 11th-grade students using a VR-supported environment for the experimental group, while the control group received instruction through PhET simulations and video-assisted explanations. The results showed that the group using VR achieved significantly higher scores than the control group on both creativity disposition and academic achievement measures. Students in the VR group exhibited large effect sizes on both metrics, indicating that VR produced a marked advantage over traditional digital resources. In this context, the researchers emphasized that VR-based learning experiences foster students' creative thinking and, through visual–kinesthetic feedback, increase engagement with the lesson and depth of learning. The ability to manipulate objects interactively in the virtual environment helped students focus their attention on the learning objective and better comprehend the chemical process. This study demonstrated that VR serves not merely as a substitute for conventional instruction but as a tool that complements and enriches it, fostering students' active participation and higher-order thinking skills.

Likewise, the system HOBIT, developed by Bousquet et al. (2024), exemplifies the use of augmented reality (AR) in science education. HOBIT was conceived as a hybrid optical apparatus for teaching wave-optics topics by overlaying virtual layers onto a real optical bench. Within this platform, students can physically adjust and manipulate optical components such as lenses and mirrors, while simultaneously observing the consequences of their modifications in real time via virtual sensors and displays. Thus, abstract concepts that are normally imperceptible, such as the frequency or polarization of light waves, are rendered visible through augmented reality, thereby facilitating comprehension. The HOBIT platform affords flexibility by enabling rapid setup of numerous experiments with a single apparatus and by virtually modeling equipment such as lasers that may be costly or hazardous, thereby minimizing safety concerns. Such AR/VR-based laboratory applications have created innovative learning environments that allow students to gain experience and receive virtual feedback. However, review studies note that although virtual/remote laboratories include tools that support communication and group awareness, components that scaffold and regulate collaboration remain limited (Elmoazen et al., 2023; Kurtz et al., 2025). However, rather than focusing on collaborative design, this study concentrates on how students individually coordinate multiple representations.

The effectiveness of technology-enhanced science instruction largely depends on how such tools are utilized. Research has shown that the perceived usefulness of new and engaging digital tools does not always align with expectations. For example, Sheffield et al. (2024) implemented a gamified virtual laboratory simulation with pre-service science teachers in Australia over the course of one semester and subsequently evaluated their perceptions of the experience. Despite the general popularity of the concept of gamification, the pre-service teachers participating in the study reported that the application did not significantly contribute to the development of their content knowledge. Many students also noted that the laboratory simulation did not fully capture their interest or deepen their subject understanding. This finding indicates that the mere inclusion of digital technologies in educational settings does not automatically ensure high engagement or effective learning. Instead, factors such as user experience, the alignment between content and technology, and students' intrinsic motivation play a critical role in determining educational success (Dodevska et al., 2025; Irwanto et al., 2025; Wang, 2025). Therefore, incorporating student feedback into the design and implementation of educational technologies and aligning the tools with pedagogical objectives is a critical consideration.

Meanwhile, the VR-based chemistry experiment system developed by (Lu et al., 2024) demonstrates how well-orchestrated technology integration can yield concrete benefits. Using a VR headset and hand-gesture recognition hardware, the system simulates high school–level chemistry experiments with a high degree of realism. Evaluations indicated that the VR-supported chemistry laboratory offered greater realism (physical fidelity) and usability compared to similar products currently on the market. In other words, while experimenting in the virtual environment, students felt as though they were working in an actual laboratory and judged the system to be the more suitable option. This finding suggests that a well-designed virtual experiment environment can furnish learners with an experience that is both realistic and pedagogically effective. Nevertheless, considerations such as the requisite infrastructure, costs, and teacher training must be addressed for the widespread adoption of such advanced technologies in schools.

In sum, the literature unequivocally underscores the pedagogical power of multiple representations; yet the realization of this potential appears to hinge on the deliberate design of processes that facilitate students' transitions and alignment among representations.

Method

This study was designed as a case study that predominantly employed qualitative data to examine real and virtual laboratory activities on the topics of light reflection and refraction at the middle school level. In this context, the study examined the process of a combined real–virtual experiment on the "Reflection and Refraction of Light" unit taught in a public middle school. This approach involved students both conducting direct observations in the school science laboratory and, concurrently, modeling the same phenomenon through a computer simulation.

Participants

The sample consisted of 48 students (23 girls, 25 boys) enrolled in a public middle school. The students had previously encountered the topic in class and possessed prior knowledge of fundamental concepts such as angle of incidence, angle of refraction, refractive index, and the law of reflection. Prior to the activity, a 25-item concept test was administered; the pre-test produced a mean achievement score of 52.30 (sd = 9.50), and no significant differences were detected among the participants. The study was conducted on a voluntary basis, and the required parental consent forms and permissions were obtained.

Learning Environment and Instructional Materials

The hybrid learning environment combined a physical optics apparatus with a computer-based simulation. Each pair of students worked with a shared set of physical materials consisting of a laser light source, a plane mirror, a prism, and a rectangular water-filled tank mounted on a protractor base. These components allowed students to set up and observe standard reflection and refraction scenarios, such as light rays incident on a plane mirror or passing from air into water at different angles.

In parallel, students had access to an interactive ray-tracing simulation displayed on a laptop computer. The simulation presented a two-dimensional representation of a light ray crossing the boundary between two media and provided multiple representations of the situation, including a dynamic ray diagram, numeric readouts of incident and refracted angles, and sliders to adjust the refractive indices of the media. Students could change parameters such as the angle of incidence and the refractive index, observe the resulting change in the path of the ray, and toggle visual indicators (normal line, angle markers) on and off.

The instructional sequence was supported by a structured worksheet and a teacher guide. The worksheet included sections for recording measurements from the real apparatus and the simulation, constructing ray diagrams, and writing short verbal explanations that explicitly linked the different representations. The teacher guide specified the timing and goals of each phase of the activity (exploration, explanation/modeling, discussion), sample questions to be posed to the class, and explicit prompts designed to draw students' attention to correspondences and discrepancies across the real and virtual representations.

Procedure

In this study, a three-phase instructional activity was implemented to support students' learning by enabling them to use real experiments and virtual simulation environments concurrently. The simulations allowed students to engage in active learning by concretizing complex physical processes, whereas the real laboratory experiments provided opportunities for direct observation. The integrated activity, which combined the laboratory and computer-based simulation, was structured to capitalize on the strengths of both environments.

The activity was implemented over two class sessions of approximately 40 minutes each, involving 24 pairs of students working collaboratively. In line with the case-study design and our focus on fine-grained processes of representational coordination rather than long-term learning outcomes or method comparisons, this short but intensive sequence was deemed sufficient to generate a rich corpus of interactional and representational data. Each group received a physical experimental apparatus; comprising a laser light source, plane mirror, prism, and water-filled tank; along with a computer. The intervention was conducted in three phases, detailed below:

In the first phase, the exploration stage, students worked in pairs using the real experimental apparatus to direct laser light at various angles toward the mirror and the water-filled container, observing the phenomena of reflection and refraction. During this stage, each student was asked to mark the incident and reflected light rays and to measure the angle of refraction within the water. Simultaneously, a simulation running on the computer allowed students to test different scenarios involving the transition of light between media, thereby reinforcing their real-world observations. In this way, participants were encouraged to establish connections across multiple representations by reproducing the phenomena they observed in the real experiment within a virtual environment. On the worksheet accompanying this phase, students were asked to record their predictions and measurements in a simple table (incident and refracted angles, media involved, and a brief qualitative description of how the ray bent). Guiding questions included prompts such as "What happens to the refracted ray when the angle of incidence increases?" and "In which medium does the ray bend toward the normal?" At the beginning of the phase, the teacher briefly demonstrated the apparatus and reminded students of safety rules; during group work, the teacher circulated among pairs, asking them to explain how their real setup corresponded to the representation shown on the simulation screen.

In the second phase, explanation and modeling, students were asked to explain their observational data by drawing ray diagrams on paper. Additionally, they were prompted to test theoretical relationships using numerical measurement tools available in the simulation (adjusting the angle of incidence or refractive index). For instance, the refractive index of the medium was modified in the virtual setting, and the resulting angle of refraction was observed to determine whether the values aligned with theoretical expectations. In this phase, students deepened their understanding by observing in the virtual environment certain quantities they could not directly measure in the real experiment (the speed of light in different media). The corresponding section of the worksheet provided partially completed coordinate grids and ray-diagram templates on which students had to draw incident and refracted rays, mark angles with a protractor, and label media and normal lines. Students then used the numerical displays in the simulation to check whether their drawn diagrams and measured angles were consistent with theoretical expectations. At this stage, the teacher gave a brief whole-class reminder of the law of reflection and Snell's law and then asked groups to use the simulation to test these relationships under different conditions (changing the refractive index of the second medium).

In the final phase, each group presented its findings to the class and engaged in a whole-class discussion. During the discussion, results from the real experiment and the simulation were compared, and questions such as "How does the refraction of light in water actually occur?" and "What did you observe at the molecular level in the simulation?" were used to prompt reflection on relationships across representations. Through this interactive discussion, students collectively evaluated how multiple representations support one another. According to the lesson plan, each group selected one representative case (for example, a particular angle of incidence or a specific change of medium) and prepared a brief poster or board sketch summarizing the real apparatus, a simplified simulation screenshot, a ray diagram, and the corresponding angle measurements. The teacher moderated the whole-class discussion using pre-planned prompts such as "Which representation made it easiest to see the law of reflection?" and "Where did the real and simulated results differ, and how can we explain these differences?", explicitly highlighting students' use of multiple representations when comparing and justifying their conclusions.

Data Collection Instruments

During the data-collection phase, the laboratory environment and group interactions were documented using an observation form. Furthermore, each student's computer screen was recorded with screen-capture software so that their interactions with the simulation were stored digitally. This procedure made it possible to analyze in detail the students' synchronous activities during both the physical experiment and the simulation.

In addition, the ray diagrams that each group drew on their worksheets and in their notebooks, the measurement sheets they completed, and the schematic explanations they sketched on the board during discussions were gathered for analysis.

Following the activity, individual interviews of approximately 12–15 minutes were conducted with the students. During the interviews, students were asked questions such as, "What did you observe in the real experiment? What did you learn from the simulation? How did using the real and virtual experiments together affect your understanding?" All interviews were audio-recorded and subsequently transcribed verbatim.

In addition, students' knowledge was measured quantitatively using a concept test. This test was administered as a 25-item multiple-choice exam before the real-experiment session; its reliability, calculated using the KR-20 formula, was 0.84. Accordingly, the concept test was used solely as a pre-instruction measure of students' prior knowledge and group comparability and was not treated as an outcome variable in the present study.

Data Analysis

The qualitative data collected were examined using a descriptive content analysis approach. First, the observations and the interviews conducted with students were converted into textual transcripts. Key findings from the screen recordings were then incorporated into the corresponding transcripts.

Subsequently, the data transcripts were examined individually using the descriptive coding method. During the analysis process, initial codes were generated based on the research questions. Then, two independent researchers separately coded three sets of data using the coding scheme, and the resulting codes were compared. Any inconsistencies between the two coders were discussed to clarify and refine the code definitions, which were revised as necessary. For the purposes of the present analyses, the basic unit of analysis was the event/episode. An event/episode was defined as a short, thematically coherent segment of activity in which a pair of students focused on a single task or sub-task (setting up a particular ray path in the real apparatus, adjusting parameters in the simulation, or constructing a ray diagram) and used one or more representations to reason about that task. Episode boundaries were marked whenever there was a substantive shift in task goal (for instance, moving from manipulating the apparatus to drawing a diagram or from drawing to verbally explaining results) or a change in the dominant representation being used. In practice, this meant that a continuous sequence of student talk and action from the moment a new representational goal was introduced until the group transitioned to a different representation or task was treated as one event/episode.

Once the code definitions were finalized, the entire data set was coded according to the final code list with the aid of statistical software. To assess inter-coder agreement, 27.00% of the data set was independently re-coded by a second coder, and Cohen's Kappa coefficient was calculated. The resulting Kappa value of 0.82 indicates a high level of reliability between coders.

The main themes and subcodes that emerged from the coding process were analyzed. This process, along with the relationships among the research questions, data sources, and analysis procedures, is summarized in Table 1.

Table 1

Relationship among research questions, data sources, and analysis procedures

RQ	Data Source	Analysis Approach	Indicators / Outputs
RQ1. Which strategies do students use to coordinate multiple representations?	In-class observation notes; screen recordings; semi-structured interviews; student drawings / documents	Thematic / descriptive coding (strategy categories)	Strategy repertoire; category frequencies; illustrative representation examples and brief excerpts
RQ2. What are the frequencies of transitions and matching between representations?	Screen recordings + discourse transcripts	Sequential coding analysis	Stage-specific transition matrices (explore – model – discuss) for comparison
RQ3. What are the levels of abstraction and how do they change across stages?	Interview / discourse transcripts; drawings / diagrams	Level coding: Concrete – Intermediate – General principle; distribution by stage	Percentages for each level; sample excerpts; stage × level cross-tabulations
Additional quantitative measure	25-item multiple-choice test	Used solely to assess students' prior knowledge; not employed to address the research questions	

Findings

Descriptive content analysis conducted to address the first research question revealed that students employed five main strategies when establishing connections between the real and virtual experiments: Visual–Schematic Matching, Verbal–Conceptual Explanation, Mathematical/Geometrical Analysis, Experiment–Simulation Comparison, and Hypothesis Testing/Verification. On average, students used 3.60 (sd = 1.10) strategies in combination. Visual–Schematic Matching emerged as the most frequently used strategy. Descriptive statistics related to these strategies are presented in Table 2.

To examine the co-occurrence patterns of the strategies, a co-use matrix was constructed. The findings related to this pairing are presented in Table 3, which displays the frequencies with which pairwise combinations of the five strategies were reported by the same student.

When Table 3 is examined, the highest co-occurrence is observed for the pair Visual–Schematic Matching and Verbal–Conceptual Explanation (35/48; 72.90%). This is followed by Visual–Schematic and Mathematical/Geometrical Analysis (31/48; 64.60%), and Visual–Schematic and Experiment–Simulation Comparison (29/48; 60.40%). All cell values are upper-bounded by the minimum of the marginal frequencies of the two respective strategies. In summary, the co-occurrence patterns indicate that Visual–Schematic Matching most frequently appears together with Verbal–Conceptual Explanation and Mathematical/Geometrical Analysis. This suggests that, in coordinating representations, students often move from visual anchors toward verbal explanation and quantitative validation.

Table 2

Descriptive statistics on participants' strategy use by learning phase

Strategy	f	Exploration ($\bar{x}$; sd)	Modeling ($\bar{x}$; sd)	Discussion ($\bar{x}$; sd)
Visual–Schematic Matching	43	2.10 (0.90)	1.40 (0.70)	1.20 (0.60)
Verbal–Conceptual Explanation	39	0.80 (0.60)	1.50 (0.85)	1.90 (0.90)
Mathematical/Geometrical Analysis	34	0.60 (0.50)	1.70 (0.90)	1.10 (0.70)
Experiment–Simulation Comparison	31	1.00 (0.70)	1.20 (0.80)	1.30 (0.70)
Hypothesis Testing/Verification	26	0.40 (0.50)	1.00 (0.70)	1.50 (0.80)

Note: x̄; sd represent the mean and standard deviation of the number of coded events per student.

Table 3

Co-occurrence matrix of strategies (pairwise combinations reported by individual students)

	Verbal–Conceptual Explanation	Mathematical/ Geometrical Analysis	Experiment–Simulation Comparison	Hypothesis Testing/Verification
Visual–Schematic Matching	35	31	29	24
Verbal–Conceptual Explanation	-	28	27	22
Mathematical/Geometrical Analysis	28	-	23	21

To address the second research question, instances of transitions between representations, operationalized as a change in the dominant class of representation, and matching, defined as the concurrent and meaningful use of two representations within the same episode, were descriptively grouped. These events were analyzed both as the mean number of occurrences per student (events per student; n = 48) and as total occurrences.

Based on the mean values calculated for each learning phase, transition frequencies were found to be highest during the exploration phase (x̄ = 4.00, sd = 1.20), followed by the modeling phase (x̄ =2.50, sd = 1.13) and the discussion phase (x̄ =1.50, sd = 1.72). Matching events were most frequent in the modeling phase (x̄ =4.20, sd = 1.11), followed by the discussion (x̄ =3.50, sd = 1.70) and exploration (x̄ =2.00, sd = 1.80) phases. The total number of events corresponding to these means was 192 (exploration), 120 (modeling), and 72 (discussion) for transitions, and 96 (exploration), 202 (modeling), and 168 (discussion) for matching events, yielding an overall total of 384 transitions and 466 matching events.

All directional transitions were grouped in detail and presented in Table 4. According to Table 4, when all phases are considered collectively (f = 384), the most prominent transitions during the exploration phase were from Real to Simulation (f = 66) and from Simulation to Real (f = 56), followed by transitions from Real to Drawing/Diagram (f = 36) and from Simulation to Drawing (f = 40). During the modeling phase, increased frequencies were observed in the transitions from Drawing to Mathematics (f = 41) and from Simulation to Mathematics (f = 22). Transitions toward verbal representations appeared to be relatively limited ($f_{\text{Mathematics–Verbal}}$ = 18; $f_{\text{Real–Verbal}}$ = 8).

Table 4

Distribution of directional transitions between representation types (all phases; total f = 384)

Source – Target	f	Source – Target	f
Real - Simulation	66	Simulation - Real	56
Real - Drawing/Diagram	36	Drawing/Diagram - Real	12
Simulation - Drawing/Diagram	40	Drawing/Diagram - Simulation	15
Drawing/Diagram - Mathematics	41	Mathematics - Drawing/Diagram	24
Simulation - Mathematics	22	Mathematics - Simulation	10
Mathematics - Verbal	18	Verbal - Mathematics	10
Real - Verbal	8	Verbal - Real	6
Drawing/Diagram - Verbal	10	Verbal - Drawing/Diagram	10

The overall distribution of matching events across pairs of representations (f = 466) is presented in Table 5. Examination of the table reveals that the highest frequencies occur for the Drawing–Mathematics pair (f = 140) and the Real–Simulation pair (f = 130). These are followed by Simulation–Drawing (f = 78) and, at a lower frequency, Mathematics–Verbal (f = 28); matches involving Real/Verbal and Simulation/Verbal combinations are comparatively infrequent.

Table 5

Frequency of matching between representations; representation types (undirected; total f = 466)

Matched pair	f	Matched pair	f
Drawing – Mathematics	140	Real– Drawing	36
Real– Simulation	130	Simulation – Mathematics	24
Simulation – Drawing	78	Real– Mathematics	12
Mathematics – Verbal	28	Real– Verbal	8
Drawing – Verbal	4	Simulation – Verbal	6

Note: Matching is undirected; it refers to the simultaneous, side-by-side use of two representations for the same finding.

The directional transitions between representations observed during each learning phase are presented in Table 6. During the exploration phase (f = 192), the highest flows were observed in the transitions from Real to Simulation (f = 43) and from Simulation to Real (f = 38). Transitions from Real to Drawing (f = 24) and from Simulation to Drawing (f = 27) indicated a shift from observational data to diagrammatic representation. The highest row totals at this phase were from Simulation (71) and Real (69) sources.

In the modeling phase (f = 120), the most prominent flows were from Drawing to Mathematics (f = 23) and from Simulation to Mathematics (f = 12), with a reverse transition from Mathematics to Drawing (f = 14) also recorded. Row totals were highest for Simulation (f=32) and Drawing/Diagram (f=32), indicating these as central sources of representational activity.

During the discussion phase (f = 72), a clear orientation toward verbal representations was observed, with transitions such as Mathematics to Verbal (f = 8), Real to Verbal (f = 4), and Drawing to Verbal (f = 4), indicating a moderate level of bidirectional flow toward and from verbal explanation.

In summary, the findings indicate that the exploration phase was characterized by intensive transitions between observational and digital representations, whereas in the modeling phase the use of matching along the Drawing–Mathematics axis increased notably. This pattern suggests that, while students moved across multiple representations in the early stages, at later stages they tended to place representations side by side, shifting toward a form of coordination focused on verification and quantitative relationships.

Table 6

Directed transition matrix by learning phase (revised format; total frequency = 384)

Source \ Target	Real	Simulation	Drawing/Diagram	Mathematics	Verbal	Total
Explore						
Real	0	43	24	0	2	69
Simulation	38	0	27	6	0	71
Drawing/Diagram	8	10	0	11	3	32
Mathematics	0	2	6	0	5	13
Verbal	1	0	3	3	0	7
Total	47	55	60	20	10	192
Modeling						
Real	0	13	8	0	2	23
Simulation	12	0	8	12	0	32
Drawing/Diagram	3	3	0	23	3	32
Mathematics	0	6	14	0	5	25
Verbal	2	0	3	3	0	8
Total	17	22	33	38	10	120
Discussion						
Real	0	10	4	0	4	18
Simulation	6	0	5	4	0	15
Drawing/Diagram	1	2	0	7	4	14
Mathematics	0	2	4	0	8	14
Verbal	3	0	4	4	0	11
Total	10	14	17	15	16	72
Grand total	74	91	110	73	36	384

To address the third research question, students' utterances were coded to examine both the levels of abstraction exhibited in their statements and how these levels varied across stages. The coding showed that participants were capable of producing statements at more than one level. Specifically, 60.40% of participants (29/48) articulated at least one Concrete/Descriptive-level statement, 50.00% (24/48) produced an Intermediate/Conceptual-level statement, and 35.40 % (17/48) offered an Abstract/Theoretical-level statement.

When phase-based means (unit = occurrences per student; n = 48) were examined, the discourse pattern was found to follow a systematically increasing trajectory of abstraction throughout the process. In the exploration phase, Concrete/Descriptive statements were more frequent ($\bar{x}$ =3.80, sd = 1.40), whereas Intermediate/Conceptual ($\bar{x}$ = 1.40, sd = 0.92) and Abstract/Theoretical ($\bar{x}$ =0.60, sd = 0.43) statements were more limited. In the modeling phase, the focus shifted to the Intermediate/Conceptual level ($\bar{x}$ = 3.60, sd = 1.20), the mean frequency of Abstract/Theoretical statements increased ($\bar{x}$ =1.80, sd = 0.90), and Concrete/Descriptive statements decreased ($\bar{x}$ = 1.90, sd = 1.16). In the discussion phase, Abstract/Theoretical discourse increased markedly ($\bar{x}$ =3.20, sd = 1.30), Intermediate/Conceptual statements remained at a moderate level ($\bar{x}$ =2.50, sd = 1.13), and Concrete/Descriptive statements were at the lowest level ($\bar{x}$ =0.90, sd = 0.60). This distribution indicates that students progressed from observation-based descriptions to conceptual framing and, subsequently, to the formal expression of general optical principles.

The analysis of sequential transitions between abstraction levels (f_{total} = 294 transition events) supports this finding. The most frequently observed directions were Concrete - Intermediate (f = 88) and Intermediate - Abstract (f = 72), while the reverse transitions occurred less frequently ($f_{Intermediate\text{-}Concrete}$= 36; $f_{Abstract\text{-}Intermediate}$ = 41; $f_{Concrete\text{-}Abstract}$= 29; $f_{Abstract\text{-}Concrete}$ = 28). Accordingly, the analysis indicates that as the process progressed, students' discourse exhibited a gradual increase in the level of abstraction, predominantly following a Concrete - Intermediate - Abstract pattern, with theoretical and generalizing statements becoming noticeably more frequent in the final phase.

Discussion

In this study, five core strategies employed by students in a learning environment that combined real and virtual experiments were identified. These strategies were thematically categorized as: Visual–Schematic Matching, Verbal–Conceptual Explanation, Mathematical/Geometrical Analysis, Experiment–Simulation Comparison, and Hypothesis Testing/Verification. The fact that participants frequently employed more than one strategy concurrently, at rates above the average, was interpreted as an indication that, when working with multiple representations, they tended not to follow a singular or linear pathway, but rather showed a tendency to integrate multiple representations within the same learning episode. This pattern is largely consistent with the literature on learning with multiple representations, which conceptualizes representational competencies in terms of linking, sense making, and conceptualization (Becker et al., 2020; Lore et al., 2024; Stöger & Nerdel, 2024). In particular, recently developed models of representational competence highlight as critical students' abilities to gather evidence from multiple representations and use this evidence to construct explanations (Flores-Camacho & Gallegos-Cázares, 2025; Nielsen et al., 2022).

Despite this coherent pattern, the findings should also be evaluated from alternative perspectives. Specifically, the central role of visual–schematic matching, and its sequential or simultaneous coupling with verbal–conceptual explanation and mathematical/geometrical analysis, suggests that students typically structure their coordination of representations along a "visual anchor -verbal explanation - quantitative validation" pathway. This finding is consistent with studies suggesting that visual representations provide a perceptual anchor and are particularly functional for understanding abstract processes such as those in optics (Bousquet et al., 2024; Jiang et al., 2025). However, representation theories also emphasize that such visual centrality is not invariably advantageous; in the absence of appropriate scaffolding, students may focus on surface features and overlook underlying conceptual relations, and the use of multiple representations may even increase cognitive load and hinder learning (Jaakkola & Veermans, 2020; Lore et al., 2024; Stöger & Nerdel, 2024). Therefore, although the diversity of strategies observed in this study can be regarded as a positive indicator of the depth of representational coordination, it should not be directly interpreted as evidence that all students achieved equally meaningful or deeply integrated understanding.

Secondly, students' use of multiple strategies may not necessarily reflect fully autonomous or spontaneously developed representational flexibility; rather, it can also be attributed to the guiding influence of the designed instructional activities (Rexigel et al., 2024; Skulmowski, 2022). Recent studies employing multiple, dynamically interrelated representations have shown that students typically follow the linking opportunities provided by researchers, and that their repertoire of strategies is strongly shaped by the structure of the activities and the accompanying instructions (Lore et al., 2024; Rau, 2017). Consistent with this view, CKCM-based interventions in Turkish middle school science classrooms have similarly demonstrated that carefully sequenced instructional designs can strongly shape how students mobilize evidence and engage with the epistemic dimensions of science (Bakırcı, Çalık, & Çepni, 2017). In this regard, the present findings successfully demonstrate the potential of the design to support representational coordination; however, they leave open the question of whether students would employ these strategies with the same level of flexibility in more loosely structured contexts.

Third, the incorporation of the Experiment–Simulation Comparison and Hypothesis Testing/Verification strategies is highly encouraging, as it shows that students engage in evidence-based comparison and model-testing processes between empirical findings and simulation outputs; this outcome is consistent with perspectives that regard multiple representations not merely as "more than one display" but as epistemic tools (Bousquet et al., 2024; Flores-Camacho & Gallegos-Cázares, 2025). At the same time, pluralistic and pragmatic approaches discussed in the philosophy of representation and the science education literature emphasize that the use of multiple representations or strategies does not inherently imply "better" understanding; what matters is how these representations are used, what kinds of inferences they afford, and for what purposes students select them (Jaakkola & Veermans, 2020). From this perspective, beyond the sheer number of coded strategies, the quality of strategy use and the ways in which students justify their choices of particular combinations of representations emerge as critical areas of analysis.

Fourth, previous research has indicated that the impact of multiple representations is closely related to learners' prior knowledge and level of expertise. Some studies have shown that additional representations are particularly beneficial for students with higher levels of competence, whereas for those with lower proficiency, they may increase cognitive complexity and thereby hinder learning (Stöger & Nerdel, 2024; Tóthová & Rusek, 2025). Although the students in this study had relatively homogeneous and moderate levels of prior knowledge, the assumption that the observed diversity of strategies translated into equally deep conceptual gains for all learners should be approached with caution. Qualitative data may reveal that although some students formally employed multiple strategies, they did not exhibit deep conceptual integration in their explanations. This highlights the need for a more detailed analysis of representational competencies.

Fifth, some empirical studies on multiple representations (Ainsworth, 1999; van der Meij & de Jong, 2006) reported that even when students are presented with several representations, they often systematically engage with only one or two of them, while disregarding the others. Although the above-average use of strategies in this study suggests that the design encouraged students to activate various representations, it remains important to distinguish between students who genuinely preferred to use multiple strategies and those who interacted with different representations only superficially due to task requirements.

The contribution of this study lies in showing that, within a combined real–virtual laboratory setting, students can work not only with individual representations but also with coherent clusters of strategies. However, when generalizing these findings to other contexts and subject domains, the decisive role of both the strong scaffolding provided by the design and the characteristics of the student population must be carefully considered.

In sum, the present findings highlight the considerable potential of representational coordination, yet they also show that the effects of multiple representations must be examined in light of factors such as design quality, students' representational competencies, cognitive load, epistemic goals, and individual differences. Within this framework, instructional design should adopt visual–schematic representations as an initial anchor and link them, in a stepwise fashion, to explicit verbal explanations and quantitative validation tasks, while simultaneously subjecting this structure to critical evaluation for each learner.

In this study, the patterns of transitions between representations showed that, particularly during the exploration phase, transitions in the Real–Simulation direction and flows from Real/Simulation to drawing/diagram representations were highly concentrated. This pattern aligns with studies in science and physics education that emphasize the "complementary epistemic roles" of real and virtual laboratories (Rau, 2020; Wörner et al., 2022). While virtual environments serve to make otherwise unobservable processes in optics visible, to rapidly manipulate parameters, and to provide idealized conditions, real laboratories offer important insights into the nature of scientific knowledge through measurement errors, experimental constraints, and direct physical interaction. Hybrid optical setups and augmented reality–based platforms similarly aim to create a rich representational ecology for conceptual understanding by integrating physical manipulation with digital or simulation-based representations. In this context, the high frequency of Real–Simulation transitions suggests that students used these two sources not as mutually exclusive, but rather as complementary and mutually validating tools for knowledge construction. This finding is consistent with previous research indicating that the combined use of virtual and real laboratories can enhance conceptual learning and transfer more effectively than either environment used in isolation (Lestari et al., 2023; Wang et al., 2025).

However, interpreting this pattern solely as an indicator of "ideal complementarity" may be a one-sided reading. A high frequency of transitions between representations does not always signify deep conceptual integration. At times, it may reflect more superficial scanning behaviors, such as complying with task instructions, rapidly shifting visual attention across screens, or struggling to determine which representation is more explanatory. The literature on multiple representations emphasizes that random or excessively frequent switching between representations can increase cognitive load and make it more difficult for students to focus on core conceptual relationships (de Jong, 2010; Schnotz & Bannert, 2003). Therefore, the frequent Real–Simulation transitions observed in this study gained meaning only through a structured activity design; however, it should also be acknowledged that, in different contexts, similar arrangements may yield nothing more than "representational clutter" if they are not accompanied by appropriate pedagogical guidance (Renkl & Scheiter, 2017; Rexigel et al., 2024).

The pronounced prominence of Drawing–Mathematics matching in the modeling phase indicates that drawings and diagrams functioned as a bridge for students, enabling them to translate concepts such as refraction, reflection, and refractive index into quantitative models through ray diagrams and measurements. This finding is consistent with empirical evidence suggesting that, when appropriately integrated with targeted tasks, diagrams facilitate students' transitions to symbolic and mathematical representations (Stöger & Nerdel, 2024; Volkwyn et al., 2020). At the same time, this pattern also implies that the activity steered students toward a particular representational sequence. Hence, it underscores the need to design representational coordination flexibly, so that it accommodates not only a single normative flow but also the alternative pathways and explanations students may construct on their own.

The limited transitions and matchings between verbal representations and other forms suggest that students struggle to translate visual and quantitative findings into clear, coherent, and well-reasoned scientific explanations. This outcome parallels studies indicating that learners who work with multiple representations often require additional scaffolding to convey their models and calculations in the language of scientific argumentation (Lore et al., 2024; Nielsen et al., 2022; Stöger & Nerdel, 2024). Such a result, however, should be viewed not merely as evidence of a "deficiency," but also as a natural consequence of a design predominantly centered on visual-quantitative coordination.

The findings of this study indicate that transitions between representations are broad and frequent during the exploration phase, whereas matching becomes more pronounced and elaborated in the modeling and discussion phases. This trajectory was interpreted as consistent with the "initial flexible circulation, subsequent structured integration" perspective proposed in the literature (Giardino, 2017; Naftaliev & Yerushalmy, 2011). In the initial stages, students move across different representations to familiarize themselves with the phenomenon from multiple angles; in later stages, they juxtapose selected pairs of representations, particularly Real–Simulation and Drawing–Mathematics, to compare, verify, and generalize. At the same time, philosophical and didactic approaches that emphasize representational plurality argue that forcing all representations into a fully unified conceptual framework is not always necessary or realistic, and that different representations may, in certain contexts, offer partially incompatible yet productively complementary perspectives (Flores-Camacho & Gallegos-Cázares, 2025; Paillusson & Booth, 2025). From this perspective, the observed patterns among Real, Simulation, Drawing, Mathematical, and Verbal representations should not be interpreted merely as an attempt to converge toward a single, coherent model. Rather, they may also reflect students' processes of exploring, comparing, and negotiating among different epistemic resources.

In conclusion, the patterns of transitions and correspondences observed in this study suggest that a well-structured real–virtual laboratory design can support students' strategic movement across representations. However, the educational value of such movement does not stem solely from increasing the number or frequency of representational transitions, but from integrating these transitions with conceptual reasoning, verbal explanation, and critical comparison.

Findings related to levels of abstraction indicate that students generally exhibited a gradual progression in their discourse throughout the learning process, moving from Concrete/Descriptive to Intermediate/Conceptual, and finally to Abstract/Theoretical levels. The dominance of observation-based descriptive expressions during the exploration phase, the emergence of conceptual frameworks and quantitative relationships in the modeling phase, and the increased emphasis on general principles and theoretical formulations in the discussion phase all suggest that students' use of representations and discourse forms was progressively restructured in alignment with the instructional process. The concentration of transitions particularly between the Concrete–Intermediate and Intermediate–Abstract levels aligns with theoretical perspectives that define learning with multiple representations as a process of meaning intensification through sequential re-representation across different representational forms (Duval, 2006; Yao, 2022).

The literature emphasizes that in environments where visual, verbal, and symbolic representations are used in combination, effective learning occurs not through single-step shifts between representational forms, but through gradual transformations of this kind. Each act of re-expression is argued to strengthen students' epistemic awareness, modeling competencies, and pursuit of conceptual coherence (Rau et al., 2021; Stull et al., 2012). The fact that the findings make this stepwise progression visible both in the representations employed and in the level of discourse supports the conclusion that the designed real–virtual laboratory activity is aligned with key principles of learning with multiple representations (Ainsworth, 2006; Kapici et al., 2019; van der Meij & de Jong, 2006). However, interpreting this trajectory solely as a linear and universal success narrative carries the risk of overlooking several important nuances. First, the general trend observed across levels of abstraction is based on averages; when individual student pathways are examined, it becomes evident that there are also back-and-forth transitions, partial leaps, and even occasional regressions among the Concrete, Intermediate, and Abstract levels. In the literature on multiple representations, such "returns" are not necessarily viewed as indicators of deficiency, but rather as instances where students re-negotiate meaning and strengthen their representational understanding. From this perspective, while the Concrete–Intermediate–Abstract model provides a normative framework, the inherently dynamic and reconstructive nature of learning must also be acknowledged.

The observed pattern of abstraction was interpreted not only as a process arising from students' own cognitive initiative, but also as a reflection of the strong guidance embedded in the instructional design. The structure of the activity, with its focus on observation and description during the exploration phase, quantitative relations during the modeling phase, and generalization during the discussion phase, renders the systematic progression from Concrete to Abstract at least partly an outcome that "bears the imprint" of the design. This raises the question of the extent to which processes of re-articulation are shaped or "imposed" by the design, and whether students would construct a similar ladder of abstraction independently in a more open learning environment. In this regard, the findings call for a dual reading that points both to the effectiveness of the design and to the context sensitivity of abstraction.

The relative weakness of bridges grounded in verbal representations points to a critical area for improvement in supporting students to transform abstract and theoretical knowledge into clear, coherent, and well-justified scientific explanations. The comparatively frequent use of visual and mathematical representations suggests that students are willing and to some extent competent in working with these forms; however, they experience difficulties in extending this work to the level of scientific explanation and argumentation. This finding is consistent with previous studies indicating that students often experience difficulties translating models and calculations into scientific discourse, written explanations, and evidence-based reasoning (Hsu et al., 2015; Kulgemeyer, 2018). In future instructional designs, it is therefore important to include tasks, particularly during the discussion phase, that explicitly require students to verbalize and articulate their representational coordination.

It should also be emphasized that the observed increase in abstraction levels should not be equated with the assumption that more abstract concepts are inherently better. Several studies have pointed out that, particularly for students with lower levels of prior knowledge, excessive abstraction may lead to conceptual disconnection, while maintaining concrete and contextually grounded explanations is critical for the sustainability of learning (Fyfe et al., 2014; Jaakkola & Veermans, 2018). From this perspective, expressions at the Concrete level are not expected to vanish entirely during the discussion phase; instead, Abstract-level explanations should be legitimized by tying them to concrete examples and observation-based evidence. The marked decline in Concrete-level utterances observed in the present findings has therefore been interpreted, on the one hand, as evidence of successfully achieving conceptual abstraction and, on the other, as a possible sign that the bridges of meaning may have weakened for some students.

In this context, the observed pattern indicates that, when appropriately structured, combined real–virtual laboratory settings can support students in moving from descriptions grounded in concrete observations to progressively more sophisticated conceptualizations and, ultimately, to more general and abstract formulations of optical principles.

Conclusion and Implications

This study investigated how students utilized multiple representations, transitioned between them, and progressed in their levels of abstraction while learning about the reflection and refraction of light in a hybrid (real and virtual) laboratory environment. The findings suggest that students were not passive recipients randomly engaging with different types of representations. Instead, they developed selective strategies—purposefully emphasizing certain types of representations while downplaying others.

The transition patterns observed across the exploration, modeling, and discussion phases indicate that the hybrid environment offered representational variety; however, this variety alone did not guarantee representational integration. In particular, while many students demonstrated ease with concrete observations and visual representations, they appeared to require additional support in systematically connecting these to mathematical relationships and overarching scientific principles.

The findings suggest that incorporating multiple representations into a hybrid laboratory environment should be viewed not merely as technological enhancement but as a deliberate instructional-design endeavor aimed at fostering representational coordination. To enable students to establish meaningful transitions among real experiments, simulations, drawings, and symbolic expressions, these representations must be sequenced according to a coherent pedagogical logic, their interrelationships made explicit, and tasks provided that prompt students to interrogate those connections. The results also underscore the pivotal role of teacher guidance: explanations that clarify the purpose of each representation, questions that elicit verbal articulation of inter-representational links, and classroom orchestration that brings diverse representational uses into discussion all serve to strengthen students' strategic deployment of representations. For example, during whole-class discussions teachers can ask questions such as "How does the angle you measured with the real apparatus correspond to the angle displayed in the simulation?" or "Can you sketch a ray diagram that matches what we just observed on the screen and explain how you know the two representations correspond?". In addition, a short consolidation activity in which students produce a summary poster that combines a sketch or photograph of the real setup, a hand-drawn ray diagram, and key numerical values taken from the simulation can make these connections more visible and actionable for classroom practice.

In this regard, the study proposes that the effective use of multiple representations in hybrid environments should be addressed at three levels. First, learning activities should be designed not on the basis of an implicit expectation that students will independently establish relations among representations, but so as to incorporate explicit transitions and re-representation tasks. Second, teacher education should focus on fostering a professional awareness that enables teachers to analyze the epistemic functions of representations, potential misconceptions, and appropriate transition points. Third, assessment should be enriched with tools that attend not only to the correctness of answers, but also to how students transform across representations, how they reference one representation through another, and which combinations of representations they use to warrant abstract principles. When such a holistic approach is adopted, the potential of hybrid laboratory implementations to generate more coherent learning experiences that strengthen students' representational competence and support their conceptual understanding and levels of abstraction becomes more evident.

Limitations and Future Research

The findings of this study should be interpreted in light of certain methodological and contextual limitations. First, the research was conducted in a single school with a limited number of students within a specific socioeconomic and institutional context. This limits the generalizability of the identified representational strategies and abstraction patterns to different types of schools, student profiles, or cultural settings. Future research should conduct comparative studies across diverse regions, school types, and heterogeneous samples to better capture the context sensitivity and potential common patterns of representational coordination in hybrid learning environments.

The research design focused on providing a detailed description of representational processes rather than testing the effects of the hybrid learning environment within a causal framework. The absence of a control group or direct comparisons with alternative instructional settings does not permit strong claims that the hybrid environment is "more effective" or "more advantageous." Future studies employing experimental and quasi-experimental designs that compare different representational sequences, tool combinations, or instructional scenarios would enable a more systematic examination of how the observed strategies relate to learning outcomes. Furthermore, the intervention spanned only two 40-minute sessions, which constrains the extent to which we can draw conclusions about the stability or longer-term development of students' representational strategies.

Although the data sources are rich, the analyses are based on the coding of specific types of interactions and products. Since the coding schemes were developed in line with the research questions, other dimensions of representational coordination (affective responses, epistemological beliefs, technological literacy) were not directly addressed in this study. Furthermore, due to the qualitative nature of the coding, interpretive subjectivity cannot be entirely eliminated, even though reliability coefficients are reported. Future research is needed that integrates process data (video, screen recordings, eye-tracking, concurrent think-aloud protocols, etc.) with micro-analytic techniques and employs coding schemes tested by different research teams. Such pluralistic data and researcher designs would allow representational strategies to be characterized with greater nuance.

The hybrid environment and tools employed in this study are confined to a particular simulation design, activity set, and form of teacher guidance. Alternative simulation interfaces, representational options, feedback types, or orchestration styles could produce meaningful differences in students' strategic choices. Consequently, future research should compare hybrid-environment designs and systematically determine which features most effectively support transitions, matching, and integration among representations. Adaptive systems and dynamic task designs grounded in learner modeling, in particular, offer a productive avenue for developing hybrid learning environments that are sensitive to individual representational profiles.

Finally, the present study modeled only to a limited extent the quantitative relationships among conceptual learning, representational coordination, and levels of abstraction. It did not examine how representational strategies influence long-term retention, transfer, or performance in other subject areas. Future investigations should track students' representational development over time through longitudinal designs and developmental analyses, and more comprehensively test the links between representational strategies and achievement, reasoning modes, and the ability to evaluate scientific models. Such work would broaden the findings reported here and provide a stronger basis for both the theoretical grounding of hybrid laboratory practices and the creation of evidence-based design principles.

Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding Statement

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability

Data will be made available on request.

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Journal of Turkish Science Education, 2025, *22*(4), 724-742.
DOI no: 10.36681/tused.2025.036

Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

The impact of virtual reality on self-efficacy, self-regulation, motivation, and academic performance in sciences

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ABSTRACT
This study aimed to investigate the impact of using VR technology on the academic self-efficacy, self-regulation, academic motivation and academic performance of Iranian eighth-grade pupils in the field of experimental sciences. The research employed a quasi-experimental model with two experimental groups and a control group. A pre-test and post-test design was administered to both groups. The study population consisted of all male eighth-grade students at the secondary school level in Bam, Iran. The sampling method used was purposive convenience sampling, as conducting the research required specific facilities and equipment, such as VR goggles. In this study, four standard questionnaires were employed as research tools: one for self-efficacy developed by Midgley (2000), one for self-regulation (SRQ) developed by Miller and Brown (1991), one for the academic motivation questionnaire by Harter's scale (1981), and to measure academic performance, a researcher-made test in the field of experimental sciences. The collected data were analysed using SPSS 23 software. The results showed a significant relationship between the use of virtual reality and academic performance, self-efficacy, self-regulation, and motivation. Virtual Reality is a tool that can be used to help school learners and meet the needs of future science teachers.

RESEARCH ARTICLE

ARTICLE INFORMATION
Received:
03.04.2024
Accepted:
16.07.2024
Available Online:
23.12.2025

KEYWORDS:
Virtual reality, academic performance, self-efficacy, self-regulation, and academic motivation.

To cite this article: Nikpour, A., & Barat Dastjerdi, N. (2025). The impact of virtual reality on self-efficacy, self-regulation, motivation, and academic performance in sciences. *Journal of Turkish Science Education*, *22*(4), 724-742. http://doi.org/10.36681/tused.2025.036

Introduction

The ever-evolving world witness the continuous expansion of information and communication technology (ICT). To effectively navigate these shifts, individuals must embody a lifelong learning mindset, innate curiosity, adaptability, and skill development. They require the necessary skills to comprehend, interpret, and process information for continuous education that benefits both the individual and society. Human education and its presentation have continuously evolved. With the emergence of each new technology, education has adapted accordingly. ICT with features such as personalised learning, a multisensory approach, and increased interaction with content can play a significant role in shaping knowledge and skills. In the not-so-distant future, learners may not require a physical presence in classrooms, focusing instead on digital tools such as blackboards or projectors (Zhenbo et al., 2019). By integrating virtual reality (VR) with the e-learning system, a comprehensive virtual learning world has been created for electronic education (Harry & Kha, 2021). Effective learning in the classroom depends on the ability and skill of teachers to instruct and engage learners in discussions and lessons. Among these, VR learning environments encompass innovative methods such as teamwork, creative thinking, meaning-making through social interaction, and learning by doing, which can have a significant impact on learning motivation. Virtual reality-based curriculum often contradicts traditional curriculum. VR technology involves the simultaneous overlay of virtual images, including two-dimensional, three-dimensional, film and animation onto the real world, with an appropriate angle and spatial position designated as an added element to the real world. This sentence doesn’t make sense in conventional curricula, there is a greater emphasis on delivering theoretical content (Emmelkamp et al., 2019), while a virtual reality-based curriculum aims to engage and involve learners in learning topics (Riva, 2018), mitigating quality control challenges ??, individual differences among learners, and providing learning feedback in real environments, thus enhancing learners' understanding of subjects and concepts. This jumbled sentence needs revisiting! In a virtual reality-based curriculum, education becomes simulation. A virtual reality-based curriculum utilises computer software and audio-visual equipment to create an artificial environment, simulating real-world scenarios, thereby enabling more effective and realistic learning experiences (Jang & Kim, 2020). One of the primary objectives of educational systems is to enhance the academic performance of learners. Academic performance encompasses all activities and efforts that an individual demonstrates to acquire knowledge and pass various educational levels in educational institutions (Martin et al., 2016). The academic performance of students is the key feature and one of the essential goals (Narad and Abdullah, 2016) of education, which can be defined as the knowledge gained by the learner, which is assessed by marks by a teacher or educational goals set by students and teachers to be achieved over a specific period of time. Academic performance is something of immense significance for anyone concerned with education (Osiki, 2001). In fact, academic performance can be understood as the nucleus around which a whole lot of significant components of the education system revolve, which is why the academic performance of students, specifically belonging to Higher Education Institutions (HEIs), has been the area of interest among researchers, parents, policy framers and planners. Since a sound academic performance is considered a prerequisite for securing good jobs, a better career and subsequently a quality life, the significance of the students’ academic performance is immense. Although it may seem to be a simple outcome of education, the impact of students' academic performance in any nation is multifaceted. Narad and Abdullah (2016) mentioned in their research. the success or failure of any academic institution depends mainly upon the academic performance of its students. They also reiterated the general belief that good academic performance signals better career prospects and, therefore, a more secure future.

The academic performance of students is immensely significant, as the economic and social development of any country are both attributable to the academic performance of the students. The better students perform academically, the better the prospects are for developing a pool of quality manpower who will contribute to the nation's economic and social development (Ali et al., 2009). Students performing better than the expectations and norms set by society are mostly expected to contribute to the growth, development, and sustainability of society (Akinleke, 2017). This provides a compelling reason to rephrase for educators, granting the highest priority to the academic performance of their students (Farooq et al., 2011).

One of the influential factors on academic performance is students' self-efficacy (Duff et al., 2015), which is central to Albert Bandura's social cognitive theory. According to Bandura (2001), self-efficacy is an individual's belief in their ability to organise and perform a wide range of activities required to cope with different situations and circumstances. In other words, self-efficacy is the belief in one's ability to succeed in a specific problem. According to Bandura, this belief is a determining factor in individuals' thinking, behaviour, and feelings. Self-efficacy is the ability to organise and coordinate behavioural, emotional, social, and cognitive skills for numerous goals. Individuals with strong self-efficacy perceive challenging issues as problems to overcome, show a deeper interest in activities they are engaged in, feel a greater commitment to their interests and activities, and quickly overcome feelings of despair. In addition to self-efficacy, self-regulation can also impact the personal and academic lives of students. Self-regulation is the ability to set aside interfering emotions and tensions and to think before acting (Garcia & Pintrich, 2016). Self-regulation of behaviour means that individuals recognise appropriate and inappropriate behaviours and choose their actions accordingly (Altun & Erden, 2020). Zimmerman defines self-regulation as systematic efforts that guide thoughts, emotions, and actions toward achieving goals and desires; for this reason, its application in educational and psychological fields has become highly significant. Bandura believes that humans have specific capabilities that are generally examinable in three dimensions: imitation and modelling, self-reflection, and self-behaviour regulation. He considers self-regulation as the third human capability and identifies functions for it, including goal setting, self-observation, self-monitoring, evaluation, and judgment of performance and self-reaction. Thus, individuals consistently strive to determine their own goals and then compare their successes with these goals and standards; thereby, individual criteria can stimulate greater motivation for further effort or behavioural change towards achieving a specific goal or standard (Zelkowitz & Cole, 2016). Nurturing motivated, goal-oriented, and progressive learners is a significant issue in the educational system. Motivation is a force that creates, maintains, and directs behaviour. It is something that compels us to perform our tasks to the best of our abilities. Pintrich (2004) states that the structure of academic motivation in educational environments applies to behaviours associated with learning and progress. Deci and Ryan (2002) define academic motivation as students' inclination to engage in and be involved in educational activities, as well as their continuous effort to complete and finish those activities. There are students who, after consecutive failures in their studies, attribute all their failures to their own incompetence. As a result of this perception, these students refrain from making efforts and conclude that their efforts will be fruitless. Therefore, teachers should interact with students in a manner that indicates their interpretations are incorrect. Teachers' positive views of students reinforce in students the feeling that, in the event of failure in their studies, they can boost their motivation to compensate for that failure and pave the way for their progress. Psychologists emphasise the importance of appreciating motivation in education due to its effective connection with new learning, skills, strategies, and behaviours. Academic motivation is one of the basic constructs they have proposed to explain it (Kavousipour et al., 2015). Students' academic motivation for learning is associated with self-confidence, concentration, hard work, perseverance in complex tasks, a willingness to continue studying after class, and choosing assignments that demand more effort. Students' motivated strategies. For learning is one of the main components affecting successful learning, and if appreciated, a learning environment becomes more attractive and engaging for learners (Amrollahi Beyooki et al., 2020).

In the realm of education, teachers have always sought different solutions to concretise various aspects of knowledge for learners. One of these subjects is experimental sciences, which often causes three learning challenges for pupils. Firstly, the high cognitive aspect of scientific content diminishes their sense of proximity to any given problem. In conventional teaching classes, teachers attempt to explain concepts using diagrams, models, and other tools; however, in this subject, due to its high cognitive aspect, students struggle to visualise the presented scenarios (Tan & Waugh, 2016). Secondly, the inability to interact and engage with phenomena, WHAT phenomena? in science class is an issue. Experimental sciences are a subject that primarily focuses on practical and research skills, requiring pupils to interact with educational equipment and conduct experiments, thereby enhancing their problem-solving skills (Andersen et al., 2018). Thirdly, the high cognitive load in some science topics imposes a significant cognitive burden on students due to their complex and intellectually demanding nature. Leading to learning difficulties. VR is a three-dimensional simulated environment where users can interact as if it were a physical environment. Generally, a VR-based curriculum provides simulated real-life situations, fosters interaction and communication with phenomena, helps reduce cognitive load, and aims to increase proximity to the problem, personal control over problem-solving, and self-confidence in problem-solving for learners. For this reason, some researchers have recommended the use of VR curriculum for science subjects. Many concepts taught in these areas are abstract, making them very complex for pupils to grasp. In such cases, the use of VR technology can aid in the proper understanding of these topics. One of the unique advantages of VR is its ability to visualise abstract concepts or inaccessible or dangerous events. Since learning is always the primary focus of any educational endeavour, and education is meaningful only when accompanied by learners' acquisition of knowledge, it is essential to pay attention to academic motivation. This whole section is disjointed. It needs restructuring, as one of the most important components in successfully addressing educational, occupational, familial and social challenges (Tan & Waugh, 2016).

Literature review indicates that in recent years, research on the use of VR technology in various courses and educational levels has been ongoing. For instance, studies by Liu et al. (2023) and Pogorskiy and Beckmann (2023) have shown that learning self-regulation skills has a positive correlation with desktop-based VR, predicting higher satisfaction and increased motivation among students. (i.e., enjoyment, engagement, focus, and presence), helping learners effectively compensate for deficiencies in self-regulation skills. Additionally, O'Connor and Mahony (2023) concluded that students' cognitive strategies influence their perception and interaction with technology and learning tasks, and that augmented VR has a positive impact on students' academic self-efficacy in higher education. Moreover, in the research by Özeren and Top (2023), the academic progress and motivation of students in the experimental group, using augmented reality applications, significantly exceeded those of the control group students. The results of studies by Cetintav and Yilmaz (2023) and Ozdemir et al (2022) also demonstrate that VR applications are engaging and interesting for students, positively affecting academic progress, self-regulated learning skills, student motivation, and active participation in class.

Hsiao (2021) concluded that experiential education with virtual reality affects self-efficacy and learning motivation. The results of studies by Jiang & Fryer (2024) also demonstrate that students' motivation increased after the VR intervention or was higher than in other pedagogical conditions. Based on these findings, the current research seeks to answer the following four questions:

1. Is there a relationship between the use of virtual reality and students' academic performance in science lessons?
2. Is there a relationship between the use of virtual reality and students' self-efficacy in science lessons?
3. Is there a relationship between the use of virtual reality and students' self-regulation in science lessons?
4. Is there a relationship between the use of virtual reality and students' motivation in science lessons?

Methods

This study aims to investigate the impact of using VR technology on academic self-efficacy, self-regulation, academic motivation, and academic performance of Iranian eighth-grade students in the field of experimental sciences. The present research, in terms of its nature, objectives, background, and the application of its results in the field of education and learning, is considered an applied study, utilising a quasi-experimental method with two experimental groups.

Table 1

Pre-test-post-test with control group

Select type	group	pre-test	dependent variable	post-test
R	experimental	◎◎	x	◎◎
R	control	◎◎	◎	◎◎

Note: The experimental group and the control group, and a pre-test-post-test design have been employed, as illustrated in Table 1.

The population of the study comprised all male eighth-grade students at the secondary school level in Bam city, Iran. The sampling method used was purposive convenience sampling, as conducting the research required specific facilities and equipment, such as VR goggles. Therefore, one of the secondary schools in Bam city equipped with these facilities was selected for sampling. Subsequently, two eighth-grade classes in this school were chosen, and 30 pupils in one class were randomly assigned to the experimental group, while 30 students in another class were assigned to the control group. Both groups underwent a pre-test, followed by the teaching sessions, during which the control group received. Both groups underwent a pre-test before the teaching sessions began. The control group received traditional teaching methods, such as lectures and question-and-answer sessions, without the use of technology to teach science lessons. In this group, science instruction was solely based on the topics covered in the textbook; note earlier comment about use of this phrase, the experimental group received instruction with the assistance of virtual reality (VR). It is important to note that one of the authors of the programme was an experienced science teacher with 15 years of experience in science education and expertise in educational technology. This teacher had a deep understanding of technological tools and science lessons. Therefore, no additional training was required, and the teaching sessions for the experimental group were conducted over a period of 6 months, as indicated in Table 2. It should be mentioned that due to the complexity and detail of specific topics, multiple training sessions were needed. As a result, although the original plan was to have 10 sessions, additional time was allocated to ensure thorough coverage of these topics. Furthermore, since there was only one pair of virtual reality glasses available in the classroom, the training duration was extended to approximately 6 months to provide equal opportunities for all students to work with the glasses. The results of the pre-test were then compared with the post-test assessments for the participants. In this study, four questionnaires were employed as research tools. The standard self-efficacy questionnaire, developed by Midgley (2000), consists of 25 questions that encompass components of personal efficacy. The reliability of this questionnaire was calculated using Cronbach's alpha coefficient as 0.78.

The self-regulation questionnaire (SRQ) was developed by Miller and Brown (1991), comprising 63 questions and seven subscales titled receiving relevant information, evaluating the information and comparing it to norms, triggering change, searching for options, formulating a plan, implementing the plan, and assessing the plan's effectiveness. This questionnaire is measured based on the Likert scale. Its reliability was calculated as 0.89.

The academic motivation questionnaire comprises 33 items aimed at investigating academic motivation among students. This instrument is a modified version of Harter's scale (1981) for measuring academic motivation. Harter's original scale measures academic motivation with bipolar questions, where one pole represents intrinsic motivation, and the other pole represents extrinsic motivation. The respondent's answer to each question can only include one of the intrinsic or extrinsic reasons. Since both intrinsic and extrinsic motivations play a role in many academic subjects, Lepper et al. (2005) transformed the Harter scale into standard scales, where each question considers only one of the intrinsic or extrinsic motivational reasons. This questionnaire is based on the Likert scale (never, 1; rarely, 2; sometimes, 3; often, 4; almost always, 5). Its reliability was calculated as 0.92.

To measure academic performance, a researcher-made test in the field of experimental sciences was utilized. To confirm the validity of the instrument, science teachers from different schools were also employed. These teachers confirmed the relevance, clarity, and comprehensibility of the questions. In this study, the validity of the questionnaire. was also confirmed by several professors and experts. Additionally, its reliability was obtained as 0.87 using Cronbach's alpha coefficient. the researchers also conducted informal observations and interviewed the pupils in the experimental group. The purpose of these assessments was to evaluate the pupils' satisfaction levels when working with virtual reality glasses, as well as to determine the impact this tool had on their science lesson comprehension and motivation.

To conduct the research, various VR goggles were examined, considering the advantages and disadvantages of different models available in the market. Eventually, the "Meta Quest" VR goggles were selected. Another notable point about the Meta Quest is its completely wireless structure. Unlike older models that relied heavily on computers or mobile phones, this model is entirely wireless. This means that the Meta Quest incorporates powerful hardware responsible for processing VR content. Prior to commencing the pupils' training, the experimental group was familiarised with these goggles and how to use them. Given the teaching subject, the Share Care Your software was utilised for instructional purposes. Before the training commenced, pre-tests for self-efficacy, motivation, self-regulation, and academic performance were conducted. Subsequently, the training began, with the control group taught through traditional methods and the experimental group receiving instruction with the assistance of VR goggles. Finally, post-tests were administered, and the collected data were analysed. Then, 75-minute teaching sessions were conducted using VR in the anatomy section of the eighth-grade science textbook, utilising the Sharecare software.

Figure 1

A view of MetaQuest virtual reality glasses

Figure 1 shows a view of MetaQuest virtual reality glasses.

This free VR software, designed for teaching human anatomy, is suitable for both university and high school levels and displays body parts with high quality. Sharecare allows each student to freely explore and investigate the accurate three-dimensional anatomical model of the human body, its organs, and their natural functions. They can visualize the functioning of their own body, explore organs and systems in a fully immersive 3D environment, understand physiology, and simulate diseases. It enables students to personalize the human body as a representation of their own body.

Figure 2

A view of the share care for your software environment.

Figure 3

Pictures of research implementation

Note: For data analysis, descriptive statistics (mean and standard deviation) as well as inferential statistics (analysis of covariance) were utilized, and ultimately, the collected data were analysed using SPSS23 software.

Table 2

The topics covered in each session

Session	Activity
First	Pre-test and familiarisation with the functioning of the VR goggles and using VR.
Second	Overview of human anatomy using VR, covering its components such as ligaments, tendons, joints, cartilage, bones, their types, how organs function, and diseases related to them.
Third	Review of spinal anatomy and its components, how it functions, and diseases associated with it.
Fourth	Review of muscle anatomy and the nervous system, their components, how they function, and related diseases.
Fifth	Review of eye anatomy and its components, how it functions, and diseases associated with it.
Sixth	Review of ear anatomy and its components, how it functions, and diseases associated with it.
Seventh	Review of tongue anatomy and its components, how it functions, and diseases associated with it.
Eighth	Review of nose anatomy and its components, how it functions, and diseases associated with it.
Ninth	Review of chest anatomy and its components, how it functions, and diseases associated with it.
Tenth	General review of the presented topics and conducting the post-test.

Findings

Table 3

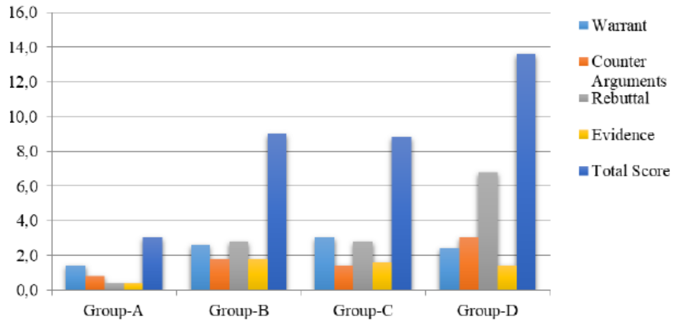
Descriptive statistics of scores in the pre-test and post-test stages in the two groups

Group	Measure	Control		Experimental	
		Mean	SD	Mean	SD
Pre-test	Self-efficacy	66.1	9.79919	80.0667	10.14357
	Self-regulation	199.9667	17.63711	210	15.80921
	Motivation	111.5333	13.5589	110	23.26311
	Academic Performance	4.3	2.11969	4.4667	2.25501
Post-test	Self-efficacy	69.5667	6.20724	76.1333	9.32085
	Self-regulation	188.5	16.96599	204.4667	33.77587
	Motivation	109.0333	13.3274	111.9	16.1829
	Academic Performance	5.7333	7.93914	6.4	2.11073

Note: As seen in Table 3, the mean scores of academic performance, self-efficacy, self-regulation, and motivation of eighth-grade students in the experimental and control groups did not show significant changes between the pre-test and post-test stages. However, in the experimental group, a noticeable change was observed from the pre-test to the post-test stage, indicating the effectiveness of the intervention.

Figure 4

Argumentation skills score of PSTs



Note: As shown in Table 4, the significance level of the Kolmogorov-Smirnov test for all variables is greater than 0.05, indicating the acceptance of the assumption of normality of the data for the variables in both control and experimental groups.

Figure 4 shows the Argumentation skills score of PSTs.

Table 4

Results of the Kolmogorov-Smirnov test to assess the normality of the data before the test

	Control		VR	
Variable	Statistic	Sig	Statistic	Sig
Pretest				
Self-Efficacy	0.137	0.154	0.119	.200e
Self-Regulation	0.1	.200e	0.157	0.056
Motivation	0.123	.200e	0.101	.200e
Academic Performance	0.123	.200e	0.151	0.077
Posttest				
Self-Efficacy	0.172	0.054	0.138	0.15
Self-Regulation	0.168	0.06	0.115	.200e
Motivation	0.139	0.142	0.178	0.016
Academic Performance	0.137	0.151	0.146	0.1

Table 5

The results of the linearity test between pre-test and post-test self-efficacy scores

ANOVA[a]					
	Sum of squares	Df	Sum of mean	f	sig
regression	724.821	1	724.821	15.898	[b]000.
remain	1276.545	28	45.591		
total	2001.367	29			

Coefficients[a]

group	Unstandardized values		standardized values	t	sig
	B	Std. Error	Beta		
Pre-test	465.1	367.	602.	987.3	000.

Note: As can be seen in Table 5, the relationship between pre-test and post-test is linear. (*0/05]*P-Value ≤*=15.898* ،F) This linear relationship is also illustrated in Figure 5.

Figure 5

Linear relationship between pre-test and post-test measures of self-efficacy

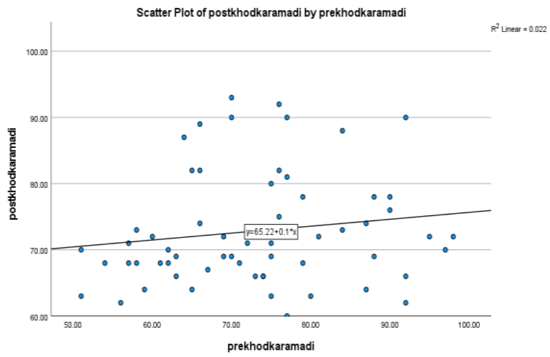


Figure 5 showed the *Linear relationship between pre-test and post-test measures of self-efficacy.*

Table 6

The results of the linearity test between pre-test and post-test self-regulation scores

ANOVA[a]					
	Sum of squares	Df	Sum of mean	f	sig
regression	709.432	1	709.432	25.918	[b]000.
remain	766.434	28	27.373		
total	1475.867	29			

Coefficients[a]

group	Unstandardised values		standardised values	t	sig
	B	Std. Error	Beta		
Pre-test	148.1	225.	693.	091.5	000.

Note: As can be seen in Table 6, the relationship between pre-test and post-test is linear *0/05]* P-Value ≤*=25.918* ،F. This linear relationship is also illustrated in Figure 6.

Figure 6

Linear relationship between pre-test and post-test measures of self-regulation

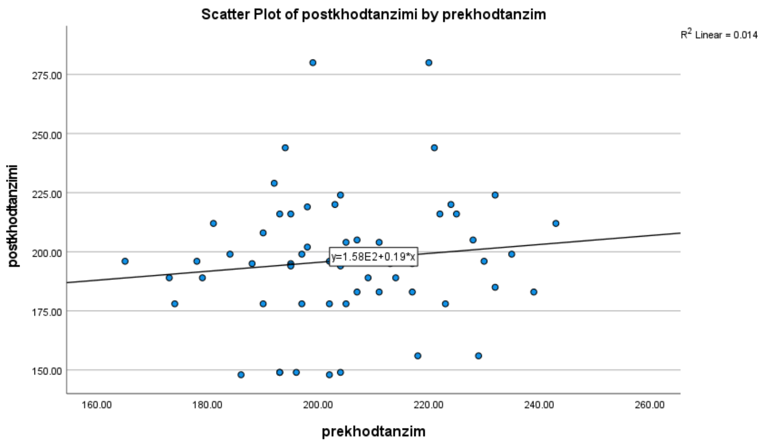


Table 7

The results of the linearity test between pre-test and post-test motivation scores

	ANOVAa				
	Sum of square	Df	Sum of mean	f	sig
regression	709.432	1	709.432	23.201	b000.
remain	766.434	28	27.373		459.1448
total	1475.867	29			875.8
			1696.967		
group	Unstandardized values		standardized values	t	sig
	B	Std. Error	Beta		
Pre-test	798.	062.	924.	12.755	000.

Note: As can be seen in Table 7, the relationship between pre-test and post-test is linear *0/05/05]* P-Value ≤=*23.201* ،F.، This linear relationship is also illustrated in Figure 7.

Figure 7

Linear relationship between pre-test and post-test measures of motivation

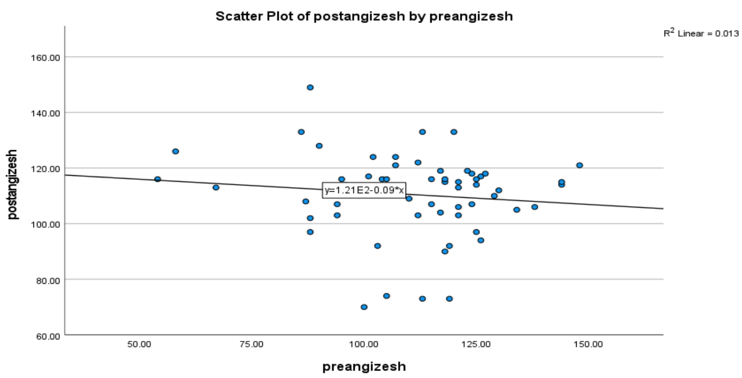


Figure 7 showed a Linear relationship between pre-test and post-test measures of motivation**.**

Table 8

The results of the linearity test between pre-test and post-test academic performance scores

			ANOVA[a]		
	Sum of square	Df	Sum of mean	f	sig
regression	2782.016	1	2782.016	11.761	[b]040. .
remain	367.850	28	13.138		016.2782
total	3149.867	29			850.367
		3149.867			
group	unstandardized values		standardized values	t	sig
	B	Std. Error	Beta		
Pre- test	998.	069.	940.	552.14	000.

Note: As can be seen in Table 8, the relationship between pre-test and post-test is linear *0 ⁄05 ⌋* P-Value ≤*=11.761* ،F. This linear relationship is also illustrated in Figure 8.

Figure 8

Linear relationship between pre-test and post-test measures of academic performance

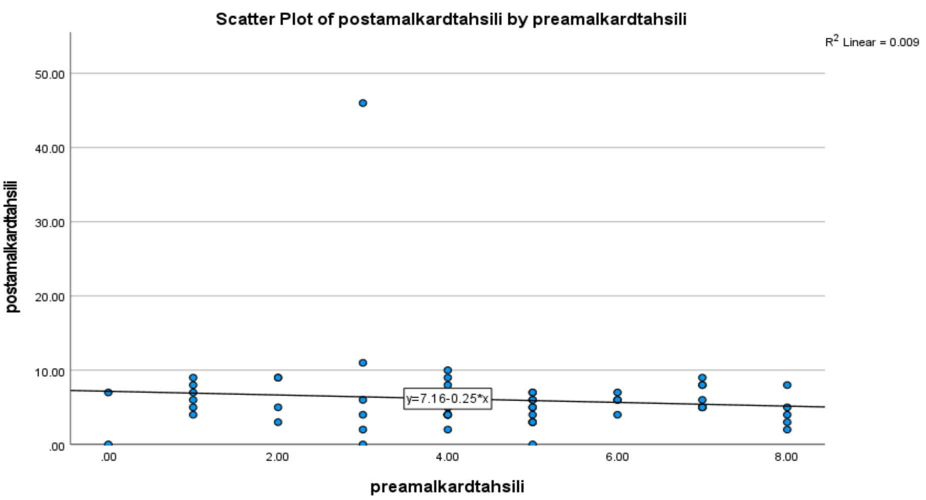


Figure 8 shows a Linear relationship between pre-test and post-test measures of academic performance.

Table 9

Results of the covariance analysis to compare the mean scores of student self-efficacy in the science course

Source	Sum of Squares	Df	Mean Square	F	Sig.	Eta Squared
Pre-test	37.963	1	37.963	0.601	.441	.010
Group	590.007	1	590.007	9.345	.003	.141

Note: As observed in Table 9, the difference between the pre-test and the post-test scores was significant [P-Value ≤ 0.05, F = 0.601]. The F value in the group is reported to be important at a level less than 0.05 [P-Value ≤ 0.003, F = 9.345]. It means that after controlling for the effect of the pre-test, a significant difference exists between the mean scores of the two groups in the post-test. This indicates that there is a relationship between the use of VR and student self-efficacy in the science course. Eta squared was reported as 0.141, indicating the magnitude of this influence.

Table 10

Results of the covariance analysis to compare the mean scores of student self-regulation in the science course

Source	Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Pre-test	55.532	1	55.532	2.077	.043	.091
Group	3247.013	1	3247.013	4.473	.039	.103

Note: As observed in Table 10, the difference between the pre-test and the post-test scores was significant [P-Value ≤ 0.05, F = 2.077]. The F value in the group is reported to be significant at a level less than 0.05 [P-Value ≤ 0.039, F = 4.473]. It means that after controlling for the effect of the pre-test, a significant difference exists between the mean scores of the two groups in the post-test. Eta squared was reported as 0.103, indicating the magnitude of this influence.

Table 11

Results of the covariance analysis for comparing the mean scores of student motivation in the science course

Source	Sum of Squares	Df	Mean Square	F	Sig.	Eta Squared
Pre-test	161.994	1	161.994	6.734	.035	.113
Group	111.776	1	111.776	5.506	.028	.109

Note: As shown in Table 11, the difference between the pre-test and the post-test scores was significant [P-Value ≤ 0.05, F = 6.734]. The F value in the group is reported to be significant at a level less than 0.05 [P-Value ≤ 0.028, F = 5.506]. This indicates that, after controlling for the pre-test effect, a significant difference exists between the mean scores of the two groups in the post-test. Eta squared was reported as 0.109, demonstrating the magnitude of this influence.

The level of participation, satisfaction and motivation of the students in the experimental group was assessed through recorded class sessions. Informal observations and interviews were conducted to gauge the pupils' enthusiasm for participating in class discussions and their willingness to use virtual reality glasses to learn the science topics. During many meetings, they reported having a good understanding of the lesson topics and not feeling the need to practice or review outside of class. Many students also reported increased interest in science lessons compared to before. Furthermore, the observations revealed that students developed greater self-efficacy in learning after a few sessions and were able to grasp the topics independently in the virtual reality environment without requiring additional explanations from the teacher. These comments reaffirm the findings of the current research.

Table 12

Results of covariance analysis for comparing the mean academic performance scores of students in the science course

Source	Sum of Squares	Df	Mean Square	F	Sig.	Eta Squared
Pre-test	18.251	1	18.251	6.537	.037	.139
Group	7.537	1	7.537	7.222	.026	.154

Note: As seen in the table 12, the difference between the pre-test and the post-test scores was significant [P-Value ≤ 0.037, F = 6.537]. This means that after controlling for the effect of the pre-test, a significant difference exists between the mean scores of the two groups in the post-test. Therefore, it can be concluded that the use of VR affects students' academic performance in the science course. Eta squared was reported as 0.154, indicating the magnitude of this influence.

Discussion

The results of comparing the mean self-efficacy scores in the two experimental and control groups showed that the mean self-efficacy scores for the experimental group (VR) are higher than those of the control group. That is, after controlling for the pre-test effect, a significant difference exists between the mean scores of the two groups in the post-test, which is consistent with the findings of O'Connor and Mahony (2023) and Hsiao (2021). Self-efficacy is an individual's belief in their ability to organise and execute a wide range of activities required to deal with different situations and circumstances. According to Bandura, this belief is a determining factor in individuals' thinking, behaviour, and emotions. Self-efficacy is the ability to organise and coordinate behavioural, emotional, social, and cognitive skills for achieving goals. Individuals with strong self-efficacy perceive challenging issues as problems to overcome, show a deeper interest in the activities they are involved in, feel a greater commitment to their interests and activities, and quickly overcome feelings of hopelessness.

VR offers several important components for educational environments, including clarifying abstract concepts, enhancing three-dimensional thinking skills, presenting three-dimensional cases, increasing self-efficacy, and providing an interactive environment (Erbas & Demirer, 2019).

Teaching based on VR enables learners to play an active role in the learning process, allowing them to participate more fully in the lesson and experience a greater sense of accomplishment. Since VR-based teaching facilitates active participation throughout the learning process, it positively influences students' beliefs in active involvement and their sense of self-efficacy. Additionally, consistent with prior research (Cetintav & Yilmaz, 2023; Liu et al., 2023; Pogorskiy & Beckmann, 2023; Prahani et al., 2022), comparisons of the groups’ mean self-regulation scores indicated that the experimental (VR) group had higher self-regulation than the control group.

Since self-regulation involves regular efforts that guide thoughts, feelings, and actions toward achieving goals and desires, behavioural self-regulation means that individuals recognise appropriate and inappropriate behaviours and choose their actions accordingly (Altun & Erden, 2020). Self-regulation has functions that include goal setting, self-observation and self-monitoring, self-assessment and judgment of performance, and self-reaction. Thus, individuals constantly strive to set their own goals and then compare their successes with these goals and standards, thereby allowing individual criteria to stimulate greater motivation for more effort or behaviour change towards achieving a specific goal or standard (Zelkowitz & Cole, 2016). Therefore, teaching with VR, which combines videos, images, and other elements in the physical world, creates numerous incentives, increases efforts to understand concepts, and produces pleasure that leads to improved performance. Teaching with VR encourages active participation from individuals in various activities. The attractiveness of this type of teaching increases interest in the environment and follows individuals' enthusiasm and interest, which is one of the important stages of learning. Teaching with VR increases students' self-awareness and learning speed and consequently enhances their enthusiasm for learning. The results of comparing the mean motivation scores in the two experimental and control groups showed that the mean motivation scores for the experimental group (VR) are higher than those of the control group. After controlling for pretest scores, results showed a significant difference between the groups’ adjusted posttest means, suggesting that the VR-supported instruction had a statistically significant effect on students’ motivation in science lessons. This finding is consistent with prior research (Cetintav & Yilmaz, 2023; Jiang & Fryer, 2024; Mufit et al., 2024; Ozdemir et al., 2022; Özeren & Top, 2023).

As noted earlier, academic motivation is the desire or eagerness to achieve success and participate in activities whose success depends on personal effort and ability, and individuals academically succeed. The need for progress and the desire to perform tasks are applied to functions that lead to learning and progress in school. Academic motivation leads to an individual's presence in educational environments and obtaining an academic degree. Academic motivation is one of the prerequisites for learning and is a factor that gives direction, intensity, and sustains the learners’ behaviour, gives them energy and directs their activities. Supporters of the socio-cognitive theory believe that background factors such as teaching methods, teacher feedback to students, task difficulty level, self and peer understanding, importance of the presented content, and similar factors affect academic motivation (Tsai et al., 2020). In this regard, the VR-based teaching method acts as a group creativity for general ideas. The use of VR-based teaching in lessons increases learners' motivation because VR-based teaching supports collaboration, facilitates expression of opinions during group work, demands detailed explanations from their teachers during the learning process, and encourages deep learning efforts. Additionally, creating a positive attitude in pupils towards learning new information, existing ideas, and scientific subjects not included in the curriculum is a reason for increasing their motivation (Dorgan, 2016). The VR-based teaching method in science education has led students to show more interest and effort in educational activities, increasing their academic motivation. The results of comparing the mean academic performance in the two experimental and control groups indicated that the mean academic performance scores for the experimental group (VR) were higher than those for the control group. After controlling for pretest scores, a significant difference was found between the groups' posttest means, consistent with previous findings (Arslan et al., 2020; Cetintav & Yilmaz, 2023; Ozdemir et al., 2022; Özeren & Top, 2023).

Conclusion and Implications

Today's learners, often referred to as "digital natives," are fundamentally different from their predecessors. This is primarily due to their constant exposure to technology and media. As a result, their learning goals and teaching approaches need to be adjusted to meet the demands of the 21st century. In an information age and knowledge-based society, the integration and effective use of technology is essential. Technology is no longer a mere option for students and teachers, but a fundamental literacy skill (Mishra & Mehta, 2017). High academic performance occurs when students acquire essential skills, including personal, social, educational, critical thinking, and reasoning skills. In other words, comprehensive success in education refers to achieving mastery in a particular skill or expertise. One of the criteria for the effectiveness of the educational system is the academic performance of students, and the educational system is concerned with it. Generally, society and particularly the educational system are interested in and concerned about students' successful growth and development, expecting them to progress and excel in various aspects, including cognitive dimensions, acquiring skills and abilities, as well as emotional and personality dimensions. Teaching method is an important factor in academic performance. VR-based teaching enhances interaction and engagement with course content, enabling students to actively participate in the learning process and giving them more control over their learning activities. Moreover, VR-based teaching enables students to think more about the subjects. Therefore, as students ask more questions, they can actively participate in class and establish connections between real life and study subjects (Doğan, 2016). Therefore, VR-based teaching has led to an increase in student participation in educational activities, the acquisition of more skills and abilities, and the attainment of higher academic performance. Based on the results obtained, it is suggested that in order to improve academic performance, principles and concepts should first be taught to students, and then VR-based education should be used alongside traditional methods as a complementary approach for practical and applied skills. Empowerment programs for teachers should be held to familiarize them with the foundations, principles, and methods of VR-based teaching so that they can impact student motivation by presenting such innovative teaching methods, and help students develop a positive attitude towards subjects, make progress in school subjects, and achieve better academic performance. Education leaders and administrators face the challenge of creating accessible opportunities that provide necessary support for students in non-traditional classroom settings. When technology is designed with the needs of both teachers and students in mind, and when attention is paid to the learning content, both parties can benefit. The development of emerging technologies, such as virtual reality, must acknowledge the vital role played by teachers as mediators of digital experiences. While there is a wide range of high-quality digital resources available to teachers and students, it is crucial to evaluate these resources based on their alignment with the curriculum and their effectiveness according to best practices (Brenneman, 2010). Technology can contribute to achieving this goal, but it requires significant effort to ensure that widespread access becomes a reality. However, there are limitations and challenges that come with integrating emerging technologies such as VR. These include access and infrastructure, teacher training and professional development, cost and sustainability, curriculum alignment, pedagogical integration, and ethical and privacy considerations. To address these limitations and challenges, collaboration is necessary among educators, policymakers, and technology providers. This collaboration should focus on providing equal access to resources, comprehensive teacher training and support, cost-effective solutions, curriculum and pedagogy alignment, and addressing ethical considerations. By fostering collaboration between policymakers and educators, it becomes possible to effectively address the limitations and challenges associated with integrating emerging technologies into education. This collaboration can lead to the development of supportive policies, provision of resources and training, curriculum alignment, research-based decision-making, and establishment of ethical guidelines, ultimately promoting the successful integration of VR in education. Despite the contributions of this study, there are several limitations that need to be addressed. First, the present study only included students from one city in Iran due to time limitations and lack of sufficient course support. Future research should include students from different cities in Iran to extend the results. Second, the cultural background of the study was another concern. Western education systems dedicate a significant amount of time and responsibility to guide students towards self-determination in their learning, which is different from Eastern education systems. Therefore, future studies should collect samples from different cultural backgrounds and conduct a comparative study to further explore the findings of this study.

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Appendix

lesson plan		
1- Muscle Anatomy **2-** Nervous System **3-** Their Components and They Function, **4-** Related Diseases.	**eighth-grade**	**Chapter 5: Sense and Movement**

general purpose

- While familiarizing with the components of sensory and motor devices, explain how they function and suggest ways to use them correctly, considering their importance.
- -Acquiring students' self-regulation, and academic performance- skills and increasing their academic motivation in learning science lesson.
- Deep learning of lessons and higher academic performance.

Staged goals

- Get to know the types of sense organs and determine what kind of stimuli each one is stimulated by.
- Remind them of the structure of sensory organs.
- be able to explain how sensory receptors work in sensory organs.
- be able to name the parts of the motor system and write their function.
- Identify the most important bones in skeleton mollags.
- Familiar with types of muscle tissue and compare them.
- Get to know the different types of muscles and be able to recognize them on the moulage.
- By knowing the sensorimotor system and its strengths and weaknesses, they should be diligent in maintaining their health.

Behavioural and educational goals

- Students get to know the sensory organs. (cognitive, understanding)
- Have students think about different parts of the body. (cognitive, understanding)
- Students get to know the movement of the body. (cognitive, understanding)
- Have students think about how to hear, how to smell and taste. (cognitive, knowledge)
- Students get to know the bones of the body. (cognitive, composition)
- Students can do semester tests. (cognitive, understanding)
- Students will learn about joints and cartilage. (cognitive, understanding)
- Students answer the activities and questions related to the lesson. (cognitive, understanding)
- Students can tell the general result of the lesson. (cognitive, understanding)

Teaching Method and Class Model

Lectures, questions and answers, solving problems individually or in groups of two, using virtual reality glasses.
The model and structure of the class is U-shaped, and all students are in front and around the table, while they are also in charge of the board.

Educational Technology and Media

Virtual reality goggles, share care you Anatomy software, Video projector, laptop, smart boards, digital image, speaker, printer, scanner

Initial Evaluation

- By designing questions in the context of the discussion, by drawing attention to the images in the text, by using context-oriented questions, we provide a suitable context to start teaching.
- What is the main factor of movement?
- How does cartilage turn into bone?
- Name the sense organs?

Lesson Presentation

Teacher activity:

In this lesson, students first get to know how sensory organs work. Here, the emphasis is on the types of sensory receptors and how the effect of environmental stimuli is transformed into nerve messages and in which parts of the body the understanding of sensory messages takes place. After that, we explain the components of the movement system, which consists of two parts, the skeleton and the muscles. In the skeleton section, we describe the types of bones and joints and mention the structure of bones and cartilage. In the muscle section, the types of muscle tissue are compared, with an emphasis on the structure of skeletal muscles and how they function in creating movement, and then the most important muscles of the body are introduced in the form of know more.

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- Using virtual reality glasses and share care you Anatomy software in connection with the lesson: sensory organs
- Write questions on the board. Like the following question:
- What are the sensory organs?
- Allow students to come up with the appropriate answer through class discussion. Write the important and interesting points of the students' conversation as answers on the class board and ask them to write it down in their notebooks. (The summation of students' opinions is the answer to the questions.)

Student activity:

- Show appropriate reactions when working with virtual reality glasses
- Expressing your opinions after working with the software
- Answering the questions raised by participating and accompanying the group
- Concurrence and consultation with group members
- Finding appropriate and correct answers
- Answering questions in turn and respecting the rights of others

Journal of Turkish Science Education, 2025, *22*(4), 743-769.
DOI no: 10.36681/tused.2025.037

Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

Investigating Filipino pre-service science teachers' misconceptions, understanding, and acceptance of evolution

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ABSTRACT
Despite growing research on Evolution education, limited studies explore how misconceptions about Evolution relate to understanding and acceptance, particularly in the Philippine context. This descriptive-correlational study was participated by 114 senior pre-service science teachers enrolled in five teacher education institutions in the province of Nueva Ecija, Philippines. Results revealed that the respondents have a fairly high level of misconceptions regarding Evolution concepts, as reflected by 70.02 (SD = 7.43) BEL-MIS for the 23 BEL Survey statements with an average of 46.65% misconception rate. Moreover, understanding of Evolutionary theory was very low (ECKT: M = 34.25, SD = 13.76), while acceptance was moderate (MATE: M = 68.41, SD = 9.07). Furthermore, the analysis demonstrated an unexpected positive correlation between three out of five parameters of Evolution-related misconceptions and level of acceptance. This finding implies that even though the respondents have a fairly high level of misconceptions regarding Evolution, they still accept the theory. This result encouraged a holistic approach to studying the relationship of Evolution-related misconceptions to other Evolution education constructs in the future. The findings of the study demonstrated that the level of understanding and acceptance of Evolution are highly and positively correlated with one another. Thus, the result of this study supports the growing literature about the positive correlation between these two variables. The study contributes valuable insights to the Philippine context and highlights the importance of targeted interventions to improve Evolution education among pre-service science teachers.

RESEARCH ARTICLE

ARTICLE INFORMATION
Received:
03.04.2024
Accepted:
14.03.2025
Available Online:
18.12.2025

KEYWORDS:
Evolution, misconception, acceptance, pre-service science teachers, biology education.

To cite this article: Hizon, J.D., & De Leon, A. M. (2025). Investigating Filipino pre-service science teachers' misconceptions, understanding, and acceptance of evolution. *Journal of Turkish Science Education, 22*(4), 743-769. http://doi.org/10.36681/tused.2025.037

Introduction

The scientific community considers Evolution an integral part of Biology. "Nothing in Biology makes sense except in the light of Evolution" (Dobzhansky, 1973, p. 125) is a widely cited message in the scientific community from a paper by Theodosius Dobzhansky. Truly, it is the sole theory that serves as a thread that meaningfully 'links' the knowledge related to all domains of Biology. It would be impossible to understand Biology without understanding Evolution. Evolution, as a unifying theory in Biology, explains similarities among organisms, biological diversity, and many physical characteristics that are among the most basic characteristics of the living world, allowing students to understand the biological significance of phenomena such as reproduction, cell division, and how ecosystems function (Banet & Ayuso, 2003). It is considered one of the 'big ideas' in science that students must grasp to become scientifically literate and make informed decisions about the applications of science (Harlen et al., 2015; Abdullah, 2022). Despite its importance, teaching and learning evolution remain fraught with challenges, particularly in countries where scientific literacy rates are low (Borgerding & Deniz, 2018).

In the Philippines, the K to 12 science curriculum was designed to produce scientifically literate individuals who can make responsible decisions and apply scientific knowledge to solve community problems (K to 12 Science Curriculum Guide, 2016). However, in the latest findings of the Programme for International Student Assessment (PISA) 2022, the Philippines' average score in science dropped by one point from 356 in PISA 2018 to 355, ranking the Philippines third-lowest among 81 countries in science (OECD, 2023). In Biology, understanding Evolution is required for scientific literacy (Bishop & Anderson, 1990). Aberilla et al. (2018) stated that learning Evolution is critical for learners to acquire the process of scientific inquiry, which is necessary for making informed decisions and increasing innovativeness and competitiveness in the 21st century.

Science classrooms continue to be one of the few "arenas" where pupils can learn about Evolution (Nelson, 2008). Within these classrooms, learners are faced with a choice between believing and rejecting science. The former involves grasping the nature of science and recognising the fundamental theoretical underpinnings of science, including Evolution (Glaze, 2018). One of the indispensable components of classrooms is the teacher. Teachers are considered to be the "missing link" between scientists' understanding of Evolution and the public's ignorance of (or resistance to) Evolutionary theory (Nehm & Schonfeld 2007). Therefore, they should be prepared to communicate the ideas of Evolutionary theory to their students without any misinterpretations or misconceptions. Pre-service teachers are in the process of transitioning from students to teachers. Therefore, to build a scientifically literate society, it is also necessary to assess their scientific literacy since they will soon be on the front lines of educating society. Moreover, it is critical to understand their level of acceptance of Evolution since their ideas and beliefs about teaching and learning Evolution will influence the pupils they educate (Glaze, 2018).

Studies about misconception research in Evolution focused primarily on identifying these misconceptions and inquiring about several contributing factors. However, what is overlooked is investigating its relationship with other influential constructs in Evolution education, such as understanding and acceptance of Evolution.

Lastly, research on Evolution education is sparse, with most studies focusing on Western and Middle Eastern contexts. Studies in Asian countries are very limited. In the Philippines, there is limited empirical data on how misconceptions about Evolution relate to understanding and acceptance among pre-service teachers. Studies often overlook the interconnectedness of these constructs, leaving a gap in understanding how these factors influence one another.

Aims of the Study

This study aims to explore the misconceptions, understanding, and acceptance of Evolution among Filipino pre-service science teachers in selected teacher education institutions (TEIs) in Nueva Ecija. By examining the relationships between these variables, this study provides critical insights into the status of Evolution education in the Philippines and identifies areas for improvement in teacher preparation programs.

To achieve this, the study addresses the following research questions:

1. What is the demographic profile of the respondents in terms of sex, age, type of Teacher Education Institution, and self-rated knowledge of Evolution?
2. What misconceptions about Evolution are held by the respondents?
3. What is the level of understanding of Evolution among the respondents?
4. What is the level of acceptance of Evolution among the respondents?
5. Is there a significant relationship between the respondents' Evolution-related misconceptions and their level of acceptance of Evolution?

6. Is there a significant relationship between the respondents' level of understanding and their level of acceptance of Evolution?

Literature Review

Misconception Research about Evolution

Studies on misconceptions about Evolution have been chronicled thus far in different populations such as high school students (Woods & Scharmann, 2001; Yates & Makek, 2015), university students (Archila et al., 2024, Brumby, 1984; Bishop & Anderson, 1990; Wescott & Cunningham, 2005; Robbins & Roy, 2007; Pazza et al., 2010), science/Biology teachers (Yates & Marek, 2013; Yates & Marek, 2014; Yesilyurt et al., 2019), and pre-service teachers (Karataş, 2020).

High School Students' Perception of Evolution: Woods and Scharmann (2001) investigated the perceptions of 518 high school students in the United States about Evolution. The researchers collected data using both quantitative and qualitative methods. A causal-comparative or *ex post facto* design was used to examine quantitative data sources, which consisted of subjects' responses to a questionnaire set, while a short post-questionnaire interview protocol was utilized to obtain qualitative data.

Overall, the researchers revealed that based on their findings, these high school students who participated in the study do not fully comprehend the concepts of the Evolutionary theory. The proof of this statement is that the respondents were harboring misconceptions about Evolution that narrow their understanding of the full scope of what Evolution is. The most notable misconception was, "man evolved from monkey or ape," which sixteen (16) students used this phrase to define Evolution. The researchers also pointed out that high school students tend to use anthropomorphic terms, teleology, and vitalism in their definitions (e.g., Evolution as a conscious process based on the organism's needs). Woods and Scharmann (2001) concluded their paper that there is a need to provide learning opportunities that foster a better grasp of the nature of Evolutionary theory and why biologists regard it as a compelling unifying theme for study in the biological sciences. According to the researchers, failure to do so will result in students memorizing what their teachers want to hear from them about Evolution. Worse, they may be alienated from studying biological sciences in the future. Worst of all, it may contribute to the persistence of popular misconceptions about Evolutionary theory among future adults.

Yates and Marek (2015) utilized their constructed questionnaire called the Biological Evolution Literacy Survey (BEL) to assess quantitatively the prevalence of biological Evolution-related misconceptions held by high school students in Oklahoma. The BEL Survey consists of 23 biological misconception statements grouped into five categories to identify students' misconceptions and calculate conception index scores. Nine hundred ninety-three (993) students enrolled in their initial high school Biology course during the 2010-2011 academic years in one of 42 Oklahoma public high schools served as their respondents. The analysis revealed that student participants produced a mean 39.1% misconception rate for the 23 BEL Survey statements. Participants' mean misconception rates per category were: *Science, Scientific Methodology and Technology*, 35.2%; *Intentionality of Evolution*, 37.5%; *Nature of Evolution*, 43.8%; *Mechanisms of Evolution*, 39.4%; and *Evidence Supporting Evolution*, 39.7%. These results paved the way for the authors to conclude that misconceptions were prevalent within the high school student population.

University Students: The subsequent studies showed that students admitted to the college or university harbor misconceptions, despite taking Biology or science-inclined course or not. A recent study by Archila et al. (2024) examined whether a significant difference existed in the understanding of Evolution between STEM and non-STEM university students in Colombia. Interestingly, misconceptions about Evolution did not vary significantly between STEM and non-STEM students. The researchers highlighted this as an opportunity to leverage the distinction between microEvolution and macroEvolution as a foundation for fostering interdisciplinary skills such as creativity and collaborative work.

Moreover, Brumby (1984) showed misconceptions held by medical students in Australia about natural selection. One hundred and fifty (150) first-year medical students from one university participated in her study. Despite that these students all have a solid scientific background in chemistry, math, and other science and are considered among the most successful science students entering tertiary education due to the intense entrance competition; still, misconceptions about biological reasoning about natural selection were found when they were subjected to several unfamiliar qualitative problems based on the concept of natural selection designed by the researcher and given to the students in three different formats.

Results from the analysis of students' explanations demonstrated that the majority of these medical students still believe in the long disproved Lamarckian view of Evolution (Evolutionary change occurs as a result of need). The researcher noted that this view caused a faulty pattern of reasoning. The researcher thought that this "intuitive Lamarckism" was due to an initial incorrect observation that individuals can change their characteristics during their lifetime and that this acquired change is passed genetically on. Though the concept of genetics was introduced, the students failed to include the critical difference between induced and spontaneous mutations. Moreover, the concept of adaptation was confused with immunity among the students, and other immunological concepts of resistance, tolerance, and antibodies were introduced incorrectly in the students' reasoning. Thus, Brumby (1984) stated that she was surprised not by how little these students knew about natural selection but how much they knew incorrectly, for their answers were given with assurance, not hesitatingly.

University students who are non-Biology majors also held misconceptions about Evolution as reflected in the studies of Bishop and Anderson (1990), Wescott and Cunningham (2005), Robbins and Roy (2007), and Pazza et al. (2009).

Bishop and Anderson (1990) found that 110 college students enrolled during two successive quarters in a one-term to a nonmajors' introductory Biology course possessed a misconception about the three umbrella concepts in Evolution, namely (1) *origin and survival of new traits in the population,* (2) *the role of variation in a population, and* (3) *Evolution as the changing proportion of individuals with discrete traits.* Thus, the students' naive explanations are also implicitly Lamarckian; they do not regard variability as necessary to Evolution, and they attribute gradual progressive quality in Evolutionary change not to the proportion of individuals in the population but to gradual changes in the traits themselves, viewing traits as improving or deteriorating from one generation to the next. Furthermore, Bishop and Anderson (1990) stated that college students also misunderstand or confuse the two often used Evolutionary terms: *adapt/adaptation and fitness,* because their meaning in daily English differs from their definition in an Evolutionary context.

Wescott and Cunningham (2005), Robbins and Roy (2007), and Pazza et al. (2009) utilized a quantitative approach by using a questionnaire as opposed to the research methodology used by Bishop and Anderson, as well as Brumby (1984) in identifying the misconceptions among tertiary students.

Wescott and Cunningham (2005) claimed that though 547 undergraduate participants who are enrolled in *Introduction to Biological Anthropology* class also have many misconceptions, as revealed by their data analysis using a 25-statement questionnaire, they *do not follow the same patterns* in their misconceptions as found by other researchers in the United States, like the study done by Bishop and Anderson (1990) and Wilson (2001). Wescott and Cunningham (2005) explained that while many of these students' misconceptions are shared by students in other regions in the US, the student-participants in their study appear to be *more scientifically educated* about other concepts in Evolution. The researchers were honest in admitting that they do not know what factors influenced this difference; however, they suspected it could be due to educational, religious, generational, and possibly motivational differences between their university respondents and those surveyed by Bishop and Anderson (1990) and Wilson (2001).

Pazza et al. (2009), on the other hand, examined the misconceptions of first-year Brazilian students who are attending different classes such as biological sciences (morning and evening schedule), exact sciences (agronomy, physics, chemistry, and math), and human sciences (history, geography, and pedagogy), using a 10-item questionnaire about Evolution, comprising the vital concepts of

Evolutionary theory in different levels of difficulty. The findings showed that these students have misconceptions about the following chief issues in Evolution: Darwin and Lamarck, Homologies and Analogies, Variation and Natural Selection, Human Evolution, and the Random Effect. In totality, Pazza et al. (2009) concluded that data obtained from their study suggest that these first-year students do not understand how Evolution occurs. Specifically, they do not know about the role of random effects, variation, and natural selection in the Evolutionary process.

Robbins and Roy (2007) not only identified misconceptions about Evolution but also tested several strategies to correct them. These strategies include pre-quiz to identify and respond to common misconceptions, peer instruction, and using Evolution as a lens to examine aspects of other topics (such as natural history, anatomy, and biochemistry) instead of teaching it as a separate unit. Their efforts in using these interventions were not in vain since the researchers reported significant improvements. Students were asked to explain the theory of Evolution in a short paragraph before the unit on Evolution. Only 6% did so correctly, in which the misconception, *"Evolution says that humans came from monkeys,"* was on top of the list, with 42% of 141 students agreeing to this statement. However, by the end of the unit, 92% correctly explained the theory of Evolution. Indeed, a considerable improvement from 6% before instruction.

Science/Biology Teachers: Recent studies about misconception research focusing on teachers were done in the two consecutive studies by Yates and Marek (2013, 2014) and Yesilyurt et al. (2019).

Yates and Marek (2013) did a regional study of the prevalence of biological Evolution-related misconceptions held by introductory Biology teachers. The unit of analysis for this study included 76 teachers who taught at least one part of Biology I in one of 71 Oklahoma public high schools from 2010 to 2011. The Biological Evolution Literacy Survey, which contains 23 biological misconception statements classified into five categories, was used as a study instrument to identify participants' misconceptions and calculate conception index scores. The study's findings revealed that participants' knowledge of biological Evolution concepts is lacking, as shown by a mean 72.9% rate of understanding coupled with a 23.0% misconception rate. Moreover, the researchers were disturbed to find that a minimum of 30.0% ($n \geq 23$) of the teachers did not accept the following Evolution concepts: (1) New traits within a population appear at random, (2) Individual organisms do not adapt to their environments, (3) Evolution is not a totally random process, (4) Survival of the fittest does not mean that 'only the strong survive,' (5) Complex structures such as the eye could have been formed by Evolution, and (6) There exists a large amount of evidence supporting the theory of Evolution.

Yates and Marek (2014) published another study about Evolution education in Oklahoma only a year after. However, this time, the researchers explored the factors contributing to high school Biology students' acquisition of biological Evolution-related misconceptions and the possible transmission of teachers' misconceptions to their students. Thus, to carry out their study, 35 teachers who taught at least one section of Biology I in one of 32 Oklahoma public high schools during the 2010-2011 academic year and their respective 536 students were the study's respondents. The Biological Evolution Literacy Survey is used once more to identify teachers' misconceptions prior to student instruction and students' misconceptions both prior to and following the instruction in biological Evolution concepts and to calculate conception index scores and collect demographic data. Multiple statistical analyses were carried out to find statistically significant (p.05) relationships between variables associated with students' acquisition of biological Evolution-related misconceptions. Results demonstrated significant relationships between student misconception acquisition and teachers' bachelor's degree field, terminal degree, and hours dedicated to Evolution instruction. Furthermore, the study discovered a significant relationship between teachers' levels of misconceptions and student achievement, which may provide further evidence of misconception transmission from teachers to students. The findings indicate an inverse relationship between the number of teachers' misconceptions and the post-instruction BEL Survey index scores of students. Yates and Marek (2014) argue that the transmission of misconceptions from these teachers to their students cannot be ruled out as a causative agent, though several variables may be at work in the decrease in students' post-instruction BEL Survey index scores after instruction by teachers with high levels of misconceptions.

Yesilyurt et al. (2019) investigated science teachers' understanding of micro- and macroEvolutionary processes. Using a case study approach, the researchers compared the Evolutionary conceptions of novice and experienced middle school science teachers. Data were gathered through four Evolutionary scenarios combined with cognitive interviews.

The findings revealed that the novice teacher retained Lamarckian misconceptions, such as the inheritance of acquired traits and a transformational perspective on Evolution. In contrast, while the experienced teacher applied several macroEvolutionary principles to explain Evolutionary changes beyond the species level, her causal explanations were primarily based on natural selection and exhibited cognitive biases regarding Evolution. Notably, both teachers, regardless of experience, demonstrated a tendency toward teleological reasoning when interpreting Evolutionary changes, even though the experienced teacher had a stronger grasp of Evolutionary concepts. Based on these results, the researchers emphasized the need to examine how teachers' cognitive biases influence their instructional practices in the classroom when teaching Evolutionary theory.

Pre-Service Teachers: The study of Karataş (2020) focused solely on identifying the misconceptions harbored by Pre-Service teachers. Participants of the study were 190 pre-service teachers in the Science Education Department in one of the universities in Turkey. Out of 190 participants, 91 were senior pre-service teachers who had already completed an Evolution course, while the remaining 99 were sophomores and juniors who were not yet taking an Evolution course. Karataş (2020) reported that misconceptions were found in 57 of the 190 preservice teachers who took part in the study, accounting for 30% of the students. The vast majority of this rate (43%) was caused by misconceptions in students who had never taken an Evolution course (sophomores and juniors). Meanwhile, 14 of the 91 students who completed the course had misconceptions (seniors). Despite the fact that the number of misconceptions among students who completed the course decreased, the researcher stated that misconceptions were not completely cleared up.

The ranked misconceptions found among the Turkish pre-service teachers were the following: 1) Students explaining Evolution as gaining better characteristics, 2) Students explaining Evolution with a human-related perspective, 3) Students explaining Evolution as a change a living being/organism goes through during life, 4) Students explaining Evolution with metamorphosis, and 5) Students considering Evolution/Creation theories as alternatives to each other.

Literature Synthesis

Studies on misconceptions about Evolution have extensively examined high school and university students, as well as in-service science teachers. Findings consistently reveal deeply rooted misunderstandings, including Lamarckian inheritance, teleological reasoning, and anthropomorphic interpretations of Evolutionary processes (Woods & Scharmann, 2001; Brumby, 1984; Yates & Marek, 2013, 2014, 2015). While educators are expected to address these misconceptions, research suggests that many teachers themselves harbor inaccuracies, which may be inadvertently passed on to their students (Yates & Marek, 2014; Yesilyurt et al., 2019).

Despite extensive research on students and in-service teachers, studies focusing on pre-service teachers remain limited. Karataş (2020) identified Evolutionary misconceptions among Turkish pre-service teachers, highlighting the persistence of misconceptions even after formal instruction. However, little is known about how pre-service teachers in the Philippines conceptualize Evolution, presenting a critical gap in the literature.

This gap in the literature underscores the originality of the present study. While prior research has investigated misconceptions in various academic populations, there is a dearth of studies focusing on the misconceptions, understanding, and acceptance of Evolution specifically among Filipino pre-service teachers. Addressing this gap is crucial, as these individuals will soon become educators responsible for shaping students' scientific literacy. By examining the conceptual barriers faced by future science teachers in the Philippines, this study provides a culturally and contextually relevant contribution to the broader discourse on Evolution education.

Methodology

Research Design

The researcher utilized a descriptive-correlational design for this study. The descriptive design was used to determine the Evolution-related level of understanding, misconceptions, and level of acceptance of pre-service science teachers. The correlational design was used to determine if there is a significant relationship between the Evolution-related misconceptions, level of understanding of Evolution, and level of acceptance of Evolution of Pre-service science teachers.

Respondents

Senior pre-service science teachers in five selected Teacher Education Institutions (TEIs) in the province of Nueva Ecija, Philippines, who are currently enrolled or have enrolled in Teaching Internship or Practicum in Teaching for the academic year 2021-2022 were the respondents of this study. A total of 114 respondents from these five TEIs participated. The researcher employed a purposive sampling method, selecting institutions that were identified as the top producers of licensed teachers in the past five consecutive years in the province, based on consolidated data from the Professional Regulation Commission (PRC). The purpose of choosing senior Pre-Service Science teachers relies on the assumption that these respondents have finished all their science major subjects; thus, they have also finished all their Biology subjects. Therefore, the necessary Evolution concepts are expected for these respondents to have learned.

Research Instruments

The researchers utilized the following survey-questionnaire tools for the study:

Socio-demographic Profile Survey

The demographics survey was used to collect information about respondents' gender, age, type of Teacher Education Institution, and Evolution knowledge self-rating.

Biological Evolution Literacy Survey (BEL)

The Biological Evolution Literacy Survey, which presents 23 biological misconception statements grouped into five categories, served as the research tool for identifying students' misconceptions and calculating conception index scores. This research tool is adopted from Yates and Marek (2015) with Cronbach's alpha of 0.848.

Two methods of scoring responses were used during data analysis. First, the responses "strongly agree" and "somewhat agree" were combined, indicating participant agreement with the statement. Likewise, the responses "strongly disagree" and "somewhat disagree" were combined, indicating participant disagreement with the statement. Second, by means of Likert scaling of responses, a biological Evolution misconception scoring index was calculated. The possible range of BEL Survey index scores was 0 to 115, with a score of 115 representing a lack of associated misconceptions, whereas lower indices represented high levels of biological Evolution-related misconceptions. In addition, a count of the number of misconceptions revealed by responses to the statements was conducted.

Evolution Content Knowledge Test (ECKT)

A 21-item Evolution Content Knowledge Test with one correct answer and four distracters, initially developed by Johnson (1986) and modified by Rutledge and Warden (2000), was used to assess pre-service science teachers' understanding of Evolution. The test covers the following content areas: natural selection, extinction processes, homologous structures, coEvolution, analogous structures, convergent Evolution, intermediate forms, adaptive radiation, speciation, Evolutionary rates, the fossil record, biogeography, environmental change, genetic variability, and reproductive success. A total of 21 points would indicate a perfect understanding of the content, and a score of 0 represents no understanding of the content. The research panel of experts evaluated and accepted the test as valid. Moreover, the internal consistency of the test was measured, and the result was 0.78 (Rutledge & Warden, 2000).

The ECK test scores were reported as the per cent of questions answered correctly with score ranges representing the student's level of understanding: very high (90–100), high (80–89), moderate (70–79), low (60–69) and very low (59 or less).

Measure of Acceptance of the Theory of Evolution (MATE)

The Measure of Acceptance of the Theory of Evolution (MATE) (Rutledge & Warden, 1999) was utilized to assess students' acceptance of the Evolutionary theory. This instrument has 20 statements and was scored using a Likert scale. The response with the highest level of acceptance of Evolution received a score of 5, while the response with the lowest level of acceptance of Evolution received a score of 1. As a result, the total score range was 20-100. Rutledge (1996) developed the following acceptance categories based on the MATE's initial field testing: very high acceptance: 89-100; high acceptance: 77-88; moderate acceptance: 65-76; low acceptance: 53-64; very low acceptance: 20-52.

Data Gathering and Analysis

A letter requesting authorisation to conduct the study was personally delivered or sent online to the different deans of the College of Education or the Campus Director of the five TEIs prior to the start of the study. Once approved, the researcher made a Group Chat (GC) in Facebook Messenger for all the pre-service respondents. The survey questionnaires were created and administered using Google Forms. The link was sent to the GC for easy dissemination and tracking.

The data collected from the socio-demographic profile survey, the scale responses and number of biological Evolution misconceptions from BEL, test scores from ECK, and scale responses from MATE were analysed by descriptive statistical methods including frequency counts, per centages, and means. The statistical technique of Pearson-product-moment correlation was used to explore relationships between the variables.

Results

The Socio-Demographic Profile of the Respondents

The socio-demographic profile of the respondents, such as sex, age, type of Teacher Education Institution affiliated with, and evolution knowledge self-rating, is presented in Table 1.

It can be gleaned from the table that the majority, or 74 per cent of the respondents (64.91%) were female, while 40 per cent or 35.09 per cent were male. This is consistent with the observation by Lacap (2015) that teacher education is primarily a female-focused field of study.

Table 1

Socio-Demographic Profile of the Respondents

Parameters	Frequency N = 114	Per centage
Sex		
Male	40	35
Female	74	65
Age		
21	23	20
22	78	68
23	8	7
24	2	2
25 and above	3	3
Teacher Education Institution		
Public	99	87
Private	15	13
Evolution Knowledge Self-Rating		
Poor	0	0
Fair	1	1
Moderate	66	58
Good	42	37
Excellent	5	4

Table 1 also indicates that the majority of the respondents were 22 years old, with a frequency of 78 or 68.42 per cent. The K-12 curriculum was implemented in the Philippines in 2012, and these senior science pre-service teachers were the first batch of this enhanced curriculum. Therefore, due to the additional two years, the expected college seniors' age before (20 years old) will also be added by two years, which is why most of the respondents are 22 years old.

The table also shows that the majority of 99 respondents (86.84%) were affiliated or enrolled in public Teacher Education Institutions (TEI). Fifteen or 13.16 per cent were affiliated or enrolled in a private TEI. This result implies that pre-service science teachers are primarily produced by public colleges and universities in the province of Nueva Ecija.

Lastly, Table 1 also shows that 66 or more than half of the respondents (58%) rated their knowledge about Evolution as “Moderate.” No one rated having a “Poor” knowledge of Evolution. Thus, these pre-service science teachers consider themselves to have neither excellent nor poor knowledge about Evolution.

The Misconceptions Held by Respondents in the Evolution Concepts

The misconceptions held by respondents about Evolution concepts are determined in the following discussions, as shown in Table 2.

Table 2 shows each BEL Survey statement and the per centage of respondents who responded to it. The combined per cent responses of respondents highlighted in orange identify the per centage of respondents who held the associated misconception of the accompanying statement, whereas the combined pair of per cent responses in the adjacent regions highlighted in blue identify the per centage of respondents who held the correct concept as related to the statement (Yates & Marek, 2015). Undecided and No Response were highlighted in grey.

Table 2

BEL Survey Statement Pre-Service Science Teachers' Per cent Responses

#	Category*	Statement	Pre-Service Teachers Response (%)					
			1	2	3	4	5	6
1	SSMT1	A scientific theory that explains a natural phenomenon can be defined as a "best guess" or "hunch."	18.42	50.88	11.40	14.91	4.39	0
2	SSMT2	The scientific methods used to determine the age of fossils and the Earth are reliable.	58.77	37.72	1.75	1.75	0	0
3	SSMT3	According to the second law of thermodynamics, complex life forms cannot evolve from simpler life forms.	17.54	50	14.91	14.91	2.63	0
4	SSMT4	The Earth is old enough for Evolution to have occurred.	23.68	38.60	18.42	11.40	6.14	1.75
5	SSMT5	Evolution cannot be considered a reliable explanation because Evolution is only a theory.	13.16	32.46	33.33	19.30	1.75	0
6	IE1	Evolution always results in improvement.	41.23	41.23	13.16	3.51	0.88	0
7	IE2	Members of a species evolve because of an inner need to evolve.	42.98	47.37	4.39	5.26	0	0
8	IE3	Traits acquired during the lifetime of an organism—such as large muscles produced by body building—will not be passed along to offspring.	38.60	38.60	9.65	13.16	0	0
9	IE4	If webbed feet are being selected for, all individuals in the next generation will have more webbing on their feet than do individuals in their parents' generation.	12.28	55.26	20.18	8.77	2.63	0.88
10	IE5	Evolution cannot cause an organism's traits to change within its lifetime.	8.77	23.68	34.21	28.07	4.39	0.88
11	NE1	New traits within a population appear at random.	24.56	52.63	15.79	5.26	0.88	0.88
12	NE2	By means of Evolution, individual organisms adapt to their environments.	67.54	28.95	2.63	0	0	0.88
13	NE3	Evolution is a totally random process.	21.93	42.98	21.93	7.89	3.51	1.75
14	NE4	The environment determines which traits are best suited for survival.	54.39	41.23	3.51	0	0	0.88
15	ME1	Variation among individuals within a species is important for Evolution to occur.	48.25	41.23	7.89	0	1.75	0.88
16	ME2	"Survival of the fittest" means basically that "only the strong survive."	46.49	31.58	14.91	6.14	0	0.88
17	ME3	The size of the population has no effect on the Evolution of a species.	12.28	23.68	35.09	27.19	0.88	0.88
18	ME4	Complex structures such as the eye could have been formed by Evolution.	23.68	47.37	15.79	11.40	0.88	0.88
19	ME5	Only beneficial traits are passed on from parent to offspring.	12.28	27.19	28.95	29.82	0.88	0.88
Table 2. BEL Survey Statement Pre-Service Science Teachers' Per cent Responses (Continued)								
20	ESE1	There exists a large amount of evidence supporting the theory of Evolution.	36.84	49.12	10.53	2.63	0	0.88
21	ESE2	According to the theory of Evolution, humans evolved from monkeys, gorillas, or apes.	49.12	31.58	9.65	7.89	0.88	0.88
22	ESE3	Scientific evidence indicates that dinosaurs and humans lived at the same time in the past.	19.30	30.70	22.81	21.93	4.39	0.88
23	ESE4	The majority of scientists favor Evolution over other explanations for life's diversity.	32.46	43.86	15.79	3.51	2.63	1.75

Note:

1	Strongly Agree		Misconception
2	Somewhat Agree		
3	Somewhat Disagree		Correct Concept
4	Strongly Disagree		
5	Undecided		Undecided/No Response
6	No Response		

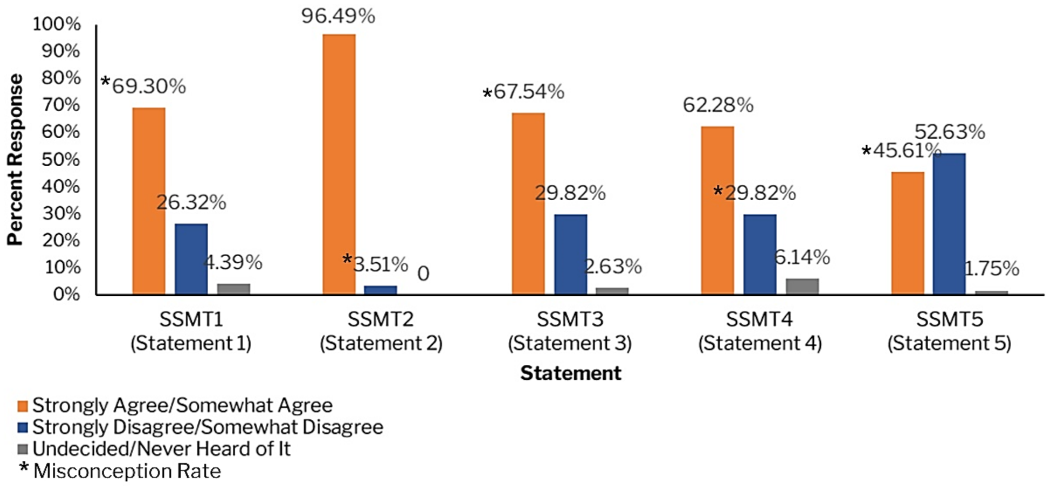
SSMT, Science, scientific methodology, and terminology; IE, intentionality of Evolution; NE, nature of Evolution; ME, mechanisms of Evolution; ESE, evidence supporting Evolution.

Science, Scientific Methodology, and Terminology

Statements 1 through 5 address the general opinions of student respondents concerning Science, scientific methodology, and terminology as they relate to Evolution. The responses to each of these statements are depicted in Figure 1.

Figure 1

Per cent Response to Science, Scientific Methodology and Terminology



It can be gleaned from Figure 1 that responses to statement 1 *("A scientific theory that explains a natural phenomenon can be defined as a 'best guess' or 'hunch'"*) reveal that 69.30 per cent (n= 79) of the respondents failed to interpret the word "theory" as used by the scientific community and its difference with its word usage in daily communication. Only 26.32 per cent (n=30) correctly interpreted the word theory.

The response performed slightly better for statement 5 *("Evolution cannot be considered a reliable explanation because Evolution is only a theory"*), with 45.61 per cent (n=52) of the respondents agreeing with this statement, suggesting a misconception. According to Yates and Marek (2015), in common parlance, the terms 'guess' or 'hunch'—implying speculation or conjecture—are synonymous with theory. But "theory" from the scientific point of view is far from speculation or conjecture. When scientists use the term *"theory,"* they mean a logical, tested, and well-supported explanation for a wide range of facts; thus, scientific theories are not mere guesses (Smith & Sullivan, 2007). Students who have misconceptions about scientific theories typically understand theory in the speculative sense, as in *Evolution is just a theory.* This claim is supported by the results of the study of Prinou et al. (2008), in which the researchers reported that when Evolution is referred to as a "theory," students believe it is not supported by evidence. This kind of misconception is called *vernacular misconception,* which results from the distinction between a word's scientific and common usage and the resulting misunderstanding of the distinction (Alters & Nelson, 2002).

Statement 2 *("The scientific methods used to determine the age of fossils and the earth are reliable")* obtained a relatively high per centage of respondents agreeing with this statement, with 96.49 per cent (n=110) agreeing and only 3.51 per cent (n=4) disagreeing with the statement, thus holding a misconception. A comparative statement, statement 4 (*"The Earth is old enough for Evolution to have occurred"),* received a less favourable response, with 62.28 per cent (n=71) in agreement, while 29.82 per cent (n=34) disagreed. Thus, even though the pre-service science teachers generally recognise the reliability of scientific dating techniques, some still believe that the Earth is not old enough for Evolution to have occurred. The same misconception was reported by Robbins and Roy (2007) when they found out that the students' doubts about Evolution stem from their belief that Evolution occurs over *centuries* rather than tens and hundreds of millennia, indicating the students' difficulty in understanding the basic premise in the theory of Evolution, which is that Evolutionary processes require a long period to occur.

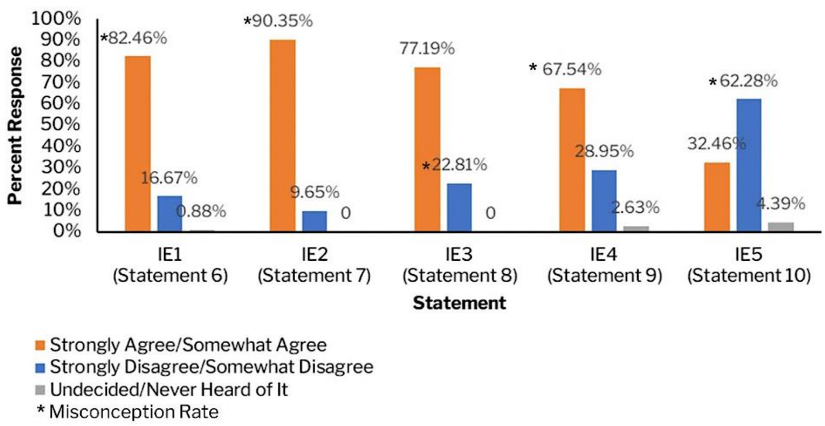
Responses to statement 3 *("According to the second law of thermodynamics, complex life forms cannot evolve from simpler life forms")* revealed that the majority of the respondents have a misconception about this statement, as reflected by 67.54 per cent (n= 77) agreeing to it, while only 29.82 per cent (n=34) of the respondents lacked the associated misconception. According to Schreiber and Gimbel (2010), the anti-Evolutionists' argument that *"Evolution violates the second law of thermodynamics"* is based on a misunderstanding of the second law of thermodynamics, which states that disorder (or entropy) constantly increases, implying that complex organisms could not have evolved from simple organisms because systems become more disordered over time. Schreiber and Gimbel (2010) did, however, explain that the increase in entropy is only to be expected in *thermally isolated systems* (closed systems) or those in which no energy is added or removed. However, organisms do not live in such a system because the Sun constantly adds energy, and they can use it to overcome the increase in entropy. Based on the findings, the majority of Science pre-service teachers failed to understand that life operates within an *open system* with a constant inflow of energy, leading to a misconception that Evolution violates the second law of thermodynamics.

Intentionality of Evolution

The five statements of the BEL Survey Intentionality of Evolution section were designed to determine the respondents' misconceptions about biological Evolution intentionality. Figure 2 depicts the responses to each of these statements.

Figure 2

Per cent Response to Intentionality of Evolution



Responses from statement 6 (“Evolution always results in improvement”) showed that a hefty 82.46 per cent (n=94) agreed with this statement, signifying misconception, while only 16.67 per cent (n=19) understood that Evolution does not always result in improvement. Statement 7 (“Members of a species evolve because of an inner need to evolve”) produced a comparable result in which the majority of the respondents also or 90. Thirty-five per cent (n=103) agreed with this statement, whereas only 9.65 per cent (n=11) disagreed. This finding suggests that these science pre-service teachers perceive Evolutionary processes as deterministic in nature, with improvement as their goal. Furthermore, acceptance of statement 9 (“If webbed feet are being selected for, all individuals in the next generation will have more webbing on their feet than do individuals in their parents’ generation”) also implies a deterministic view of Evolutionary mechanisms. Findings demonstrated that 67.54 per cent (n=77) of the respondents have this misconception, and only 28.95 per cent (n=33) disagreed.

Statement 10 (“Evolution cannot cause an organism’s traits to change within its lifetime”) elicited 32.46 per cent (n = 37) agreement among respondents, with 62.28 per cent (n = 71) disagreeing, indicating that the majority of respondents believe Evolutionary processes can cause a change in individual organisms during their lifetimes. Furthermore, statement 8 (“Traits acquired during the lifetime of an organism--such as large muscles produced by body building—will not be passed along to offspring”) yielded agreement among 77.19 per cent (n=88) of the respondents, as opposed to 22.81 per cent (n=26) who apparently believed in the Lamarckian misconception of inheritance through acquired characteristics. These findings show that, while the majority of respondents correctly understand that acquired traits cannot be passed down to the next generation, the majority of respondents also still believe that characteristics acquired by an organism during its lifetime are produced by Evolutionary processes, as reflected by the responses in statement 8 and 10, respectively.

Surveyed literature done by Yates and Marek (2015) showed that the tendency of students toward biological Evolutionary explanations based on purpose is widespread and consistent in the literature. For example, Alters and Nelson (2002) reported that in a survey of 392 university students, nearly 43 per cent believed that "Evolution involved a purposeful striving toward higher forms (that it is steady progress from microbes to man)." Moreover, Prinou et al. (2008) stated that in their study, the majority of students believed that new features emerged in the organisms out of need since 59.3 per cent agreed that “new features appear in organisms because they need them in order to survive.” Misconceptions regarding the intentionality of Evolution also exist among teachers (Tidon & Lewontin, 2004; Nehm & Schonfeld, 2007).

Nature of Evolution

The Nature of Evolution statements, 11-14, addressed respondents' views on the nature of Evolution, including the roles of randomness, the environment in Evolutionary processes, and adaptation. The responses to each of these statements are depicted in Figure 3.

Figure 3

Per cent Response to Nature of Evolution

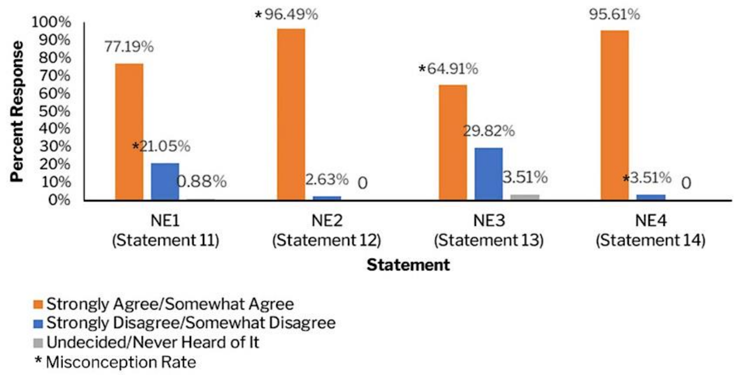


Figure 3 demonstrates that responses for statement 11 *("New traits within a population appear at random")* produced only 21.05 per cent (n=24) disagreement, supporting the misconception, while 77.19 per cent (n=89) agreed. A comparative statement, statement 13 *("Evolution is a totally random process"),* resulted in 64.91 per cent (n = 74) of respondents in agreement, thus having an associated misconception, while 29.82 per cent (n =34) disagreed.

Conversely, although fewer respondents disagreed with statement 11, the majority of them agreed with statement 13, presenting the conflicting misconceptions that Evolution is a totally random process, yet new traits within a population *do not* appear at random. The same result was also found by Yates and Marek (2015). However, it should be pointed out that these rates of misconceptions among respondents about the concept of randomness are concerning, as Isaak (2003) contends that there is no other misconception that is a better indicator of a lack of understanding of Evolution than the misconception that Evolution proceeds by random chance. He argued that while chance certainly plays a role in Evolution, this argument completely ignores natural selection, which is the opposite of chance. Furthermore, Smith and Sullivan (2007) clarified that the simple phrase *"Evolution is random"* is dangerously clumsy since it simply does not acknowledge the complexity of Evolution. The complete diversity of life, including its order, balance, and complexity, is the outcome of a *nonrandom selection of random variations* in living organisms.

Statement 14 *("The environment determines which traits are best suited for survival")* revealed that a large 95.61 per cent (n=109) correctly agreed with the statement, and only 3.51 per cent (n=4) disagreed, thus having a misconception. On the contrary, responses from statement 12 *("Individual organisms adapt to their environments")* found that only 2.63 per cent (n = 3) of respondents disagreed, whereas a hefty 96.49 per cent (n = 110) agreed, claiming the associated misconception.

The relatively high per centage of respondents who held this misconception raised concerns. The same concern was also raised by Yates and Marek (2015) regarding this misconception of this statement. Since Yates and Marek (2015) surveyed high school students, they assumed that this very high misconception rate for statement 12 is because they may have failed to address the term adapt in an Evolutionary context due to their *limited academic exposure* to biological Evolution concepts. However, for this study, the respondents were pre-service teachers who had undergone four years of studying in a teacher education institution, majoring in Science. Therefore, they have had *more exposure* to biological Evolution concepts than the respondents of Yates and Marek (2015). This finding only signifies that these pre-service science teachers still did not fully grasp the word "adaptation" in an Evolutionary context despite their four years of college or university studies. Unfortunately, they failed to understand that the smallest unit that adapts in an Evolutionary context is not an individual but a population.

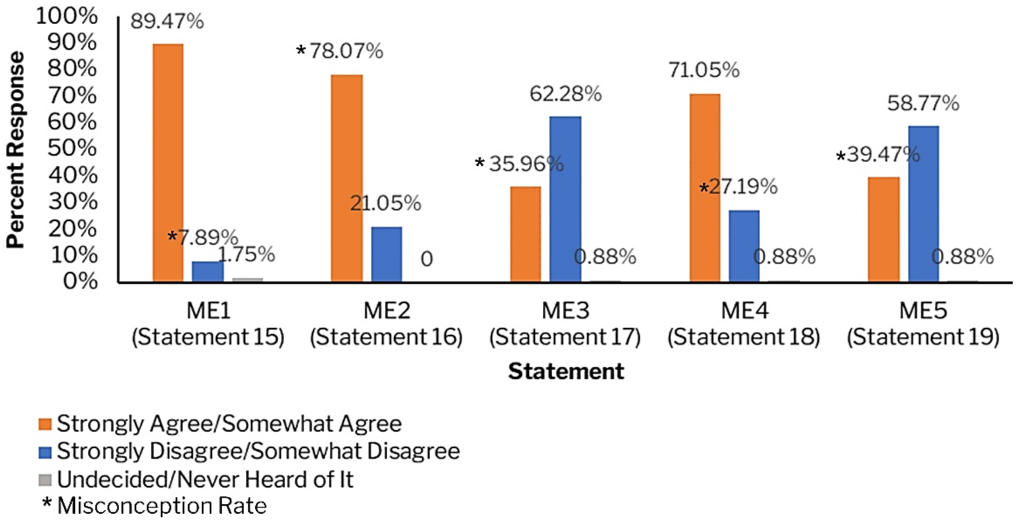
Mechanisms of Evolution

Statements 15 through 19 addressed respondents' perspectives on the mechanisms that lead to Evolutionary change. Figure 4 illustrates the responses to these statements.

Responses from statement 15 *("Variation among individuals within a species is important for Evolution to occur")* show that the majority of respondents (89.47%, n = 102) agreed with statement 15. In comparison, only 7.89 per cent (n = 7) believe that variation among members of a species is not an important contributing factor to Evolutionary processes, adhering to a misconception. This finding is also found by Wescott and Cunningham (2009), in which the majority of university students (83%) also tend to agree that variation matters in Evolution.

Figure 4

Per cent Response to Mechanisms of Evolution



Responses from statement 16 *("Survival of the fittest' means basically that 'only the strong survive")* demonstrated that the majority of students have a misconception since 78.07 per cent (n=89) of the respondents agreed with this statement, while 21.05 per cent (n=24), disagreed. Out of all the misconceptions in this category, statement 16 has the highest rate of misconception among the respondents. Smith and Sullivan (2007) clarified that the word *fitness* in an Evolutionary context pertains to the statistical likelihood that an organism will have offspring. Thus, those respondents who have misconceptions about statement 16 have a faulty understanding of the word "fitness" in an Evolutionary context, another example of vernacular misconception. Like the word "adapt," other researchers reported that the scientific meaning "fitness" has undoubtedly been distorted by its use in common parlance (Alters & Nelson, 2002; Bishop & Anderson, 1990). Based on the surveyed literature, students may associate the meaning of "survival of the fittest" with physical strength, speed, intelligence, longevity, the number of mates possessed, or even physical fighting between different species, with the strongest species winning (Bishop and Anderson,1990; Anderson et al. 2002; Robbins and Roy 2007; Wescott & Cunningham, 2009), indicating how pervasive this misconception is.

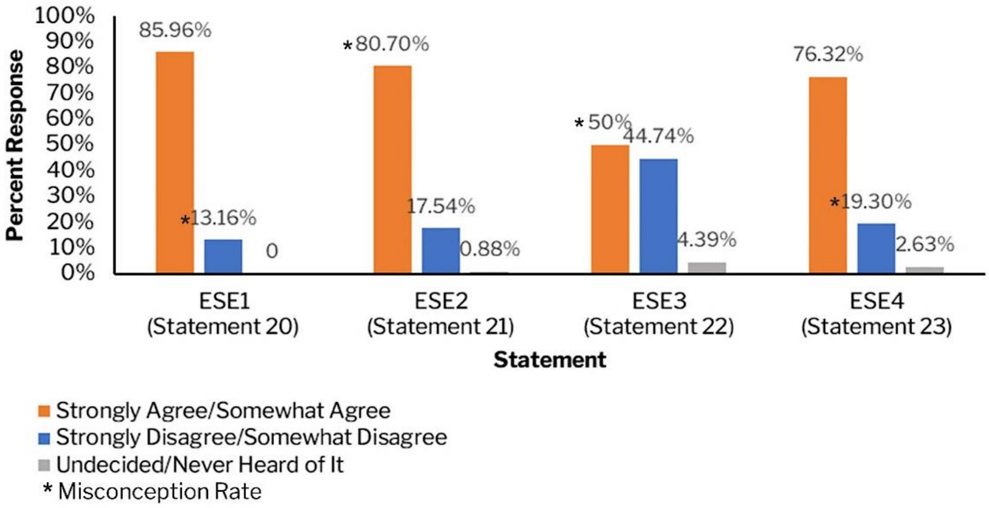
Statement 17 *("The size of the population has no effect on the Evolution of a species")* resulted in disagreement among 62.28 per cent (n = 71) of respondents, while 35.96 per cent (n =41) voiced their agreement with the statement, thus revealing a misconception. Statement 18*("Complex structures such as the eye could have been formed by Evolution")* demonstrated a response, being favored by 71.05 per cent (n = 81) of respondents, whereas 27.19 per cent (n = 31) disagreed, thus having a misconception. Lastly, Statement 19 *("Only beneficial traits are passed on from parent to offspring")* showed that 39.47 per cent (n= 50) affirmed this statement, thus adhering to the misconception that hereditary mechanisms are the reason for passing only *advantageous traits* from generation to generation, while 58.77 per cent (n=70) disagreed, correctly understand that inheritance does not dispense only beneficial traits, *but harmful traits as well.*

Evidence Supporting Evolution

Statements 20 through 23 addressed respondents' opinions on evidence supporting Evolution. The responses to each of these statements are depicted in Figure 5.

Figure 5

Per cent Response to Evidence Supporting Evolution



It can be gleaned from Figure 5 that responses from statement 20 *("There exists a large amount of evidence supporting the theory of Evolution")* revealed that the majority of respondents, or 85.96 per cent (n = 96), agreed, whereas 13.16 per cent (n = 15) revealed the associated misconception that there is not. Thus, the majority of respondents recognize that a large amount of evidence supports Evolution. The fossil record of ancient life, such as plants and animals, can assist scientists in determining the truth about life on Earth. For instance, the fossil record contains over 200,000 examples of extinction (Smith & Sullivan, 2007). That is why, according to Mayr (2001), the discovery of fossils of extinct organisms in older geological strata is the most convincing evidence for the occurrence of Evolution.

However, responses from Statement 22 *("Scientific evidence indicates that dinosaurs and humans lived at the same time in the past")* revealed a *surprising result* in which 50 per cent (n=57) agreed with this statement, indicating a misconception, while 4.39 per cent (n=5) were undecided/never heard of the statement, therefore, despite the fact that the fossil record indicates the two groups are separated by *approximately 65,000,000 years* (Alters & Nelson, 2002), half of the respondents accept the coexistence of humans and dinosaurs. Based on this finding, it is disconcerting to see so many pre-service science teachers having this misconception since adherence to this single misconception alone reveals a *less than adequate understanding* of the evidence supporting Evolution (Yates & Marek, 2013). The misconception rate generated in this statement is notably higher than the misconception rate found by other researchers. In a similar statement, only 27 per cent of Californian college students thought humans and dinosaurs lived at the same time (Wilson, 2001), 11 per cent of university students have this misconception (Wescott & Cunningham, 2009), 33.6 per cent of high school students (Yates & Marek, 2015) and 25 per cent of Biology teachers (Yates & Marek, 2013).

Statement 21 related to human Evolution *("According to the theory of Evolution, humans evolved from monkeys, gorillas, or apes")* garnered a large 80.70 per cent (n=92) of respondents' affirmative responses to this statement, thus holding to one of the most prevalent and persistent misconceptions in Evolution--- humans evolved from monkeys, gorillas or apes. Smith and Sullivan (2007) explained that humans did not evolve from monkeys, gorillas, or apes. Humans *share a common ancestor* with chimps and, before them, with the group that evolved into monkeys. The authors further emphasize that to say humans evolved from monkeys is *simply wrong,* and Evolution has never claimed it. Mayr (2001) pointed out the culprit of this misconception, stating that one of the common misconceptions about macroEvolution held by most students is that Evolution is exclusively a *linear process* in time. As a result, various studies also recorded this misconception among students (Woods, 2001; Robbins & Roy, 2007; Wescott & Cunningham, 2009) and teachers (Yates & Marek, 2013).

Lastly, Statement 23 *("The majority of scientists favor Evolution over other explanations for life's diversity")* yielded 76.32 per cent (n = 87) agreement among respondents, with 19.30 per cent (n = 22) in disagreement, having a misconception. Thus, the majority of respondents recognize that majority of scientists favor Evolution over other explanations for life's diversity.

Summary of BEL Responses

In totality, out of a possible Biological Evolution Literacy Survey Maximum Index Score (BEL-MIS) of 115, pre-service science teachers in this study (N = 114) earned a 70.02 (SD = 7.43) BEL-MIS for the 23 statements with an average of 47 per cent misconception rate, 51 per cent correct concept rate and combined 2 per cent undecided and nonresponse rate. The developers of BEL did not establish a specific scale for verbal interpretation of the possible indices that fall between 0 and 115 for the BEL Survey index scores. However, they recommend converting the BEL-MIS score to a per centage to interpret the data. Thus, following this method, a 70.02 BEL-MIS indicates that the respondents scored 61 per cent of the maximum score of 115 overall, indicating a fairly high level of misconceptions.

The Level of Understanding of the Respondents of Evolution

The respondents' level of understanding of Evolution is presented in Table 3. It can be deduced from the table that almost all of the respondents have a surprisingly "Very Low" understanding of Evolution, as reflected by 95.61 per cent (n=109) of the pre-service science teachers. Only 1.75 per cent (n=2) have "Moderate" and "High" levels of understanding, while only 0.88 per cent (n=1) of the respondents has "Low" level of understanding. No one has a "Very High" level of understanding of Evolution. Overall, the level of understanding of pre-service science teachers is "Very Low" (Mean=34.25; SD=13.76).

Table 3

Level of Understanding of the Respondents to Evolution

Range	Descriptive Rating	Frequency Mean = 34.25 Sd = 13.76	%
59 or less	Very Low	109	95.61
60 – 69	Low	1	0.88
70 – 79	Moderate	2	1.75
80 – 89	High	2	1.75
90 – 100	Very High	0	0.00

This result indicates that there is a problem with how these pre-service science teachers learned the theory of Evolution. Considering that they are currently in their fourth year of studying the course, they are expected to have already learned at least the basic concepts of Evolution in their Biology subjects; however, the results revealed that these were not learned efficiently. Thus, it implies that there is a problem in emphasizing Evolution education in science teacher preparation curriculum in Teacher Education Institutions in the Philippines. This indicates the need for more targeted instructional interventions to address these knowledge gaps.

The finding conforms with the study of Clores et al. (2014), in which they also found that pre-service and in-service secondary Biology teachers in the Philippines, specifically Regions V (Bikol) and IX (Zamboanga City), had a poor understanding of natural selection, one of the essential concepts in Evolution. The result was also generally in line with the published levels of understanding or knowledge regarding the Evolution of Chinese and Indonesian pre-service teachers, in which they scored low (Ha et al., 2019; Rachmatullah et al., 2018). Moreover, Farenwald (1999), Nehm et al. (2009), and Nunez et al. (2012) reported that public high school teachers in South Dakota, pre-certified Biology and non-Biology teachers in New York, and Belizean Biology teachers also have low levels of understanding of Evolution.

The Level of Acceptance of the Respondents to Evolution

Table 4 reports that pre-service science teachers have "Moderate Acceptance" (Mean=68.41; SD=9.07) of the theory of Evolution. This finding implies that Filipino pre-service science teachers accept the theory of Evolution, but not entirely. The findings show that acceptance of Evolution among respondents is moderate but influenced by their misconceptions and understanding. This suggests that addressing misconceptions and improving understanding could enhance acceptance levels.

Table 4

Level of Acceptance of the Respondents to Evolution

Range	Descriptive Rating	Frequency Mean = 68.41 Sd = 9.07	%
20 – 52	Very Low Acceptance	2	1.75
53 – 64	Low Acceptance	47	41.23
65 – 76	Moderate Acceptance	40	35.09
77 – 88	High Acceptance	24	21.05
89 – 100	Very High Acceptance	1	0.88

This moderate level of acceptance of Evolution by Filipino pre-service science teachers supports Partosa's (2018) description of the status of acceptance of Evolution in the Philippines. She reported that it remains in need of wide public acceptance and is on the periphery even in academic discourse.

This finding is also consistent with the acceptance rates of pre-service teachers of various nationalities reported in various studies. According to Akyol et al. (2010), Turkish pre-service science teachers accept Evolution to a moderate degree. Kim and Nehm (2011) found that the average Measure of Acceptance of the Theory of Evolution (MATE) score of Korean pre-service teachers was 73.79 (SD = 9.2), indicating moderate acceptance of the Evolution. The average MATE score for Indonesian pre-service Biology teachers was 65.06 (SD = 6.76), indicating moderate acceptance of Evolution (Rachmatullah et al., 2018). According to Rutledge and Warden (2000), Indiana public high school Biology teachers accept the Evolutionary theory moderately.

Moreover, it was notable that the respondents' level of acceptance in this study is higher than the reported levels of acceptance by the studies of Nunez et al. (2012) and Peker et al. (2010), which showed low levels of acceptance of Evolution among teachers and students, respectively. Nunez et al. (2012) stated that with an average MATE score of 64.4 and a mean knowledge score of 47.9 per cent, Belizean teachers were classified as having 'Low Acceptance' while Peker et al. (2010) reported that their study results among Biology, Biology education, and science education majors resulted to an overall acceptance rate of Evolution theory was 27.75 per cent.

On the contrary, it was also notable that the respondents' level of acceptance in this study was lower than the reported levels of acceptance by the studies of Trani (2004) and Korte (2003). Analysis of the Oregon Biology teachers' responses to the MATE demonstrated a high acceptance of Evolutionary theory with a mean MATE = 85.9, SD = 17.48 (Trani, 2004). Ohio life science teachers also highly accepted Evolution after analysing their MATE scores revealed a mean MATE = 87, SD = 17.24 (Korte, 2003).

The Relationship between the Respondents' Evolution-related Misconceptions and Level of Acceptance of Evolution

The relationship between the respondents' Evolution-related misconceptions and level of acceptance of Evolution in terms of science, scientific methodology, and terminology, intentionality of Evolution, nature of Evolution, mechanisms of Evolution, and evidence supporting Evolution is determined in the following discussions as shown in Table 5.

The level of acceptance of Evolution is found to have a significant relationship with four out of five categories of Evolution-related misconceptions. Specifically, it has a positive correlation and is highly correlated with science, scientific methodology, terminology ($r = .427$), and mechanism of Evolution ($r = .424$) with p values less than 0.01. The evidence supporting the Evolution category also has a positive correlation ($r = .217$, $p < 0.05$). Seemingly, the higher the misconceptions related to science, scientific methodology, terminology, mechanism of Evolution, and evidence supporting Evolution, the higher the acceptance of Evolution, while the lower the misconceptions in these categories, the lower the acceptance of Evolution.

On the contrary, intentionality of Evolution category has a negative correlation ($r = -.190$, $p < 0.05$). Seemingly, the higher the misconceptions related to the intentionality of Evolution, the lower the acceptance of Evolution, while the lower the misconceptions in these categories, the higher the acceptance of Evolution.

Table 5

Relationship between the Respondents' Evolution-related Misconceptions and Level of Acceptance of Evolution

Evolution-Related Misconceptions	Level of Acceptance of Evolution	
	r	p-value
Science, Scientific Methodology, and Terminology	.427**	.000
Intentionality of Evolution	-.190*	.042
Nature of Evolution	.063	.507
Mechanism of Evolution	.424**	.000
Evidence Supporting Evolution	.217*	.020

Note. * correlation is significant at 0.05 level (2-tailed), ** correlation is significant at 0.01 level (2-tailed)

The findings of this study were unexpected and surprising. The researchers expected that the acceptance of Evolution has a *negative correlation* with Evolution-related misconceptions, but the results reflect that even though the respondents have a fairly high level of misconceptions regarding Evolution, they still accept the Evolution concepts. Thus, an *interesting relationship* has been revealed by this finding. The researchers initially thought that this relationship was unprecedented. However, an extensive literature review revealed that Clores and Limjap (2006) and Clores and Bernardo (n.d.) reported in their *qualitative approach* to investigating the diversity of Filipino Catholic students' beliefs about Evolution that some students accepted the theory of Evolution *based on alternative conceptions or misconceptions.*

These researchers concluded that "acceptance of the theory of Evolution is *not necessarily based on an accurate and sophisticated understanding of the theory.* Many students *submitted to a lot of misconceptions* and used them to *justify their confidence* in the theory. Even after instruction, they held on to these misconceptions and beliefs". These researchers' conclusions confirmed the unexpected and surprising result of this quantitative study, which investigated the relationship between Evolution-related misconceptions and the level of acceptance among pre-service science teachers.

The Relationship between the Respondents' Level of Understanding and Level of Acceptance of Evolution

The level of understanding of Evolution was found to have a significant relationship with the level of acceptance of Evolution.

Table 6

Relationship between the Respondents' Level of Understanding and Level of Acceptance of Evolution

Level of Understanding of Evolution	Level of Acceptance of Evolution	
	r	p-value
	.264**	.005

Note. ** correlation is significant at 0.01 level (2-tailed)

Table 6 presents that the level of understanding of Evolution has a weak positive correlation and is highly correlated with the level of acceptance of Evolution ($r=.264$, $p < 0.01$). This finding indicates that the lower the understanding of Evolution of pre-service science teachers, the lower their acceptance of Evolution. In the same manner, the higher the level of their understanding of Evolution, the higher the level of their acceptance of Evolution. Thus, the current findings imply that a faulty understanding of the theory could lead to rejecting Evolution. However, improving the pre-service science teachers' understanding of Evolution can lead to an increase in their acceptance of the Evolutionary theory.

Discussion

This study is primarily conducted to determine the misconceptions, level of understanding, and acceptance of Filipino pre-service Science teachers to biological Evolution and to investigate the relationship between these variables. A 70.02 BEL-MIS indicates that the respondents scored 61% of the maximum score of 115, overall indicating a fairly high level of misconceptions. This suggests that despite four years of science education, misconceptions about Evolution remain prevalent, emphasizing gaps in Evolution education within teacher education programs. This suggests that despite four years of science education, misconceptions about Evolution remain prevalent, emphasizing gaps in Evolution education within teacher education programs. This finding coincides with the findings of Yates and Marek (2014) that biological Evolution-related misconceptions were prevalent among Oklahoma's introductory Biology teachers.

Similar findings have been reported in other studies, where persistent misconceptions about Evolution have been observed among pre-service teachers across different educational systems (Akyol et al., 2012a; Athanasiou et al, 2012). These misconceptions often stem from early educational experiences, religious and cultural influences, and inadequate pedagogical approaches to teaching Evolution. These pre-service teachers, soon to become educators themselves, may face challenges in teaching Evolution accurately. Interestingly, most respondents self-rated their knowledge of Evolution as "Average" or "Good," yet their ECKT scores reflected poor understanding. This discrepancy mirrors findings in previous research, where confidence in scientific knowledge does not always correlate with actual understanding (Nehm & Schonfeld, 2007). Such a disparity suggests that pre-service teachers may rely on superficial or misconceived understandings of Evolution, which can be perpetuated in their future classrooms if not addressed effectively.

Notably, the data indicated that misconceptions could positively influence acceptance. This paradox may arise because respondents use their misconceptions to justify their acceptance of Evolution, reflecting a superficial alignment rather than an informed understanding. This finding suggests that traditional teaching methods, which often prioritize content delivery over critical engagement, may inadvertently sustain these misconceptions. Studies have shown that passive learning environments reinforce misconceptions, as students may memorize Evolutionary concepts without critically evaluating them (Sinatra et al., 2003). Thus, shifting towards more inquiry-based and discussion-driven pedagogical strategies is essential to ensure a deeper conceptual grasp of topics in science, such as Evolution (Usman et al., 2023; Liline et al., 2024)

Educators must address this paradox by fostering scientific thinking and critical analysis in classrooms. Nelson (2008) recommends three strategies to challenge misconceptions and enhance understanding: (1) interactive engagement focused on scientific thinking, (2) developing general critical thinking skills, and (3) comparing initial misconceptions with scientific conceptions. Studies have demonstrated that students benefit most when all three strategies are integrated, as this approach helps them restructure their cognitive frameworks and replace misconceptions with accurate scientific explanations (Sinatra et al., 2003; Mufit, F., & Fauzan, 2023; Labak et al., 2024). Therefore, the findings of this study could serve as a basis for much-needed pedagogical retooling in teaching and learning Evolution, ultimately increasing knowledge and fostering greater acceptance of Evolutionary theory.
The very low level of understanding further reinforces the concerns raised by Partosa (2018), highlighting the absence of Evolution as a dedicated subject in the Philippine teacher education curriculum, as noted in CHED Memo No. 75, Series of 2017. Evolution is often taught as a subtopic in courses like Genetics, Cell and Molecular Biology, or Ecology, which are frequently rushed or skipped due to time constraints. This fragmented exposure limits students' ability to develop a cohesive understanding of Evolutionary principles, allowing misconceptions to persist. Partosa (2018) did the sole study investigating the Evolution of education holistically in the country. According to the K to 12 Science Curriculum Guide (2016), the first introduction of Evolution concepts in the Philippine Science curriculum happens in primary grades (before the age of 10), specifically in K-3. However, Partosa (2018) emphasized that in the Philippines, there is an explicit legal provision for including Evolutionary theory in the curriculum, but this is limited to the Bachelor of Science in Biology. Nothing in the provision indicates that it will be included in teacher education programs for elementary teachers, a glaring gap that must be filled given that, according to the current science curriculum, fundamental concepts of Evolution were first introduced in primary grades, as previously stated.

Moreover, the principal concepts of Evolution are taught in Junior High School (Grade 10) in terms of natural selection as its mechanism, mutations as sources of variation, speciation, environmental pressures, and biodiversity. Subsequently, the topics Evolution and Origin of Biodiversity, as well as Systematics Based on Evolutionary Relationships, were integral parts of the content for General Biology 2 in the Science, Technology, Engineering, and Mathematics (STEM) strand in Senior High School. With the science curriculum in place, the gap also clearly indicates the absence of the teaching of Evolution in secondary teacher education programs, as suggested by the currently implemented Policies, Standards, Guidelines for Bachelor of Secondary Education (BSEd) Major in Science by the Commission on Higher Education (CHED Memo No. 75, Series of 2017). Ironically, Evolution is considered by the scientific community as the unifying theme in Biology, but in preparing teachers who will teach Biology at the elementary and secondary levels, Evolution was not included in their curriculum. Thus, Partosa (2018) advocated for a reconsideration of the teacher education curriculum to align it more closely with contemporary educational needs—a call that this study supports.

Lastly, although some studies suggest that the level of understanding of Evolution has no relationship with the level of acceptance (Bishop & Anderson, 1990; Brem et al., 2003; Sinatra et al., 2003; Akyol et al., 2010; Cofré et al., 2016), the present study supports a growing body of literature reporting a positive correlation between these two variables. Research by Deniz et al. (2008) found a low but positive relationship between understanding and acceptance of Evolution among Turkish pre-service biology teachers. Similarly, Kim and Nehm's (2011) analysis revealed a significant but low association between Evolution content knowledge (ECK) scores and MATE scores ($r = 0.22$, $p < 0.05$), implying a comparable trend among Korean science pre-service teachers. Additional studies, such as those by Fahrenwald (1999), Rutledge and Warden (2000), and Nunez et al. (2012), have also documented a positive relationship between biology teachers' understanding and acceptance of Evolution. Akyol et al. (2012b) and Athanasiou et al. (2012) reported similar findings among pre-service science teachers and pre-service preschool education teachers, respectively.

These results highlight the potential for improved understanding to enhance acceptance, suggesting that targeted interventions in teacher preparation programs could yield meaningful improvements. Incorporating Evolution education into teacher training, coupled with active learning strategies and curriculum reform, could address persistent misconceptions and foster a more scientifically literate teaching workforce. Future research should explore how cultural factors uniquely influence Filipino pre-service teachers' understanding and acceptance of Evolution, contributing further to the discourse on Evolution education in diverse educational contexts.

Conclusion and Implications

Filipino pre-service science teachers exhibited a fairly high level of misconceptions, very low understanding, and moderate acceptance of Evolution. These findings underscore significant gaps in their teacher education programs, which may hinder their ability to effectively teach Evolution and related biological concepts. Misconceptions could lead to misinterpretations of Evolution and perpetuate inaccuracies in their future classrooms. Moreover, the partial acceptance of Evolution raises concerns about their confidence in teaching this foundational theory.

The most significant contribution of this study to the existing literature is its contextualization of Evolution-related misconceptions, understanding, and acceptance within the Philippine pre-service science teacher education landscape. While previous research has explored similar issues in other cultural settings, this study provides the initial empirical evidence for these three variables and their relationship to one another, specific to Filipino pre-service teachers, thereby highlighting unique challenges and areas for intervention. By establishing the relationship between misconceptions, understanding, and acceptance of Evolution, this study informs both curriculum development and instructional strategies aimed at improving Evolution education in teacher preparation programs.

To address these challenges, enhancing Evolution education should be prioritized in teacher preparation programs. This could be achieved through three key approaches: (1) reconsidering the current curriculum to include a dedicated subject on Evolution. This course would focus on Evolutionary theory and evidence-based strategies for teaching it to high school students, and (2) pedagogical retooling to equip educators with methods that emphasize critical thinking and scientific inquiry. Strategies might include presenting compelling evidence for Evolution, engaging them with fieldwork, experiments and observations that allow them to draw conclusions, and challenging them to analyze and validate this evidence independently.

This study supports the reconsideration of the teacher education curriculum to align it more closely with contemporary educational needs. With Evolution concepts now introduced as early as elementary school and reinforced through senior high school under the current Philippine science curriculum, pre-service teacher training must reflect this shift. Teacher preparation programs should place greater emphasis on Evolution education, ideally by introducing a separate course dedicated to the subject. Therefore, pre-service teachers should receive both content enrichment on Evolution and pedagogical training that incorporates instructional methodologies presenting evidence-based Evolutionary concepts. Encouraging them to evaluate and critically engage with these concepts can lead to greater understanding and acceptance of Evolution, thereby ensuring that they enter the teaching profession well-equipped to educate future generations.

Finally, a holistic approach is the third key to addressing Evolution-related misconceptions. Future research should employ both quantitative and qualitative methodologies, including interviews, concept maps, essays, and open-ended questions, to gain a deeper insight into students' knowledge structures and reasoning processes. Further exploration into effective interventions for correcting misconceptions is also necessary. An essential step is the development of a contextualized and localized instrument aligned with the Philippine curriculum to assess the misconceptions associated with Evolution among Filipino students, pre-service science teachers, and public high school science teachers. A tailored diagnostic tool would enable educators to better identify, address, and mitigate misconceptions that are unique to the local educational context.

By implementing these changes, pre-service science teachers can develop a deeper understanding and full acceptance of Evolution, enabling them to teach it confidently and accurately. These reforms are essential to ensuring that future generations receive an Evolution education rooted in scientific integrity, preparing them for a more comprehensive understanding of Biology as a whole.

Ethical Considerations

Respondents who only agreed to the consent form stated at the beginning of the administered survey were able to proceed to the rest of the questionnaire; thus, they were the only respondents included in the study. Data privacy was diligently maintained throughout the execution of the research. Each response was handled with the utmost discretion and confidentiality.

Declaration of Interests

The authors affirm that this manuscript has not been published previously and is not presently under consideration for publication elsewhere. Furthermore, there are no conflicts of interest to declare.

Acknowledgements

The authors are grateful to the administrators that allowed them to conduct this study in their respective institutions and the pre-service science teachers who participated in this study.

Funding

This project was supported by the research grant from the National Consortium in Graduate Science and Mathematics Education (NCGSME) of the Department of Science and Technology – Science Education Institute (DOST-SEI), Republic of the Philippines.

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Journal of Turkish Science Education, 2025, 22(4), 770-800.
DOI no: 10.36681/tused.2025.038

Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

Identifying approaches to secondary school physics teaching

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ABSTRACT
The purpose of this study was to investigate the instructional approaches of physics teachers using a developed questionnaire and to assess the impact of demographic factors on these approaches. The study utilised a quantitative approach through a survey methodology. A total of 573 physics teachers from secondary schools in Iran were randomly selected to complete the researcher-made questionnaire. The data analysis revealed that physics teachers use three main approaches: one which focuses on learner-centred strategies (Approach A); one which focuses on teacher-centred strategies (Approach C); and one which shares characteristics of both (Approach B). The results showed that teachers tend to use a combination of these approaches in their teaching, with Approach B being the most commonly used. Furthermore, no significant relationship was found between teachers' teaching approaches and their gender or educational levels. However, the number of years of service did have an impact on teachers' teaching approaches.

RESEARCH ARTICLE

ARTICLE INFORMATION
Received:
12.08.2024
Accepted:
01.02.2025
Available Online:
23.12.2025

KEYWORDS:
Instructional approach, physics teachers, learner-focused strategy.

To cite this article: Bahrami, S., & Golian, F. (2025). Identifying approaches to secondary school physics teaching. *Journal of Turkish Science Education, 22*(4), 770-801. http://doi.org/10.36681/tused.2025.038

Introduction

The goal of science education has long been to educate future citizens and cultivate the next generation of scientists. In recent years, there has been a growing societal emphasis on science education that fosters scientific literacy (Muhfahroyin et al., 2024) and critical thinking skills among young learners (OECD, 2019).

Effective analysis and assessment of social issues based on science are made possible by scientific literacy, which fosters critical thinking and participation in thoughtful debates (Yacoubian, 2017). In order to adapt to this change, creative teaching strategies that prioritise scientific literacy and critical thinking are crucial. Critical thinking skills, problem-solving abilities, and information analysis are all highlighted in recent PISA findings as essential competencies for 21st-century learners (OECD, 2019).

In general, there are three important factors in the process of teaching and learning: curriculum, teaching approaches, and assessment. Teaching approaches are considered a set of tactics used in the implementation of a curriculum (Garrett et al., 1982), which are influenced by teachers' epistemological beliefs (Kang & Wallace, 2005). Tactics, characterised by techniques, determine strategies that reflect the general approach of the teacher (Qhobela & Kolitsoe , 2014).

Over the past five decades, teaching methods have evolved due to modern pedagogical theories, societal needs, and technological advancements (Jarvis, 2006; Wang, et al., 2024). Traditional methods, such as direct instruction and rote memorisation, have been replaced by dynamic, learner-centered methods such as constructivist and inquiry-based learning (Jarvis, 2006; Kasuga, et al., 2022). Technology integration has led to blended and online learning environments, enabling personalized experiences. Contemporary teaching practices now prioritise critical thinking, problem-solving skills, and a lifelong love of learning among students (Hunter, 2015; Fathonah, et al., 2022). Consequently, a comprehensive analysis of physics teachers' instructional approaches within educational systems is of paramount importance for enhancing both teacher effectiveness and student learning outcomes.

Traditional Teaching Approach Features

One of the defining features of traditional teaching is its teacher-centred nature, where the teacher serves as the primary source of knowledge and authority in the classroom. In this model, the educator is responsible for delivering content, guiding learning, and maintaining discipline, which fosters a structured learning environment. The teacher's dominant role often leads to a passive learning experience for students, who are expected to absorb information rather than engage in collaborative or interactive learning processes (Boumová, 2008). This approach aligns with conventional educational practices, where the teacher's authority is emphasized over student input.

A structured curriculum is another critical component of traditional teaching methods. Education follows a predefined syllabus designed by education authorities, detailing the content to be covered and the skills students are expected to acquire (Knight, 2015). This systematic framework allows for uniformity in educational delivery and is particularly effective in ensuring that essential knowledge and foundational skills are conveyed. However, the rigidity of such curricula may limit flexibility and adaptability to individual learning needs, which is a notable criticism of traditional educational frameworks.

Traditional teaching heavily depends on textbooks, which serve as the main resource for instruction. These books provide a wealth of information, exercises and assignments that shape the learning experience (Litz, 2005). Teachers typically base their lessons on textbook content, guiding students through the material and facilitating understanding (Knight, 2015; Emmer et al., 2023). While textbooks can offer a comprehensive overview of subjects, this reliance can restrict exposure to varied perspectives and learning modalities, as the curriculum often prioritises rote memorisation over critical thinking and problem-solving (Boumová, 2008).

The physical classroom environment is integral to traditional teaching methods. Learning occurs within the confines of a classroom, emphasising face-to-face interaction and a structured space for educational activities (Brukštutė, 2019; luo et al., 2024). This controlled environment supports a clear authority structure, where the teacher guides discussions and activities while learners engage with the content in a more passive manner (Eshel, 1991). However, the physical restrictions of a classroom may also inhibit creative teaching methods or alternative forms of assessment that could enhance learning outcomes.

Assessments in traditional teaching approaches typically take the form of tests and written assignments aimed at gauging student understanding and knowledge retention (Dikli, 2003). These methods are designed to measure performance across a consistent framework, facilitating comparisons between students’ achievements. Though standardised assessments provide a clear metric for evaluation, they often emphasise memorisation and regurgitation of facts rather than deeper comprehension of content or critical application of knowledge. This assessment style can inadvertently limit students' engagement and may not account for diverse learning styles or paces (Koretz, 2017).

Inquiry-Based Learning and Constructivist Teaching Features

Constructivist teaching approaches and inquiry-based learning have grown in popularity in modern education because they place a strong focus on critical thinking (Ezema et al., 2022), cooperative problem-solving, and active participation. The notion that knowledge is created via experiences rather than passively absorbed is fundamental to both strategies. The following is a review of key elements of learner -centered approaches.

For learning to be learner-centred, open curricula are essential. By enabling teachers to adapt instruction to unique needs, interests and experiences, they promote a more engaging and individualised learning process (Wiggins, 2005; Aina, 2017).

A fundamental component of inquiry-based learning is its focus on active learning and engagement. According to Lim and Chai (2008), learners are encouraged to ask questions, investigate problems, and draw conclusions based on their discoveries. This active participation significantly enhances students' critical thinking abilities, as they become active builders of their own understanding rather than mere recipients of information (Murni , et al., 2022) Research has consistently demonstrated that students exposed to inquiry-based environments develop superior problem-solving skills compared to those in traditional educational settings (Nesbit et al., 2023; Almulla, 2023). Also, constructivism supports this notion by asserting that learners must actively engage with the material to construct meaningful knowledge (Alfieri et al., 2011; Xu, et al., 2023). Activities that promote interaction, such as hands-on projects, discussions and group work, empower learners to connect new knowledge with their prior experiences.

Both constructivist and inquiry-based methods depend heavily on social interaction and teamwork (Mulyenı, et al., 2024) The social constructivist theory of Vygotsky contends that instructors and peers play a crucial role in the social interactions that shape knowledge (Atanasova et al., 2024; Akkus, et al., 2022). Collaborative learning settings promote discussion, the exchange of varied viewpoints, and the development of deeper comprehension through group projects (Tan & Nashon, 2015). Group activities improve the learning process by promoting students to express their ideas, question preconceived notions, and negotiate meanings, according to research (Ates, et al., 2018). When paired with learner-centred pedagogy, flexible learning environments are seen favourably by users for instruction, learning and student welfare (Kariippanon, et al., 2018).

Inquiry-based teaching methods often incorporate problem-based learning (PBL), where students confront real-world challenges that necessitate critical decision-making and research skills (Xu et al., 2023). This approach stimulates their curiosity and encourages them to explore and analyse the contexts surrounding the problems they encounter. Alfieri et al. (2011) argue that an optimal learning experience arises from a blend of structured guidance and open-ended inquiry, enabling learners to navigate complexities while receiving adequate support. The findings of Caleon et al. (2018) indicate that effective teaching strategies commonly derive from problem-based approaches, emphasising relevant challenges that promote collaboration and innovative thinking (Usman, et al., 2023).

Constructivist teaching methods advocate for assessment practices that align with the principles of reflection and ongoing improvement. Effective assessments within these frameworks are often formative (Ole, et al., 2023), integrating peer feedback, self-assessment, and authentic tasks reflective of real-world applications (Marquez et al., 2023). This emphasis on constructive feedback is crucial, as demonstrated by Gazmuri et al. (2015), who highlight the role of well-structured assessments in creating learning conditions that enhance academic success by providing targeted guidance for improvement.

Both inquiry-based and constructivist approaches also endorse authentic learning experiences that connect classroom learning to students' lives. This alignment with real-world contexts motivates students and makes their learning relevant and engaging (Holmes et al., 2021, Uzel, et al., 2022). Research conducted by Yigit et al. (2017) indicates that when students can relate their educational experiences to authentic situations, including those relevant to their local environment and cultural context, their engagement and retention of knowledge significantly improve.

Review of Related Literature

Numerous studies (Agarkar, 2019; Antonio & Prudente, 2024; Hattie & Donoghue, 2016; Alanazı, 2020) emphasise the critical importance of adopting contemporary pedagogical methods that prioritise student engagement and promote active learning in science education.

Docktor et al.'s research (2015) on conceptual problem-solving in high school physics reinforces the significance of instructional methods that foster active engagement and critical thinking. Nevertheless, a study by Wallace and Kang (2004) highlights a troubling reality: secondary science teachers often harbuor conflicting beliefs regarding inquiry-based teaching methods, thereby underscoring the urgent need for professional development aimed at enhancing their instructional efficacy.

Yigit et al. (2017) conducted a study in Turkey that revealed interesting insights regarding the classroom environment. Their research demonstrated that students in smaller science classes, particularly in urban schools, reported more positive experiences within constructivist learning settings. Savasci and Berlin's (2012) study illustrated that various external factors, such as school culture and administrative support, significantly influence teachers' capacity to implement innovative teaching concepts successfully.

Tan and Nashon (2015) argue that collaborative efforts among teachers can lead to improved educational outcomes, increase teachers' confidence in employing modern teaching strategies, and enhance their overall comprehension of the curriculum. In addition, research conducted by Özdemir and Kaptan (2013) indicates that instructors' positive attitudes and proficiency in scientific process skills—key components of effective instruction—vary significantly.

Teaching methodologies are profoundly influenced by teachers' pedagogical beliefs, experiences, and the contextual factors surrounding their educational environments. According to Lim and Chai (2008), an educator's pedagogical beliefs play a significant role in determining how they plan and implement various teaching strategies, which, in turn, affects classroom dynamics. Teachers with progressive beliefs typically adopt creative and interactive teaching methods, while those with traditional beliefs tend to favour more conventional instructional techniques, as noted by Qhobela and Kolitsoe Moru (2014). A critical factor that influences the choice of teaching approach is the extent of teaching experience. Research by Caleon et al. (2018) has shown that teaching experience profoundly impacts the attitudes and behaviours of teachers, especially in challenging subjects such as physics.

As already noted, the context in which teachers operate significantly affects their teaching approaches. Institutional policies, curriculum mandates, and available support from school administrators can heavily influence teachers' decisions regarding instructional practices. Studies indicate that teachers working in supportive environments, characterised by mentoring and professional development opportunities, are more likely to explore innovative teaching methods (Allen, 2023; Davis & Chick, 2022). Conversely, those facing rigid curricular constraints may feel pressured to adhere to traditional methods, despite their progressive beliefs (Archer et al., 2020). Additionally, teachers' subject knowledge and pedagogical content knowledge (PCK)—a concept coined by Shulman (1986)—are vital factors that shape their classroom strategies. PCK refers to the interplay between content knowledge and pedagogical strategies, and teachers who have a deep understanding of their subject matter combined with effective pedagogical techniques are more likely to implement varied teaching methods that align with both their pedagogical beliefs and their students' learning needs.

Recent research has revealed significant trends in teacher attitudes and self-efficacy in science, particularly physics. These studies highlight current perspectives and areas needing further investigation (Vlachos et al., 2024; Stylos et al., 2023). Research on pre-service science teachers shows a generally positive outlook towards science education, along with high expectations for teaching effectiveness and personal confidence (Eric et al., 2018). Additional studies have examined teachers' abilities to manage constructivist learning environments, underscoring this pedagogical approach's importance (Can & Kaymakcı, 2015). An analysis of attitudes among physics, chemistry and biology teachers towards constructivist methods indicated a positive correlation with their demographic backgrounds, fostering innovative teaching strategies (Ã-nen et al., 2018). This suggests that teachers' backgrounds may shape their openness to innovative pedagogies. Lastly, a study in Zambia explored technology integration among 202 pre-service teachers, identifying key factors such as gender and year of study that influence this integration (Bwalya & Rutegwa, 2023). The findings revealed that male pre-service teachers and those in later years of training reported higher levels of technological self-efficacy, suggesting that both demographic and academic factors shape readiness for effective technology use in teaching.

In line with developments in many countries, the Iranian physics curriculum has been revised in recent years. The new curricula emphasise active approaches based on constructivism, such as inquiry and phenomenon-based learning using experiments. In Iran, the goal of science education is to educate responsible citizens towards themselves, society, and the environment. Considering the evolution of science education and its goals, choosing an appropriate approach to teaching science has always been one of the important challenges for educators (Shekarbaghani, 2016).

Despite extensive international research, empirical studies on in-service physics teachers in Iran remain scarce. Global findings cannot be directly generalised due to Iran's unique sociocultural and educational context. This study addresses this gap by examining Iranian physics teachers' instructional approaches and their relationship with key demographic factors. Conducting research on the teaching approaches employed by Iranian physics teachers is critically important, given the significant absence of scholarship in this domain. While global educational trends are increasingly embracing innovative pedagogical techniques—such as inquiry-based and constructivist teaching—there remains a conspicuous lack of rigorous examination and adaptation of these methods within the Iranian context (Golestaneh & Mousavi, 2024). This deficit not only inhibits the development of effective teaching strategies that could significantly enhance students' learning experiences but also restricts educators' opportunities to align their practices with the evolving international standards that prioritize active student engagement and critical thinking (Golestaneh & Mousavi, 2024). Moreover, understanding the intricate factors influencing teaching methodologies in Iran is essential for educational reform. Such insights will empower policymakers and educators to devise targeted interventions that address the unique challenges within the local educational environment (Zarean, et. al, 2024). By delving into these teaching methodologies, this research aspires to illuminate the educational landscape in Iran and contribute to the establishment of a comprehensive framework that promotes effective physics instruction, ultimately benefiting both teachers and students in their pursuit of knowledge and understanding.

Aims and Research Questions

The purpose of this study was to examine the instructional approaches of Iranian physics teachers and investigate these approaches in relation to their gender, age, and years of service.

Generally, understanding the differences between the methods teachers employ and those that are appropriate for teaching physics is the primary goal of our research on the teaching strategies of physics teachers. This study included the teachers of secondary schools in Iran and was conducted with the aim of addressing the following research questions:

Q1: What approaches are used by Iranian physics teachers in the classrooms?

Q2: What is the relationship, if any, between teachers' approaches and their gender, age, and the number of years in service?

Methods

This study employed a quantitative approach using a survey methodology. Surveys are a research design specifically intended to depict the present state of affairs (Fraenkel et al., 2023). The study was conducted in two phases: the first phase to develop and to validate a questionnaire, and the second phase to answer the research questions using the developed questionnaire. IBM SPSS Statistics 26 was used for the confirmatory and explanatory analyses. The EFA was used to determine the teaching approaches used by physics teachers, and the CFA was used to confirm the emerging teaching approaches.

Study Group

In the first phase, 573 secondary school physics teachers in Iran were invited to participate through professional teacher networks, and questionnaires were distributed to those who volunteered, using a convenience sampling approach.

It was given to 300 people for Explanatory Factor Analysis (EFA) and to 273 people for Confirmatory Factor Analysis (CFA). Finally, the developed and validated questionnaire, structured into three sections on teaching approaches, was distributed to 500 physics teachers across the country through a convenience sampling approach, ensuring no individual was selected more than once.

Data Collection Tools

To create the questionnaire, a pilot study was conducted to create a set of items (teaching activities) using the properties of teacher-centred and student-centred teaching and learning theories as a basis; six-point rating scale was chosen for each item, and the validity (face and content validity) and reliability of the questionnaire were assessed. Following the development of an item pool (the question pool consisted of 53 items), the questionnaire's content validity was evaluated using both quantitative and qualitative methods by a panel of six experts, three of whom were seasoned physics instructors with knowledge of various instructional techniques and the other three of whom were university personnel with extensive backgrounds in physics education.

The expert panel was responsible to assess the structure, rating scale, and wording of the items of the questionnaire. In the first step, the expert panel reviewed the items of the questionnaire and reached consensus on wording, sequencing, and removing the items. Overall, 46 items were selected.

In the next step, the expert panel surveyed the structure of the questionnaire using pre-defined three criteria, i.e. not at all representative, somewhat representative, or clearly representative. Subsequently, a three-point rating scale ranging from 0 to 2 and also CVR (Waltz & Bausell, 1981) were calculated for each item. CVR was determined based on the formula as follows:

$$CVR = \frac{n_e - N/2}{N/2}$$

Where n_e is the number of experts who considered the item as 'clearly representative', and N is the total number of experts. The results of the evaluated CVR for each item are reported in Table 1. In the second step, none of the items were omitted. Finally, with the help of the expert panel, an even (six-point) Likert-type, including strongly disagree, disagree, somewhat disagree, somewhat agree, agree, strongly agree, was selected for all the items.

Table 1

CVR coefficients for questionnaire items

Item number	CVR	Item number	CVR	Item number	CVR	Item number	CVR
1	1	13	0.88	25	1	37	1
2	0.88	14	0.88	26	1	38	1
3	1	15	1	27	1	39	1
4	0.88	16	1	28	1	40	1
5	0.88	17	1	29	0.88	41	1
6	1	18	1	30	1	42	1
7	1	19	1	31	1	43	1
8	1	20	0.88	32	1	44	1
9	1	21	1	33	0.88	45	1
10	0.75	22	1	34	1	46	1
11	1	23	0.88	35	1		
12	1	24	1	36	1		

*Note.*The numerical value of CVR was determined from Lawshe's table for determining the minimum value.

To measure the face validity of the questionnaire, we conducted a pre-test to assess the clarity and readability of the developed 46-item questionnaire among 15 teachers, representing both genders, from novices to experienced, and different education levels from Bachelor's to Doctoral. During pre-testing, some participants gave suggestions to change question items to spoken patterns instead of sentence patterns and also modify some words of question items for further clarifying and understanding. To assure face validity, we changed the wording of the items based on pre-testing results and suggestions from the participants. These alterations were not influenced the original items' intrinsic meaning but improved the questionnaire's clarity and accuracy in data collection.

Data Analysis

The explanatory (EFA) and confirmation (CFA) factor analyses were performed using IBM SPSS Statistics 26. The EFA was used to determine the teaching approaches used by physics teachers, and the CFA was used to confirm the emerging teaching approaches. Before performing EFA, the sampling adequacy and sphericity assumptions were assessed. The Kaiser–Meyer–Olkin (KMO) measure indicated that a sample of 273 responders was adequate (KMO=0.914) to conduct EFA, and Bartlett's sphericity test rejected the null hypothesis that the correlation matrix was identical ($p<0.001$). The collected data were analysed using IBM SPSS Statistics 26 to answer the research questions. To carry out factor analysis, we needed to extract the number of factors. To this end, we used the scree plot. EFA was run using the maximum likelihood factor extraction method with the Varimax rotation and Kaiser normalization based on the polychoric correlation matrix. Only items with factor loading greater than 0.4 were considered in EFA. To check the validity of the construct, we ran CFA using IBM SPSS Amos 26. The discriminant validity was also checked by evaluating the factor correlation matrix of the final exploratory factor analysis. Also, the average variance extracted (AVE) values of all factors were calculated. In the second phase of the study, to compare the dominant teaching approach between female and male teachers, we used the Mann-Whitney U test. Also, in order to compare the dominant teaching approach between teachers with different work experiences, we employed the Kruskal-Wallis H test.

Findings

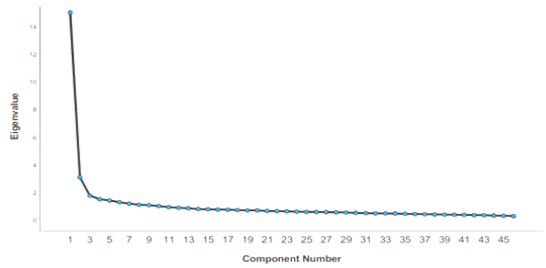
Data Extracted to Answer the First Research Question

First-Order EFA

The created questionnaire was given to 273 physics teachers to investigate the teaching methods they employed in their classrooms. We performed a univariate item analysis on the data collected. The data were converted to numeral scores, ranging from 1 to 6, for items based on participants' responses as mentioned previously. Blank responses were omitted case-wise from the analysis. The data were analyzed using the SPSS software package (version 26) and Microsoft Excel Spreadsheet Software (version 2016). The mean scores of the items in the questionnaire were 4.22 (as minimum score) and 5.49 (as maximum score), and standard deviations were from 0.769 to 1.339. The results of the scree plot and the total variance explained in the output showed that six factors could explain 57% cumulative rotation sums of squared loadings (Fig. 1).

Figure 1

Scree plot



The first EFA output revealed that among 46 items, 10, 6, 5, 6, 5, 3, 4, 3, and 2 items were loaded in factors 1, 2, 3, 4, 5, 6, 7, 8, and 9, respectively. In this step, the factor loading of items 2 and 40 was lower than 0.4 (Table 2). The discriminant validity showed no correlation coefficients were greater than 0.7; hence, the factors derived from EFA revealed adequate discriminant validity among the factors. The factors and related items are shown in the Table 2.

Table 2

Factors and related items

Factor	Number of items	Items
Interactive class (IAC)	10	Q44, Q37, Q39, Q30, Q41, Q27, Q13, Q14, Q34, Q46
Interesting class (IC)	6	Q4, Q7, Q9, Q10, Q11, Q24
Textbook-based class (TBC)	6	Q1, Q12, Q22, Q26, Q29, Q31
Technology-based class (TC)	3	Q15, Q23, Q28
Criterion-based class (CBC)	3	Q33, Q35, Q43
Process-based class (PBC)	5	Q18, Q36, Q16, Q20, Q21
Rule-based class (RBC)	5	Q3, Q5, Q6, Q8, Q19
Problem-based class (PC)	4	Q17, Q25, Q32, Q45
Discipline-based class (DBC)	2	Q38, Q42

Factors Extracted From First-Order EFA

The Interactive Class (IAC) factor reflects an approach in which the teacher designs classroom activities based on interaction and tries to promote students' learning through interaction with themselves (e.g. Q39, Q14, Q37, Q27), peers (e.g. Q44, Q13, Q41) and the teacher (e. g. Q34, Q39, Q41). In this factor, teachers aim to create an environment where students can apply scientific process skills; they also ask students to explain their perceptions of each activity, draw conclusions, and generalise those conclusions to new situations. This type of instructor creates an environment in the classroom where students feel comfortable sharing their ideas and makes use of various (optimal) setups to keep an easy eye on their actions. All learners are assessed based on their own abilities, and the teacher attempts to assist students in solving problems on their own. Such a teacher undoubtedly understands contemporary approaches to education.

The Technology-Based Class (TC) factor reflects an approach in which the teacher uses slides and clips to teach a topic and usually prepares a related clip or experiment for each training session. The teacher evaluates the students' activities by filling in checklists.

In the Discipline-Based Class (DBC) factor, when a teacher does not have sufficient time to complete a concept, instruction is continued in the following session, and questions unrelated to the current topic are deferred until after class.

In the Intersting Class (IC) factor, the instructor uses activities that draw the attention of students and hold their interest at the start of the class, such as experiments or activities based on prior knowledge; attempts to guide them based on their preconceptions about the subject and helps them to complete the activity steps independently; asks them to reflect on and discuss how they can apply what they have learned to their daily lives and tries to relate what is taught to daily life; concludes each book chapter with a test. This instructor values deep understanding and feels that positive interactions with pupils are essential for this.

In the Rule Based Class (RBC) factor, the teacher usually expresses the students' educational expectations and goals at the beginning of the class; asks her/his students to express in their own words what they have learned; designs educational activities based on the results of the diagnostic assessment. This teacher uses a variety of diagnostic assessments.

In the Textbook-Based Class (TBC) factor, the teacher usually divides the book chapters into small parts; covering the textbook content is important, and they have a structured programme for it throughout the academic year. Monitoring is essential, so the classroom is arranged to allow the teacher access to all parts of the class. When necessary, teachers also address students' faulty pre conceptions.

In the Problem Based Class (PC) factor, the instructor assigns a variety of tasks for students to practise in different topics and provides relevant books and resources. This teacher prioritises the learning process over the end result.

In contrast, the teacher in a Criterion Based Classroom (CBC) usually pays more attention to the pupils who receive the highest marks. The teacher goes on to the following subject after the majority have achieved good marks. The teacher expects students to remain quiet and compliant during teaching.

First and Second-order CFA

To determine whether EFA proposed a nine-factor model with the 46-item questionnaire can assess the teaching approach of physics teachers, we ran CFA using a different sample of 300 participants two times: the first time for first-order CFA and the second time for second-order CFA (Table 3, 4).

Table 3

Factor loading results of the final EFA model

Item	Factor									Communalities
	IAC	IC	PBC	TBC	RBC	TC	PC	CBC	DBC	
q44	.724	.094	.081	.123	.093	.200	.043	.036	.092	0.615
q37	.717	.330	.056	-.041	.066	.094	.136	.036	.011	0.661
q39	.667	.215	.032	-.100	.051	.186	.074	-.055	.220	0.596
q30	.633	.038	.127	.018	.242	.214	.032	.209	-.081	0.574
q41	.611	.161	.314	.195	.125	.029	.082	-.041	.080	0.567
q27	.602	.187	.214	.304	.222	.002	-.022	.164	.036	0.613
q14	.529	.228	.271	.075	.315	.230	.078	-.122	-.008	0.584
q13	.493	.330	.149	.173	.068	-.013	.153	-.181	.081	0.471
q34	.439	.058	.418	.027	.336	.229	-.146	.174	-.026	0.589
q46	.420	.027	-.177	.365	.233	.317	.049	.069	.001	0.504
q4	.055	.732	.048	.037	.175	-.003	.057	.074	-.094	0.590
q11	.374	.649	.072	-.027	.239	.162	.049	-.138	.080	0.678
q9	.266	.629	.013	-.070	-.002	.380	-.079	.197	.023	0.661
q7	.358	.588	.104	.220	.041	-.014	-.014	-.209	.075	0.585
q10	.259	.521	.198	.001	.354	.234	.014	.124	.199	0.612
q24	.180	.476	.473	.288	.060	.022	.110	-.092	-.066	0.596
q2	.291	.339	.117	.257	.318	.187	.037	-.046	-.008	0.419
q18	.216	.140	.666	.171	.144	-.007	.050	.063	.157	0.591
q36	.427	.015	.559	.148	.203	.016	.092	.000	.091	0.575
q20	.188	.234	.514	.406	.166	.073	.011	.022	-.069	0.558
q16	-.195	.022	.472	.235	-.013	.355	.135	.199	.227	0.552
q21	.396	.174	.459	.031	.196	.264	.137	.118	.000	0.540
q22	.113	.029	.227	.672	-.010	.127	.063	.224	-.016	0.588
q12	-.045	.065	.047	.558	.217	.138	.203	-.122	.272	0.516
q26	.467	.065	.091	.494	.138	.045	.012	.190	-.012	0.532
q29	.049	.046	.400	.458	.023	.241	.160	.135	.236	0.533
q1	.160	-.021	.197	.431	.304	.334	.195	-.181	-.009	0.526
q31	.353	.181	.192	.420	.101	-.053	.098	-.108	.268	0.476
q5	.118	.232	.043	.141	.755	-.035	.118	.050	.127	0.693
q6	.211	.344	.230	.034	.587	-.002	-.112	.075	.024	0.580
q19	.304	-.019	.374	.041	.481	.365	-.011	.135	.070	0.623
q3	.338	.102	.167	.268	.466	.144	.096	.043	.024	0.474
q8	.315	.330	.246	.138	.415	.381	.061	-.185	.007	0.643
q28	.299	.167	-.018	.199	-.015	.690	.091	.052	.004	0.645
q15	.107	.222	.145	.204	.005	.682	.031	-.094	.137	0.617
q23	.276	-.056	.125	-.029	.333	.571	.136	.190	-.020	0.588
q25	.031	.030	.028	.146	.043	-.020	.766	.137	-.060	0.636
q32	.079	-.068	.122	.298	-.090	.110	.664	.315	.057	0.678
q45	.413	.176	.017	.014	.087	.171	.541	.025	.092	0.540
q17	.161	.005	.312	-.091	.198	.207	.431	-.267	.131	0.488
q43	.086	.011	.004	-.035	.117	.063	.154	.713	.070	0.564
q35	-.017	-.215	.197	.295	.150	-.107	.112	.487	.243	0.515
q33	.420	.253	.128	.278	-.168	.055	.102	.422	.054	0.556
q40	-.036	.052	.227	.333	-.081	.179	.109	.386	.383	0.513
q38	.143	-.040	-.080	.122	.038	.085	-.139	.108	.757	0.656
q42	.098	.052	.294	.017	.111	-.011	.178	.067	.616	0.527
Variance (%)	12.699	7.343	6.859	6.497	6.121	5.912	4.266	4.140	3.642	
Cumulative (%)	12.699	20.042	26.901	33.398	39.519	45.430	49.696	53.836	57.478	

Note. IAC: Interactive class, IC: Interesting class, TBC: Textbook-based class, TC: Technology-based class, CBC: Criterion-based class,PBC: Process-based class,RBC: Rule-based class,PC: Problem-based class,DBC: Discipline-based class

Table 4

Factor correlation matrix of the final EFA model

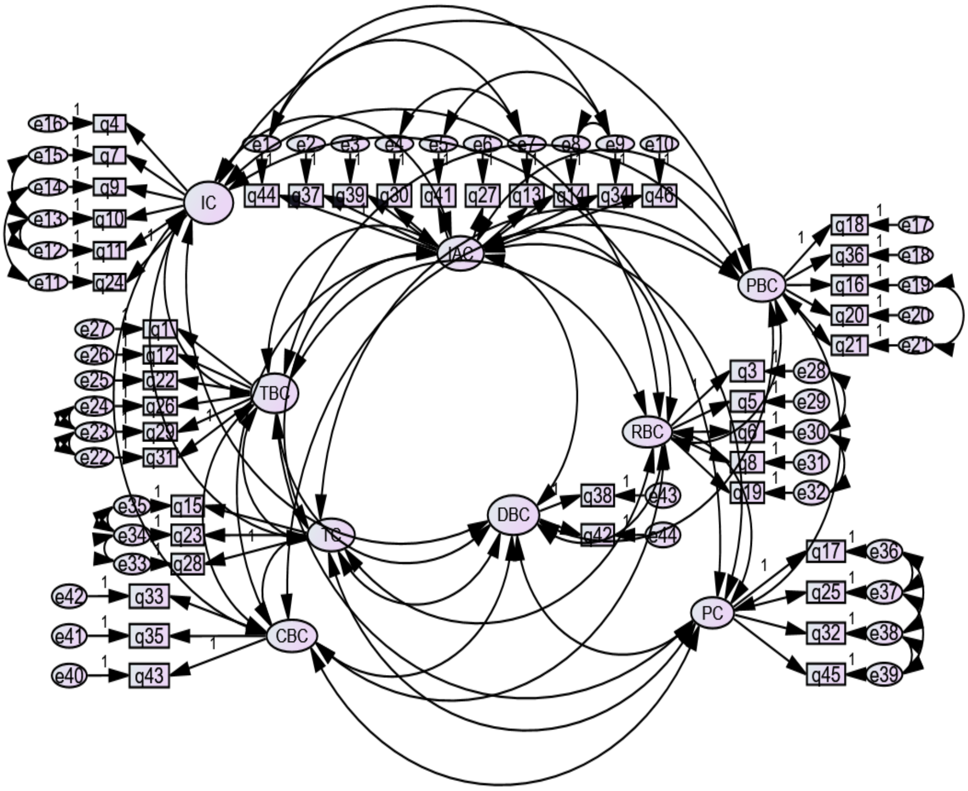
Factor	IAC	IC	TBC	TC	CBC	PBC	RBC	PC	DBC
IAC	1.000								
IC	0.647	1.000							
TBC	0.610	0.491	1.000						
TC	0.540	0.415	0.632	1.000					
CBC	0.689	0.623	0.621	0.545	1.000				
PBC	0.545	0.451	0.454	0.467	0.510	1.000			
RBC	0.397	0.269	0.423	0.441	0.334	0.373	1.000		
PC	0.316	0.156	0.394	0.370	0.244	0.226	0.327	1.000	
DBC	0.250	0.168	0.295	0.323	0.249	0.182	0.180	0.290	1.000

Note. IAC: Interactive class, IC: Interesting class, TBC: Textbook-based class, TC: Technology-based class, CBC: Criterion-based class,PBC: Process-based class,RBC: Rule-based class,PC: Problem-based class,DBC: Discipline-based class

We described the first-order CFA nine-factor model with the SEM diagram (Fig. 2).

Figure 2

SEM diagram of the first-order CFA nine-factor model



All loadings ranged from 0.466 (q38) to 0.863 (q32), and the average of each factor was greater than 0.690. Standardized factor loadings of nine factors are presented in Table 5.

Table 5

Standardized factor loadings of different factors

	Factor								
Item	IAC	IC	PBC	TBC	RBC	TC	PC	CBC	DBC
q44	0.775								
q37	0.733								
q39	0.721								
q30	0.671								
q41	0.766								
q27	0.733								
q14	0.764								
q13	0.704								
q34	0.673								
q46	0.540								
q4		0.685							
q11		0.762							
q9		0.706							
q7		0.623							
q10		0.815							
q24		0.71							
q2									
q18			0.667						
q36			0.689						

q20			0.732						
q16			0.748						
q21			0.739						
q22				0.572					
q12				0.595					
q26				0.538					
q29				0.705					
q1				0.636					
q31				0.673					
q5					0.557				
q6					0.739				
q19					0.780				
q3					0.727				
q8					0.790				
q28						0.744			
q15						0.774			
q23						0.740			
q25							0.592		
q32							0.863		
q45							0.683		
q17							0.697		
q43								0.509	
q35								0.586	
q33								0.660	
q38									0.466
q42									0.811

Note. IAC: Interactive class, IC: Interesting class, TBC: Textbook-based class, TC: Technology-based class, CBC: Criterion-based class,PBC: Process-based class,RBC: Rule-based class,PC: Problem-based class,DBC: Discipline-based class

Each item exhibited a statistically significant loading on its respective latent factor. Using these factor loadings, the average variance extracted (AVE) values of all (1-9) factors were calculated. The values of all factors, except for factor 4, were above 0.5. The value of AVE of the same factor was below 0.5, meaning that factor 4 has insufficient convergent validity. However, factors specific item loadings were acceptable for convergent validity, and there were no items with loading below 0.5. As these items were significant during CFA and measured the teaching approach of physics teachers, we preserved this factor in the model. Model fit indicating the first-order CFA nine-factor is shown in Table 6.

Table 6

Model fit indices of the first-order CFA

Factor	Value	Factor	Value
CMIN	1831.171	Df	847
Chi-square/df	2.162	GFI	0.874
NFI	0.853	CFI	0.848
RMR	0.077	RMSEA	0.062

The ratio of the chi-square to the degree of freedom ( ) was used to determine the overall model fitness. As recommended by Schreiber et al. (2006), the ratio should not exceed 3. In the current study, the observed value was 2.162, suggesting that the model is fit for purpose. Other measures of fitness have been observed, as well. Bagozzi and Yi have reported that the acceptable range for RMR is less than 0.08 and for GFI, NFI, and CFI is greater than 0.9 (Bagozzi & Yi, 1988). These results show that all the values are either in the acceptable range or closer to the acceptable range; therefore, the model fitness is appropriate.

After performing the first-order CFA nine-factor, we run a second-order CFA based on the teaching approach. This second-order model was provided in accordance with the approaches proposed by Trigwell and Prosser (1996). Thus, considering emerging factors in EFA, the following three approaches were suggested: student-focused strategy aimed at them developing their own conception (approach A), teacher/student interaction with the intention that they acquire deep concepts of the discipline by themselves (approach B), and teacher-focused strategy with the intention of learners acquiring the concepts of the discipline (approach C) (Table 7).

Table 7

Emerging approaches based on CFA

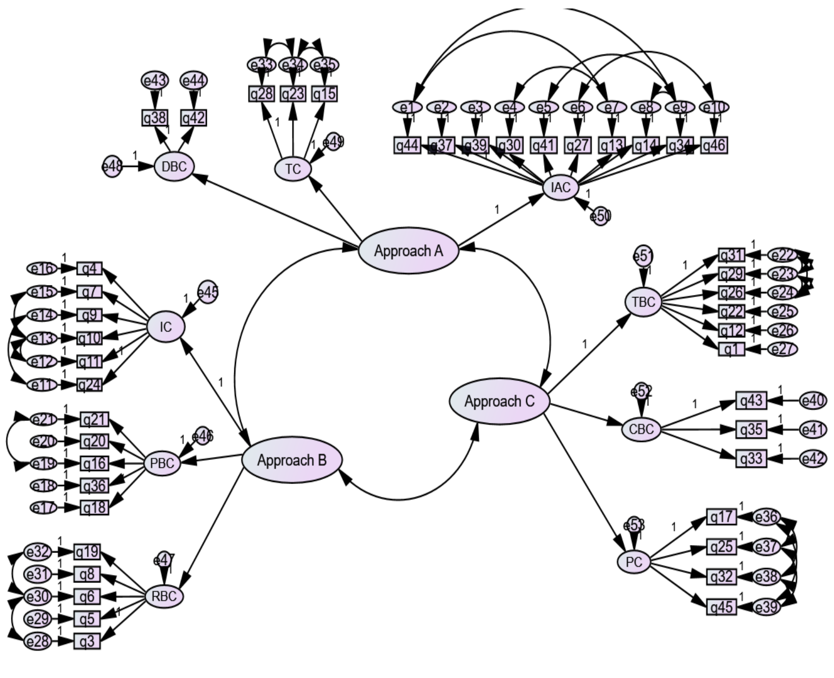
Factor	IAC	IC	TBC	TC	CBC	PBC	RBC	PC	DBC
Approach A: student-focused aimed at students developing their conception	✓			✓					✓
Approach B: teacher/student interaction with the intention that students acquire deep concepts of the discipline by themselves		✓				✓	✓		
Approach c**:** teacher-focused with the intention of students acquiring the concepts of the discipline			✓		✓			✓	

Note. IAC: Interactive class, IC: Interesting class, TBC: Textbook-based class, TC: Technology-based class, CBC: Criterion-based class,PBC: Process-based class,RBC: Rule-based class,PC: Problem-based class,DBC: Discipline-based class

The SEM diagram is shown in Figure 3.

Figure 3

SEM diagram of the second-order CFA



Model fit indices showed all the values are either in the acceptable range or are closer to the acceptable range; therefore, model fitness is appropriate (Table 8).

Table 8

Model fit indices of second-order CFA

Factors	Values	Factors	Values
CMIN	1909.260	Df	868
Chi-square/df	2.20	GFI	0.862
NFI	0.843	CFI	0.839
RMR	0.063	RMSEA	0.063

After evaluating the validity of the questionnaire, its reliability was assessed. The result is depicted in the Table 9.

Table 9

Cronbach's alpha reliability coefficient of the questionnaire

Approach	Cronbach's alpha	number of items
A	0.897	15
B	0.923	16
C	0.811	13
overall	0.954	44

Data Extracted to Answer the Second Research Question

The electronic version of the questionnaire was distributed between participants in the second phase of this study. The distribution of teachers according to gender, age, and the number of years in service is summarized in the Tables 10 , 11.

Table 10

Distribution of physics teachers according to gender

Participants	Number	Female	Male
Number of teachers	500	273	227
Percentage	100	54.6	45.4

Table 11

Descriptive statistics of physics teachers according to age and the number of years in Service

Factor	Minimum (%)	Maximum (%)	Mean	SD
Age	20	70	40.24	8.78
Number of years in service	1	52	17.69	9.48

The mean and standard deviations of physics teachers' approaches are depicted in Table 12.

Table 12

Mean and standard deviations of physics teachers' approaches

Approach	Numbers of items	Maximum attainable scores (%)	Maximum attainable scores (%)	Mean	SD
A	15	90	78.8	70.92	9.98
B	16	96	84.12	80.76	10.11
C	13	78	81.87	63.86	7.26

Overall	44	264	81.64	215.54	24.92

Also, we studied the effect of gender, education, and the number of years of service on the physics teaching approach. The scores of responders showed that each teacher uses a combination of approaches that we found in the previous phase. Thus, based on the order of the teaching approach used by teachers, we divided each approach into three levels: first, second, and third. These levels determined the teaching approach's order based on the teacher's scores in each approach. As shown in Table 13, the results showed that the dominant teaching approach among teachers was Approach B, followed by Approach C and Approach A; the dominant teaching approach did not depend on the gender of the teachers.

Table 13

Distribution of order of teaching approach based on gender

Approach	Order	Number of females	Number of males	total
A	First	24	24	48
	Second	91	68	159
	Third	158	135	293
B	First	163	123	286
	Second	89	78	167
	Third	21	26	47
C	First	97	86	183
	Second	82	75	157
	Third	94	66	160

The results of Mann-Whitney U test are presented in Table 14.

Table 14

Analysis of the order of teaching approach based on gender

Approach	Gender	N	M	SD	Z	P
A	Female	273	2.49	0.65	-0.15	0.87
	Male	227	2.48	0.68		
B	Female	273	1.47	0.63	-1.44	0.14
	Male	227	1.57	0.68		
C	Female	273	1.98	0.83	-1.02	0.30
	Male	227	1.91	0.81		

Note. Mann-Whitney U test was used in above table.

The results also showed that approach B is the dominant teaching approach for all teachers of both genders. The distribution of the dominant teaching approach based on the teacher's education level is shown in Table 15, which indicates that the dominant teaching approach does not depend on the teacher's education level.

Table 15

Distribution of order of teaching approach based on teacher's education level

Approach	Order	Number of BSc	Number of MSc	**total**
A	First	24	24	48
	Second	78	81	159
	Third	156	242	293
B	First	144	142	286
	Second	89	78	167
	Third	25	22	47
C	First	97	86	183
	Second	84	73	157
	Third	77	83	160

In order to compare the dominant teaching approach between teachers with BSc and MSc degrees, the Mann-Whitney U test was used. The results of this test are shown in Table 16.

Table 16

Analysis of the order of teaching approach based on the teacher's education level

Approach	Education level	N	M	SD	Z	P
A	BSc	258	2.51	0.66	-0.82	0.40
	MSc	242	2.46	0.67		
B	BSc	258	1.53	0.66	-0.626	0.53
	MSc	242	1.50	0.65		
C	BSc	258	1.92	0.81	-0.867	0.38
	MSc	242	1.98	0.83		

Note. Mann-Whitney U test was used in above table.

The results showed that approach B is the dominant teaching approach for all teachers with every level of education. The distribution of the dominant teaching approach based on the teacher's number of years in service is shown in Table 17. The number of years in service was categorised based on five-year intervals, and all the teachers with more than 30 years of experience were placed in one category (category 7).

Table 17

Distribution of order of teaching approach based on teacher's number of years in service

Approach	Order	> 5	5-10	10-15	15-20	20-25	25-30	<30	total
A	First	25	11	6	5	1	0	0	48
	Second	15	17	23	44	34	26	0	159
	Third	60	15	22	47	71	62	16	293
B	First	48	23	31	59	64	53	8	286
	Second	44	12	10	29	33	31	8	167
	Third	8	8	10	8	9	4	0	47
C	First	36	14	16	34	40	35	8	183
	Second	32	9	16	21	40	31	8	157
	Third	32	20	19	41	26	22	0	160

The results of the Kruskal-Wallis H test showed that the significance level of approach A was 0.0001, which was less than 0.05, and in approaches B and C, these levels were 0.52 and 0.06, respectively, which were greater than 0.05 (Table 18). The results also demonstrated a significant difference in approach A based on the teacher's work experience. To determine the difference between categories, we used the Bonferroni correction test.

Table 18

Analysis of the order of teaching approach based on the teacher's number of years in service

Approach	Number of years in service	N	M	SD	χ^2	P
A	Below 5	100	2.35	0.85	43.76	0.0001
	5-10	43	2.09	0.78		
	10-15	51	2.31	0.67		
	15-20	96	2.43	0.59		
	20-25	106	2.66	0.49		
	25-30	88	2.70	0.45		
	More than 30	16	3.00	0.000		
B	Below 5	100	1.60	0.63	5.18	0.52
	5-10	43	1.65	0.78		
	10-15	51	1.58	0.80		
	15-20	96	1.46	0.64		
	20-25	106	1.48	0.65		
	25-30	88	1.44	0.58		
	More than 30	16	1.50	0.51		
C	Below 5	100	1.96	0.82	11.80	0.06
	5-10	43	2.13	0.88		
	10-15	51	2.05	0.83		
	15-20	96	2.07	0.88		
	20-25	106	1.86	0.78		
	25-30	88	1.85	0.79		
	More than 30	16	1.50	0.51		

Note. Bonferroni correction test was used for approach A and < 5 vs. > 30, SN, p<0.0001; 5-10 vs. 20-25, SN, p<0.0001; 5-10 vs. 25-30, SN, p<0.0001; 5-10 vs. More than 30, SN, p<0.0001; 10-15 vs. 20-25, SN, p<0.0001; 10-15 vs. 25-30, SN, p<0.0001; 10-15 vs. More than 30, SN, p<0.0001; 15-20 vs. More than 30, SN, p<0.001.

Discussion and Conclusion

1. Answer to the First Research Question: What Approaches Are Used By Iranian physics Teachers in the Classrooms?

Based on modern theories of science education, physics educators need to introduce the physics "way of knowing". To achieve this goal, teaching methods should go beyond the traditional methods based on lectures and knowledge transfer (DeBoer, 2019). Sometimes, although they are aware of the high goals of education, teachers and education officials insist on using traditional methods for various reasons, such as covering the headlines of textbooks, responding to parents and officials, high-stakes testing, and saving time and money (Darling-Hammond, 2015). As Gormally (2009) argues, inquiry-based approaches are crucial for developing leaners' scientific literacy and understanding of the "physics way of knowing". Moreover, the results of some studies, such as the study by Antonio and Prudente (2024), encourage science teachers to adapt these approaches to improve their teaching practices and support students in strengthening their higher-order thinking skills.

In approach A, teachers are knowledgeable about various learning theories and believe in the essential role of students in the learning process that is consistent with findings of Hattie and Donoghue (2016). They use students' perceptions and help them construct scientific knowledge through group discussions, reasoning, and reflection. This is consistent with the findings of Aina (2017), who emphasised the importance of physics teachers considering students' prior knowledge, facilitating student interactions, and respecting their ideas for effective learning. Teachers monitor student activities to provide guidance and feedback, rearrange the classroom to facilitate observation, and use multimedia to engage them. This is consistent with the findings of YiGit et al., (2017), who suggested that teachers should focus on encouraging collaboration and designing classrooms for better learning experiences. They use checklists to track student performance and assess each students based on their abilities. This approach fosters deep understanding and critical thinking skills by emphasising interactive lesson plans and peer interaction (Agarkar, 2019). In addition, it incorporates technology and maintains an awareness of time and knowledge limits, which is consistent with constructivist principles. Teachers adopt a targeted approach to teaching with the goal of assisting them in developing their concepts. This approach appears to be consistent with inquiry-based constructivist approaches, and as Gormally (2009) argues, inquiry-based learning consistent with this approach has been shown to be effective in promoting student engagement, scientific literacy, and critical thinking skills. Furthermore, Simeon, et al., (2020) show that the design thinking approach, which is consistent with these principles, positively impacts student achievement in physics, reinforcing the importance of engaging teaching strategies in STEM education.

Teachers in Approach B establishe a methodical process during the class, accompanied by particular guidelines and the approach's key component. Also, instructors place a strong emphasis on the value of student participation in the learning process, because they think that learning occurs most effectively when students' attention is directed toward pertinent topics. They strive for a profound comprehension of subjects by relating classroom material to real-world occurrences and students' existing knowledge. Teachers encourage pupils to express what they have learned in their own terms while guiding them according to their preconceptions. To track progress, they establish clear goals, communicate expectations, and administer tests frequently based on the material in textbooks Recent research indicates that adolescents' participation opportunities significantly enhance student well-being and can lead to increased independence and self-efficacy, which are crucial for effective learning environment (ott, et al., 2023). Additionally, studies show that class participation and feedback are essential for improving academic performance, as active engagement in class activities correlates positively with better learning outcomes (Márquez, et al., 2023). All things considered, this method encourages participation, connects learning activities to students' experiences, and supports in-depth comprehension through regular interaction and evaluation. The size of the school can also influence student participation, with smaller schools often fostering a stronger sense of community and engagement compared to larger institutions (Lotulung, 2023). Furthermore, engaging high school students in active learning classrooms has been shown to enhance their overall educational experience (Davis & Balfanz, 2022; Torsdottir, 2024). In summary, the integration of clear goals, regular assessments, and a focus on real-world connections not only promotes deeper understanding but also aligns with contemporary findings on the importance of student engagement in educational success.

In Approach C, the instructional focus is on delivering information from the textbook according to a predetermined program, prioritising the learning process over the learning outcome. The teacher selects specific sources and sets criteria to guide students in acquiring subject-matter concepts. This approach views teaching as the transmission of knowledge to students. They control the classroom atmosphere by rearranging the classroom, assigning and solving problems related to the subject, and setting expectations for student behaviour and academic progress, as highlighted by Emmer et al., (2021), who discuss how contextualized teaching and learning strategies can improve student engagement and learning outcomes. Their research details the various roles teachers play in managing classroom dynamics and facilitating effective learning processes. Teachers play an essential role in the teaching-learning process and believe that a positive classroom atmosphere and external conditions lead to better learning outcomes. This finding is consistent with the findings of Luo et al., (2024), who believe that the quality of teaching is influenced by teachers' skills in communication and evaluation, and is further shaped by the pedagogical ideas and management techniques employed in the classroom.

As for the primary roles, teachers in Approaches A and B agree that students play a crucial part in the education process. They use various approaches to include them in the learning process, but they hold differing opinions about the nature of their activities and the role of learners. The instructor emphasizes interpersonal and collaborative skills in Approach A. With approach B, on the other hand, the instructor places more of an emphasis on helping each learner grow personally and engage in learning activities (internal conditions), which provides the students the framework for learning. Teachers play a number of roles that are essential to students' learner-centered learning, according to Badjadi's (2020) research. These roles include those of controllers, assessors, managers, resources, tutors, participants, investigators, role models, prompters, editors, instructors, activators, supporters, and facilitators. Teachers are facilitators in Approach A and supporters in Approach B, according to this research's findings. Our results regarding the role of students in Approaches A and B are in line with those of Bhuttah et al., (2024), who emphasized the benefits of creative pedagogical approaches on learning outcomes and student engagement as well as the significance of teacher leadership in establishing nurturing learning environments that support students' interpersonal and personal growth. In contrast to the first two methods, approach C holds that learning can only occur when external factors are under control. Teachers are an integral part of the teaching-learning process and monitor it. In this approach, the teacher has the role of a controller and this role naturally influences classroom practices (Özdemir & Kaptan, 2013).

In terms of the activities designed by the teacher, Approach A encourages students to apply and develop their scientific process abilities through tasks such as generalizing and drawing conclusions, presenting and elaborating on concepts, and reflecting. In contrast, Approach B places greater emphasis on direct instructor assistance for skill development and performance of activities, as highlighted by Gizaw and Sota (2023), who discuss how different teaching strategies can effectively enhance learners' engagement and learning outcomes in science education. Teachers play a more important and systematic role in the teaching-learning process in this approach compared to approach A, as noted by Caleon, et al., (2018), who noted that teaching experiences influence teachers' beliefs and practices, which ultimately affect their effectiveness in managing classroom dynamics and facilitating learning. They emphasised that classroom practices were more aligned with teachers' beliefs about learning physics, rather than teaching physics. Approach C involves a teacher who views problem solving as a means of teaching. The instructor designs activities that require students to solve a large number of problems, believing that this approach helps students develop their skills and learning. From the perspective of evaluation, pupils are assessed according to their abilities in Approach A and according to textbook chapters in Approach B. With strategy C, the instructor often presents the students with the highest scores after evaluating them based on the subject matter of each course. Research indicates that problem-solving methods significantly enhance student engagement and learning outcomes (Ezeddine, 2023; Emmer et al., 2021), while also promoting higher-order thinking skills (Tambunan, 2019). This integration provides a well-rounded reference base for your discussion on Approach C.

It can be claimed that Technique A is congruent with constructivism because, in general, the instructor aims for students to develop critical thinking abilities, collaboration, and a comprehensive grasp of subjects. According to research, constructivist classrooms encourage learners to engage in self-reflection and self-questioning, which enhances their ability to evaluate information critically and build knowledge independently (Xu, et al., 2023). Studies indicate that constructivist environments promote deeper knowledge acquisition through interactive learning experiences, allowing learners to relate new information to their existing knowledge bases (Le & Nguyen, 2024). Strategy C, aligns with findings that emphasise a more traditional style of teaching, where the teacher exerts significant control over classroom dynamics, often at the expense of student engagement and autonomy.

According to a study by Gazmuri et al., (2023), effective classroom management is crucial for maintaining order and achieving educational goals, but an overly controlling environment can hinder pupil participation and critical thinking. The research indicates that while some level of control is necessary for classroom management, excessive focus on content delivery can detract from fostering a collaborative learning atmosphere that encourages student input and reflection. In other words, if we consider the three approaches as a spectrum, Approach B falls in the middle of the spectrum between Approach A and Approach C, which represent two extremes. As we move closer to Approach C, the role of the teacher becomes increasingly important, and the focus shifts from conceptual understanding to the transfer of predetermined knowledge. This observation aligns with previous studies that highlight the need for a balance between teacher-led instruction and student-centred learning to foster critical thinking skills effectively.

This research showed that teachers use a combination of three approaches in their teaching. The dominant approach among physics teachers was approach B, as was also highlighted by Caleon et al., (2018); and in second place is approach C, and the use of approach A is the least popular among teachers in teaching physics.

According to the results, it can be said that the teaching approach used by teachers does not meet the objectives of Iranian physics textbooks, and this result can be seen in international tests such as TIMSS. The distribution of approaches shows that most physics teachers tend to cover all the contents of the textbook (as also noted by Wallace and Kang (2004)), and students learn the contents presented in the textbooks in depth and do not try to develop their concepts. In order to achieve this goal, they often seek direct guidance from the students or teach with their own focus and convey the concepts of physics to the students. As further noted by Qhobela and Kolitsoe-Moru (2014); Tan and Nashon (2015); Savasci and Berlin (2012), one of the causes of this behaviour is probably a nationwide university entrance exam that is administered at the conclusion of secondary school.

Parents and educational officials expect teachers to prepare students well for this examination. Another reason could be the personal and economic cost that teachers have to pay for the implementation of approaches based on conceptual development. To implement these approaches, a teacher should spend time (Docktor, et al., 2015) and money for participating in and studying the related courses. Alfieri, et al., (2011) and Nesbit et al., (2023) have highlighted that few educators in the education community tend to use pure discovery learning, because this educational approach mostly focuses on the process of science instead of the content. Likewise, construction of correct scientific ideas in pupils, even in proper environments, is time-consuming. McDermott and her collaborators (1999) have proposed discovery learning approaches, which is a combination of scientific constructivism with strong guidance to cover the content of the discipline. In scientific constructivism, a suitable environment to attain the largest fraction of profited students in the teaching and learning process is important. This approach outperforms more than pure discovery and also traditional lecture-based instruction and demonstrates a low reasonably good understanding of science to reach students to large efficiency of understanding. In this regard, Thornton and Sokoloff (1998) have used the McDermott model and revealed that using guided discovery methods during education can be beneficial for a large fraction of students having a robust and functional understanding of many complex topics. Nelsen (2014) and Ates et al., (2018) have also believed that teachers expand their teaching habits based on being educated in, being in, and working in situations made by previous teachers and their discipline's traditions. Overall, habits, capacities of individuals for responses to situations and problems arising from a specific sociocultural context, are acquisitive.

2. Answer to the Second Research Question: What is the Difference, If Any, in Teachers' Approaches Based on Their Gender, Age, and Years of Service?

We examined the correlations between some variables, including gender, educational level, and years of service, and teachers' physics teaching approaches after collecting data on these approaches. Although years of service has an impact on physics teachers' teaching style, the results showed that there was no significant correlation between teachers' gender and educational attainment and their physics teaching approach, which is consistent with the findings of Atanasova et al., (2024), Tan and Cho (2018). It appears that the likelihood of a teacher using only student-centred techniques decreases with experience, which is contrary to the conclusions of study by Lim and Chai (2008). This finding appears to be related to contextual factors such as institutional policies, curriculum mandates, available support from school administrators, and teacher self-efficacy, as suggested by Allen, 2023, Davis and Chick, 2022, and Rashidi et al., (2014) in their study.

Despite the stated limitation, the current study provides insight into the domain-specific beliefs and practices of Iranian physics teachers and underscores the important role that beliefs play in shaping practices situated within authentic classroom settings. Specifically, the findings suggest that more experienced teachers may be less inclined to implement purely student-centred approaches due to various external pressures and expectations. Overall, these findings underscore the need for ongoing professional development that encourages physics educators to adopt inclusive and interactive teaching strategies that balance content delivery with active studnt participation to meet contemporary educational goals.

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Appendix A

Teaching Approach Survey

The questions in this survey will ask you about the teaching activities often used in their classrooms. Please answer the questions patiently, and truthfully. Your answers are very important because we need to understand your teaching approach. Please do your best to answer each question and if you have no idea, skip the question and move on.

You may choose whether or not you want to fill out this survey. By filling out the survey, you agree to be part of this research. Your participation is greatly appreciated!

Gender: Woman ☐ Man ☐

Age: 20-25 years old ☐ 26-30 years old ☐ 31-35 years old ☐ more than 35years old ☐

Level of Education: Below bachelor ☐ Bachelor ☐ More than bachelor ☐ PHD ☐

Years in service: 5 years and below ☐ 6-15 years ☐ 16-25 years ☐ More than 25 years ☐

	Items	Strongly disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Strongly disagree
Q6	I ask my students to express in own their words what learned.						
Q2	Before starting the teaching, I ask about the student's prior knowledge.						
Q8	I use a variety of diagnostic evaluations						
Q9	At the beginning of the teaching, to start a discussion between students, I propose an activity or an experiment related to the topic.						
Q11	I ask the students to discuss and think about the application of what learned in their daily life.						
Q14	I try to provide conditions for students to use the skills of the scientific process, such as classification, prediction, etc.						
Q18	I use simple activities and examples to attract students' attention.						
Q5	Usually, at the beginning of the class, I express my expectations from the students.						

Q19	I design educational activities based on the results of the diagnosis assessment.						
Q21	I guide the students in activities in such a way they carry out the activity steps themselves.						
Q23	To assess the students' activities, I prepare a checklist and fill it out.						
Q26	The arrangement of my classrooms is in such a way that I have access to all parts of the class.						
Q46	I am familiar with various learning theories.						
Q15	I usually prepare a clip or experiment for each training session.						
Q3	I carefully determine the objectives related to content, before teaching it.						
Q12	Covering the topics of the textbook is important during the design of educational activities.						
Q29	I usually divide book chapters into small parts.						
Q1	I have a program for covering the topics of textbooks during the academic year.						
Q16	At the end of each book chapter, I take a test.						
Q22	I try to cover what is intended to teach.						
Q32	I assign and solve many problems for different topics.						
Q25	I assign a large number of problems to students as exercises.						
Q33	After making sure that the students are proficient in solving the problems, I start teaching the next topic.						
Q28	I use slides and clips for teaching a topic.						
Q35	During teaching, my students should be calm and quiet.						
Q38	If my students ask a non-related question during teaching, I will postpone the answer until after the class.						
Q40	The final score of the students is determined based on the total score of class tests, class activities, and a final exam.						

Q43	Usually, the students who gain the highest grades are introduced.						
Q4	I use the activities which engage students at the beginning of teaching.						
Q31	Sometimes I find it necessary to correct the students' preconceptions.						
Q7	Students preconceptions about the content taught are important to me and I try to guide them based on their preconceptions about that topic.						
Q10	I try to design activities based on student's prior knowledge.						
Q41	The atmosphere of my class allows the students to present their ideas.						
Q13	I design the problems and activities that make students think.						
Q17	In my opinion, the learning process is more important than the learning result.						
Q44	I design activities that make students interact with each other in their groups.						
Q39	I ask my students to explain their perceptions about the content which was taught.						
Q30	I use different(best) arrangements in my classroom to easily monitor the activities of my students.						
Q42	If I don’t have time to complete teaching a concept, I continue teaching it in the next session.						
Q36	In my classroom, a deep understanding of conceptions by students is more important than anything.						
Q20	I have well interaction with students during teaching.						
Q27	My feedback to the students makes them find the answer to questions themselves.						
Q24	I try to relate what is taught to daily life.						
Q37	After each activity, I ask students to draw conclusions about it and generalize it to new situations.						
Q45	I try to provide some books and resources related to the topic that is taught to help students.						
Q34	I assess each student according to her/his ability.						

Appendix B

Questionnaire based on approaches

		Items	Strongly disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Strongly disagree
Approach A	Q44	I design activities that make students interact with each other in their groups.						
	Q37	After each activity, I ask students to draw conclusions about it and generalize it to new situations.						
	Q39	I ask my students to explain their perceptions about the content which was taught.						
	Q41	The atmosphere of my class allows the students to present their ideas.						
	Q14	I try to provide conditions for students to use the skills of the scientific process, such as classification, prediction, etc.						
	Q13	I design the problems and activities that make students think.						
	Q30	I use different(best) arrangements in my classroom to easily monitor the activities of my students.						
	Q15	I usually prepare a clip or experiment for each training session.						
	Q34	I assess each student according to her/his ability.						
	Q27	My feedback to the students makes them find the answer to questions themselves.						
	Q23	To assess the students' activities, I prepare a checklist and fill it out.						
	Q46	I am familiar with various learning theories.						

	Q38	If my students ask a non-related question during teaching, I will postpone the answer until after the class.						
Approach B	Q4	I use the activities which engage students at the beginning of teaching.						
	Q18	I use simple activities and examples to attract students' attention.						
	Q10	I try to design activities based on student's prior knowledge.						
	Q20	I have well interaction with students during teaching.						
	Q24	I try to relate what is taught to daily life.						
	Q11	I ask the students to discuss and think about the application of what learned in their daily life.						
	Q9	At the beginning of the teaching, to start a discussion between students, I propose an activity or an experiment related to the topic.						
	Q7	Students preconceptions about the content taught are important to me and I try to guide them based on their preconceptions about that topic.						
	Q21	I guide the students in activities in such a way they carry out the activity steps themselves.						
	Q36	In my classroom, a deep understanding of conceptions by students is more important than anything.						
	Q6	I ask my students to express in own their words what learned.						
	Q16	At the end of each book chapter, I take a test.						
	Q5	Usually, at the beginning of the class, I express my expectations from the students.						
	Q19	I design educational activities based on the results of the diagnosis assessment.						

	Q3	I carefully determine the objectives related to content, before teaching it.						
	Q8	I use a variety of diagnostic evaluations						
Approach C	Q29	I usually divide book chapters into small parts.						
	Q1	I have a program for covering the topics of textbooks during the academic year.						
	Q22	I try to cover what is intended to teach.						
	Q12	Covering the topics of the textbook is important during the design of educational activities.						
	Q31	Sometimes I find it necessary to correct the students' preconceptions.						
	Q26	The arrangement of my classrooms is in such a way that I have access to all parts of the class.						
	Q35	During teaching, my students should be calm and quiet.						
	Q43	Usually, the students who gain the highest grades are introduced.						
	Q33	After making sure that the students are proficient in solving the problems, I start teaching the next topic.						
	Q25	I assign a large number of problems to students as exercises.						
	Q32	I assign and solve many problems for different topics.						
	Q45	I try to provide some books and resources related to the topic that is taught to help students.						
	Q17	In my opinion, the learning process is more important than the learning result.						

Journal of Turkish Science Education, 2025, 22(4), 801-821.
DOI no: 10.36681/tused.2025.039

Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

Integration of indigenous knowledge into grade 8 biology teaching and its effect on students' achievement

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ABSTRACT

This study examined the effect of integrating indigenous knowledge on eighth-grade students' ecology and biodiversity achievement in Injibara, Ethiopia. A nonequivalent pre-test-post-test quasi-experimental research design with a mixed-methods approach was employed. A total of 89 students participated in the study, with two intact classes randomly assigned: 46 students to the control group and 43 to the experimental group. Data were collected using a 25-item Ecology Achievement Test (EAT) and a focus group discussion. The face and content validity of the instruments were confirmed by advisors and subject experts. The internal consistency of the test items was assessed using the Kuder-Richardson formula (KR-20), yielding a coefficient of 0.83. Independent samples t-tests and analysis of covariance (ANCOVA) were used to test the null hypotheses, while means and standard deviations were used to address the research questions. The results showed that the experimental group outperformed the control group in integrating indigenous knowledge. Additionally, the achievement was not significantly influenced by gender, and there was no interaction between gender and the teaching method. These finding suggests that integrating indigenous knowledge into biology instruction enhances students' academic performance and fosters more effective teaching and learning outcomes.

RESEARCH ARTICLE

ARTICLE INFORMATION
Received: 18.12.2024
Accepted: 29.05.2025
Available Online: 23.21.2025

KEYWORDS:
Aacademic achievement, ecology and conservation, indigenous knowledge.

To cite this article: Yeruke, S. K., Ferede, M. W., & Merawi, T. M. (2025). Integration of indigenous knowledge into grade 8 biology teaching and its effect on students' achievement. *Journal of Turkish Science Education, 22*(4), 801-821. http://doi.org/10.36681/tused.2025.039

Introduction

Education is universally recognized as a cornerstone of sustainable development, fostering intellectual, social, moral, and practical growth across generations (Cimer, 2012; Mohanty, 2021). Beyond its role in personal development, education contributes to national progress by cultivating human capital, advancing innovation, and promoting social cohesion. In particular, science education plays a pivotal role in elevating societal standards and encouraging technological and cultural transformation (Gödek, 2004). Within this framework, biology education in Ethiopia is central to equipping learners with the scientific knowledge, attitudes, and practical skills necessary to address pressing challenges such as environmental conservation, public health, and sustainable agricultural development (Teferra et al., 2018). As a foundational science, biology supports industrialization and innovation through its applications in biotechnology, environmental management, and resource utilization (Jima, 2022).

Biology is also strategically aligned with Ethiopia's long-term development goals articulated in Vision 2030, which aims to transition the country into a middle-income economy. The national education policy emphasizes Science, Technology, Engineering, and Mathematics (STEM) by allocating 70% of higher education enrolments to these disciplines, reflecting the government's intent to build a skilled and innovative workforce (Chala, 2015; Teferra et al., 2018). Strengthening biology education, therefore, is integral to achieving Vision 2030 objectives, particularly in improving agricultural productivity, advancing healthcare, and promoting environmental stewardship. Enhancing biology learning at the foundational level, such as in Grade 8, is essential for nurturing students' scientific literacy, critical thinking, and problem-solving abilities. Integrating Indigenous Knowledge (IK) into biology instruction offers a culturally grounded and practical approach to achieve these competencies, laying the groundwork for future expertise in STEM fields. Through early exposure to locally relevant and experiential learning, students are better prepared to contribute to national development efforts and sustainable innovation.

Despite the recognized importance of biology education, student performance in the subject remains persistently low in Ethiopia. Studies reveal that many students entering secondary education exhibit weak foundational knowledge in science and mathematics (Tulu & Fantahun, 2021). Data from the National Educational Assessment and Evaluation Agency (NEAEA) further indicate that only 22.9% of Grade 10 students and 48.5% of Grade 12 students achieved scores of 50% or higher in biology (Yimam, 2023). These statistics fall short of national education standards, which require a minimum average of 50% across all subjects. Such outcomes raise critical concerns about the effectiveness of current teaching strategies and curriculum design in achieving desired learning outcomes.

Research across Africa identifies various factors influencing students' low achievement in science, including the use of teacher-centered pedagogies that disconnect learning from real-life experiences (Agboghoroma & Oyovwi, 2015; Naidoo, 2007). Additionally, cultural incongruence between classroom instruction and students' lived experiences often limits engagement and comprehension (Hodson, 2009). The inadequate incorporation of Indigenous Knowledge systems into the curriculum further compounds this issue (Nair & Abera, 2017; Ogunniyi, 2009). A recent analysis of Ethiopia's Grade 7 General Science curriculum revealed that nearly 79% of instructional activities fail to incorporate or encourage connections with IK (Yeseraw et al., 2023). Similarly, current textbooks seldom reflect indigenous contexts or pedagogical practices, underscoring an urgent need for curriculum reform that integrates local knowledge systems and values (Da Silva et al., 2024).

Indigenous Knowledge, defined as the cumulative wisdom, skills, and practices developed by communities through generations of interaction with their environments (Mukuka, 2019) offers a culturally relevant and contextually meaningful framework for science education. Within this study, IK specifically refers to the traditional knowledge of the Awi community, encompassing ecological awareness, sustainable agricultural methods, soil and water conservation techniques, medicinal plant usage, and seasonal environmental patterns. This knowledge base, rooted in culture and practical experience, serves as a pedagogical bridge linking local environmental understanding to formal biological concepts. By contextualizing biology instruction within students' cultural realities, IK-based teaching can enhance engagement, comprehension, and retention, making scientific learning more accessible and meaningful (Kassa et al., 2024).

Despite these potential benefits, many developing countries continue to rely heavily on conventional, lecture-based teaching methods that limit student participation and conceptual understanding (Upu & Okwara, 2024). Empirical studies demonstrate that such traditional methods are less effective than innovative, context-based pedagogies that integrate IK and encourage active learning

(Adam, 2023; Ajayi et al., 2023; Fenetahun, 2018; Jima, 2022). Incorporating IK into biology education fosters a more holistic and experiential approach that links science with culture, thus improving conceptual understanding and student motivation (Khusniati et al., 2023). As Oluboyo (2021) asserts, education in indigenous settings must be both culturally and linguistically relevant to ensure equitable learning outcomes.

Ethiopia possesses a rich reservoir of Indigenous Knowledge across diverse domains, including traditional medicine, seed preservation, water management, and adaptive farming practices designed to address food insecurity (Tizita, 2016). Each ethnic community contributes distinct systems of knowledge that reflect local ecological conditions and cultural values. Given the diversity and contextual nature of IK, it is imperative to conduct region-specific studies that explore how these knowledge systems can be effectively integrated into formal education. For instance, research by Ali et al. (2022) has examined IK transfer in traditional medicine and agriculture, demonstrating that its integration into science teaching enhances learning relevance and outcomes. Similarly, Yeseraw et al. (2023) evaluated the inclusion of IK elements in Amhara Region trial textbooks, while Baye and Teshome (2020) documented the contributions of IK to agricultural productivity and community well-being in Gondar and Gojjam.

However, despite this growing body of research, there remains a significant gap regarding the integration of IK into biology instruction and its direct influence on students' academic achievement in the study area. While the use of IK in teaching has been reported to improve student achievement internationally, it remains uncertain whether similar results will be observed in this region (study area). Moreover, it is unclear whether such pedagogical approaches benefit male and female students equally, as findings from previous studies on gender differences in science performance have been inconsistent. Some researchers report that females perform better under IK-based teaching (Nbina & Wagbara, 2012), whereas others, including Audu (2017), Chibuye and Singh (2024), and Uduaka et al. (2020), found that male students outperform females. In contrast, studies by Agboghoroma & Oyovwi (2015) and Ugwu & Diovou (2016) indicate no significant gender-based differences in achievement. This unresolved issue highlights the need for further investigation into gender interactions in the context of IK-based biology instruction.

Additionally, a practical gap persists among teachers regarding how to effectively integrate IK into classroom practice. Many educators lack the pedagogical training, resources, and frameworks necessary to blend traditional and scientific knowledge meaningfully. Methodologically, existing literature provides limited insight into evaluating the outcomes of IK integration and understanding the mechanisms through which it enhances student achievement (Bohensky & Maru, 2011). Addressing these empirical, practical, and methodological gaps is essential for advancing educational equity and effectiveness in Ethiopia.

This quasi-experimental study is therefore designed to examine the effects of integrating Indigenous Knowledge into biology teaching on students' academic performance, particularly in ecology and biodiversity conservation. It seeks to determine the extent to which IK-based teaching strategies improve student achievement compared to conventional methods and whether gender differences influence these outcomes. By aligning science education with local knowledge systems, this study aims to contribute to national goals of improving science literacy, promoting inclusive education, and supporting Ethiopia's broader vision for sustainable development.

Research Questions

The following research questions have been formulated to achieve the research objectives:

1. Does the integration of IK significantly enhance students' academic achievement in biology compared to traditional teaching strategies?

2. Is there a statistically significant difference in the average achievement scores between male and female students taught biology using IK?

3. How do students perceive the effects of integrating IK in the teaching and learning of biology?

Theoretical Framework

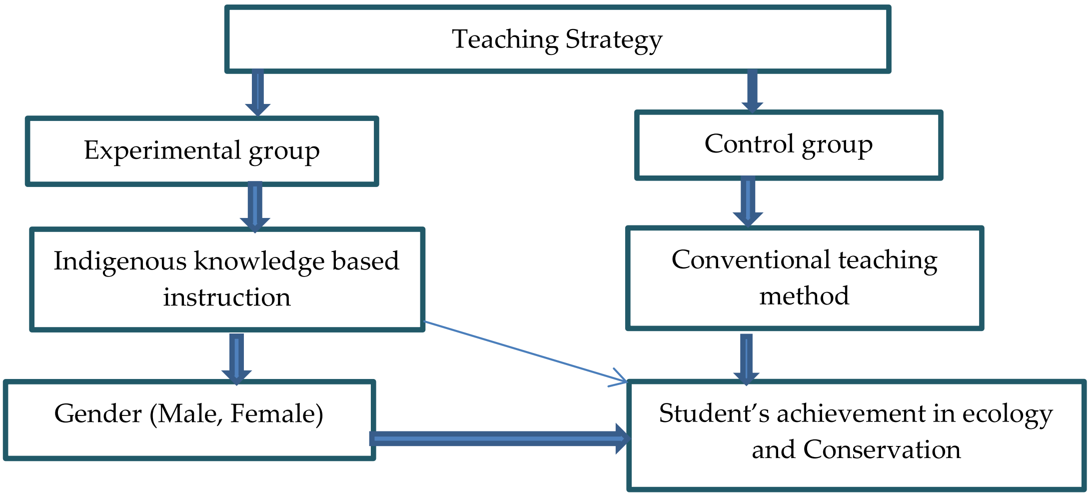
This study is based on Ausubel's theory of meaningful learning, an important concept in science education. Ausubel's theory suggested that meaningful learning occurs when new information is connected to relevant existing knowledge within a learner's cognitive structure. This illustrates the connection between students' learning and their prior knowledge (Ausubel, 2012). The theory suggested that learning happens when a learner's existing knowledge interacts with new material, such as Ethno-ecology knowledge and practices alongside school biology.

Integrating IK into biology education can enhance students' attitudes and understanding, leading to improved performance in the subject (Shishigu et al., 2021). This integration serves as an advanced organiser for new biology concepts, promoting positive attitudes and a deeper comprehension of biology (De Beer & Whitlock, 2009). For example, local Indigenous Knowledge (IK) about soil conservation—such as the traditional practice of using composted organic waste and crop rotation to maintain soil fertility—can serve as an advanced organizer for understanding the scientific concept of the nitrogen cycle. When students relate familiar practices like adding organic matter to soil with the scientific explanation of nitrogen fixation, nitrification, and decomposition, they can meaningfully connect prior experience to new biological concepts. This contextual link not only deepens comprehension of nutrient cycling but also reinforces the relevance of scientific knowledge to local agricultural sustainability, thereby fostering meaningful learning as described by Ausubel's theory.

Figure 1 illustrates the conceptual framework of the study. In this framework, teaching strategies are considered independent variables, while students' biology achievement is the dependent variable. The experimental group received instruction based on IK, whereas the control group experienced conventional teaching strategies.

Figure 1

Conceptual framework of the study



Literature Review

Integration of IK into Biology Teaching

The integration of Indigenous Knowledge (IK) into biology education represents a shift from traditional "cookbook" teaching methods toward a constructivist learning approach. Constructivism emphasizes that learners actively construct new knowledge by connecting it to their prior experiences and understanding (Onyewuchi & Owolabi, 2022). Through a step-by-step learning process, students progressively develop deeper conceptual comprehension (Taber, 2001). Studies show that incorporating learners' prior knowledge—often represented by their IK—enhances comprehension and engagement (Oladejo et al., 2022). Recognizing students' existing knowledge is, therefore, a key strategy for effective science instruction.

The effectiveness of integrating IK depends largely on teachers' expertise and pedagogical competence, which influence the quality of instruction (Ogunniyi (2009); Omorogbe & Ewansiha, 2013) highlighted a growing respect among teachers for IK, reflecting a dynamic relationship between scientific and indigenous worldviews. However, reliance on a single cultural perspective can marginalize students from diverse backgrounds (Mkhwebane, 2024). Teachers are thus encouraged to adopt multiple scientific and cultural approaches, recognizing the contributions of different knowledge systems. This requires identifying learners' cultural strengths and integrating them into science lessons to promote inclusivity and relevance.

Across Africa, governments have urged the inclusion of IK in school curricula to enhance learning outcomes and inclusivity (Oguoma, 2018). Despite this, many biology teachers either disregard this directive or lack the pedagogical skills to apply it effectively (Mavuru & Makhunga, 2020; Ngcobo, 2020). Sitsha (2022) observed that continued use of traditional methods limits student participation, while Cronje et al. (2015) found that IK is often treated as supplementary. Nonetheless, integrating IK fosters student motivation and connection to learning (Upu & Okwara, 2024).

Biology is often perceived as foreign by students; incorporating IK makes it culturally meaningful and relatable. Teaching biology through indigenous perspectives enhances students' appreciation and understanding of the subject (Anane, 2023). Integrating IK within the curriculum allows both knowledge systems to coexist, linking scientific learning with students' social and natural environments (Nwankwo, 2021). This approach promotes experiential, hands-on learning that improves comprehension and application (Liyas, 2019). Strengthening this integration through curriculum development at all educational levels is essential (Latip & Kadarohman, 2024).

Research shows that integrating IK into science subjects improves students' understanding, achievement, and attitudes (Chongo & Baliga, 2019; Mukuka, 2019; Shishigu et al., 2021). To enhance performance in biology, incorporating Ethiopian biological customs is vital. Achievement defined as the extent to which educational goals are met (Ibe, 2017; Shehzad & Aziz, 2019) in this context reflects students' ecological understanding as demonstrated through assessment outcomes.

Teaching Method and Gender Interaction

Due to the assumption that females are less valuable than males, males are given greater opportunities and authority in society due to gender factors associated with their views and beliefs (Uduaka et al, 2024). It is interesting to observe how these viewpoints permeate the educational system and, as a result, affect academic performance. That is to say, among other things, gender affects biology students' performance.

A study by Singh & Chibuye (2016) revealed that a higher percentage of females than males found biological concepts difficult to understand. This indicates that learning experiences may differ by gender. Similarly, Audu (2017) found that more females than males struggle with biological concepts, which could be linked to various factors such as socialisation and classroom experiences. Additionally, research by Chongo and Baliga (2019), and Mukuka (2019) noted significant differences in academic performance between male and female students, with male students outperforming their female counterparts.

In contrast, Agboghoroma & Oyovwi (2015) found that gender, whether male or female, had no effect on students' achievement in science. Both male and female students demonstrated improved performance when indigenous knowledge and practices were integrated into their learning compared to conventional methods (Ugwu & Diovou, 2016). This suggests that we cannot yet conclude whether gender influences understanding in biology, or which gender achieves higher in this subject. Therefore, this study incorporated gender to determine if it impacts students' achievement when integrating indigenous knowledge in teaching ecology and biodiversity conservation.

Students' Perception of Integrating IK into Biology Teaching

Omenka (2019) assert that students' interest in studying science is influenced by their perceptions of the subject. Specifically, students' interest in biology may be impacted by their views of the teaching environment. Many students appreciate IK-based instruction because it is relatively easy to understand and apply, which can enhance performance, productivity, and learning effectiveness (Anane, 2023). Additionally, lessons that incorporate IK are generally grasped more quickly. Omenka (2019) suggests that students' perceptions of school biology could improve if the curriculum bridges the gap between scientific concepts and IK, thereby addressing differences in worldviews and fostering greater student achievement.

According to Cimer (2012) and Cepni et al., (2017), students' perceptions of science are positively influenced when the subjects are taught in a way that relates to their daily lives. Additionally, Arboleda (2020) found that when students have high expectations in class, a positive attitude toward science significantly contributes to meaningful science learning. Generally speaking, students' positive perception of a subject or topic greatly improves their achievements. Adesoji (2008) suggests that investigating the impact of incorporating IK into biology instruction as a teaching strategy could be highly relevant for enhancing students' performance

Methodology

Research Design

A non-equivalent pre-test-post-test quasi-experimental research design with a mixed-methods approach was utilised. This design involved the simultaneous collection of both quantitative and qualitative data to support and validate the quantitative findings. In this approach, the quantitative method serves as the primary focus of the research, while the qualitative method acts as a secondary source that provides additional context. The qualitative component is considered less prioritised and is embedded within the dominant quantitative framework. This design is referred to as a concurrent embedded mixed research design (QUAN/qual), where the quantitative results are used to select the best participants for the qualitative study deliberately. Subsequently, the qualitative data help to clarify any quantitative results that need further explanation. As shown in figure 2 QUAN/qual notation indicates that the qualitative method is integrated within the quantitative method, with both occurring simultaneously. For the quantitative approach, the quasi-experimental pre-test-post-test non-equivalent control group design was chosen, allowing for greater control over extraneous variables (Nel, 2006).

A primary limitation of the non-equivalent pre-test–post-test quasi-experimental design is the potential for selection bias, as intact classes are used rather than randomly assigning students to groups. This means that pre-existing differences in students' abilities, motivation, or prior knowledge could influence the results independently of the intervention. To address this issue, a pre-test was administered to both the experimental and control groups to measure baseline equivalence. The resulting pre-test scores were then included as a covariate in the ANCOVA (Analysis of Covariance), which statistically controlled for these initial differences. This approach enhanced the internal validity of the study by ensuring that any observed post-test differences could be more confidently attributed to the intervention rather than pre-existing group disparities.

Figure 2

Concurrent embedded mixed research designs

Sampling Technique and Procedures

This study was conducted in Injibara City Administration, Awi zone, Amhara region, Ethiopia. As displayed in figure 3 the study used a population of six private and twelve governmental primary and middle schools in the Injibara city administration. Private schools were excluded from the study because they were not comparable to governmental schools. Private schools, compared to governmental schools, were better equipped regarding teaching infrastructure, including smart classrooms and highly qualified teachers, and students were selected and joined the schools based on their academic achievement. Even private schools were taught additional subjects like supplementary science, supplementary mathematics and spoken English, which were not in governmental schools. Again, four governmental schools were excluded based on learners' characteristics and school facilities and due to security problems. Two of these schools, Basa and Hidase, experienced security problems during data collection. The other two schools, Kosober and Bahunk, are relatively better in terms of facilities, and the learners differ in language and family background since these schools are located in the downtown area.

However, eight governmental schools were comparable in terms of the backgrounds of their teachers and students, such as teachers' and students' exposure to Awi IK, teachers' qualifications and their facilities. Two intact groups were randomly selected to eliminate any potential for subject interaction: an experimental group from Bida (Grade 8, Section C) and a control group from Bata (Grade 8, Section A).

Grade 8 was deliberately chosen as a transitional point between primary and secondary education, marking a critical educational journey. The curriculum becomes more advanced at this level, and students are expected to take greater responsibility for their learning. This transition is essential for their development and helps prepare them for high school. According to Meece (2003), the middle school years are a crucial turning point in the lives of young people. Therefore, we have focused our efforts on this grade level to enhance and establish a strong foundation for student achievement. Additionally, grade eight students were selected because they are beginning to mature, paying closer attention to their education, and adjusting better to the school environment than students in lower grades. For these reasons, conducting interventions in the 8th grade is timely and supported by evidence.

Figure 3

Sampling Procedures

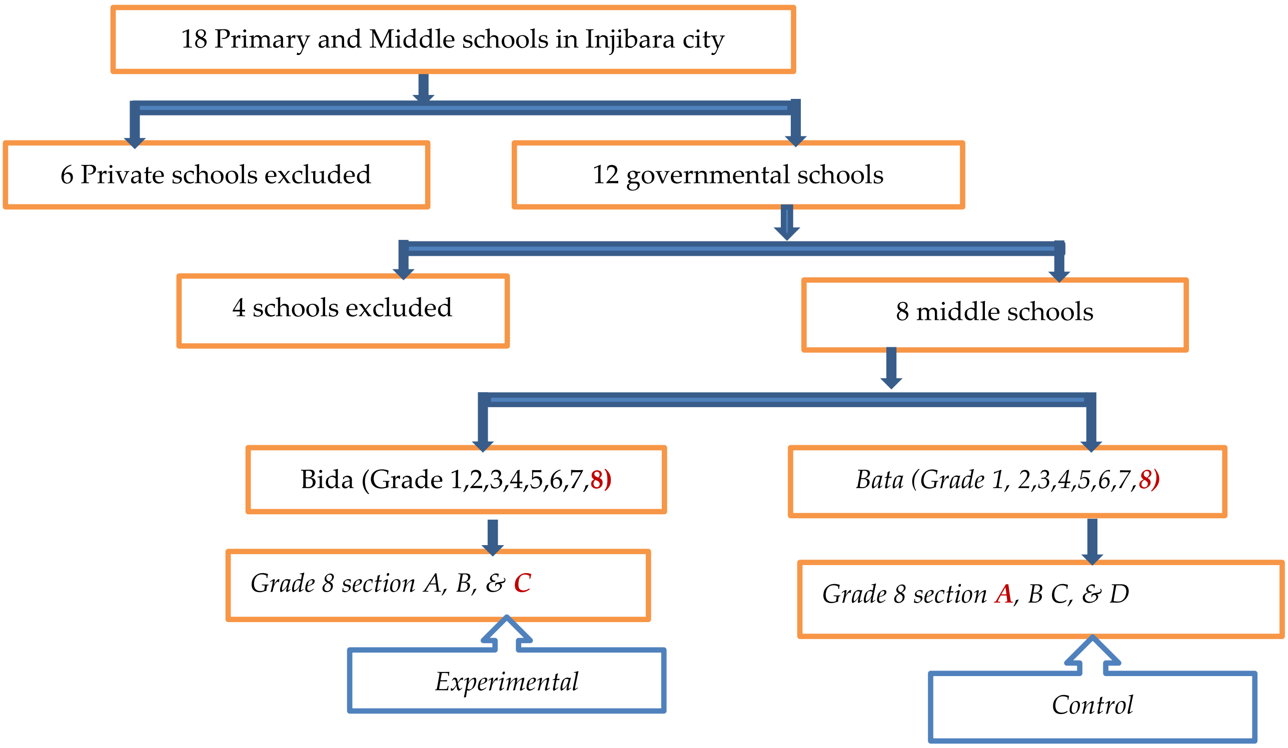
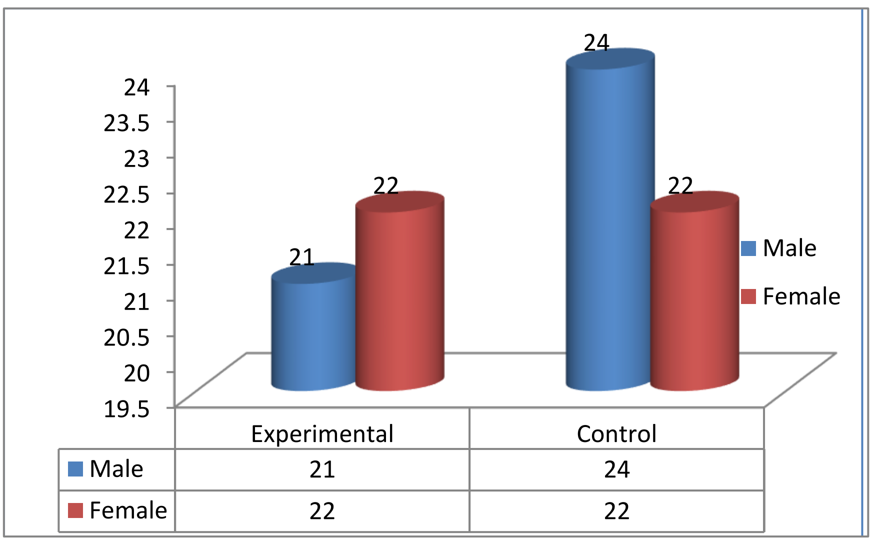


Figure 4 displayed the ***study participants***, which involved 89 students, 44 of whom were females, and 45 of whom were males (Figure 4). The control group had 46 participants, which constituted 51.7% of the entire participants, while the experimental group had 43 participants, which constituted 48.3% of the entire participants.

Figure 4

Gender distribution of participants in each group



Data Gathering Instruments

This study employed two primary instruments for data collection: the Ecology Achievement Test (EAT) and focus group discussions. The researchers developed a 25-item EAT, administered to control and experimental groups to assess students' ecological knowledge during pretests and posttests. Each of the 25 multiple-choice questions offered four response options labelled A-D. The pretest and posttest questions contained the same number of items and covered the same content, but the arrangement of the items was different. The instrument underwent face and content validation, with input from advisors, two biology teachers, and a measurement and evaluation teacher. Their corrections and recommendations were incorporated into the final version. A preliminary test of the EAT was conducted with 26 non-sample students.

The reliability of the EAT was evaluated using the Kuder-Richardson Formula 20 (K-R20), which confirmed a reliability coefficient of 0.83. The test items were carefully developed based on the Grade 8 curriculum guide, ensuring each question reflected specific learning competencies related to ecology and biodiversity conservation. Topics such as ecosystem interactions, the importance of biodiversity, and conservation practices were covered to match the intended learning outcomes. This alignment ensured that the test measured the knowledge and skills outlined in the curriculum, thereby strengthening its content validity.

Following the intervention, focus group discussions were conducted to explore students' perceptions regarding the influence of integrating Indigenous knowledge in the teaching and learning of ecology and biodiversity conservation. It is important to gather data from various sources to enhance the credibility and validity of the study's findings. The researchers developed a self-composed FGD guide titled “Indigenous Knowledge System and Practices FGD Guide.” This guide was initially prepared in English and then translated into the local language, Awgni. Discussions were also conducted in Awgni, and the researchers subsequently translated the conversations into English for thematic analysis.

A total of 12 participants (6 males and six females) from the experimental group were selected based on their scores on the achievement test, ensuring the inclusion of high achievers while also considering gender balance. The selection of only high-achieving students for the focus group discussions (FGDs) was a purposive sampling strategy aimed at gathering in-depth insights from students who were most likely to have fully engaged with the indigenous knowledge (IK)-based instructional approach. High-achieving students were expected to have a deeper understanding of the content and could articulate their experiences and reflections on the learning process more clearly, providing rich qualitative data about the effectiveness and reception of the intervention.

Intervention Procedure

Before the start of the experiment, the researcher visited the participating schools. Two sections were selected and assigned: the treatment group (Bida) and the comparison group (Bata). Permission was obtained from the authorities of the participating schools, and the students consented to voluntarily participate in the study, understanding that they could withdraw their participation at any time. The experimental and control groups received similar concepts, materials, assessment styles, and learning objectives. The key difference was that the experimental group incorporated IK concepts through various instructional activities.

As illustrated in figure 5 the teacher of the experimental group received specialised training on integrating IK into ecology subtopics, while the control group was not provided with this instruction. This training, conducted by the researcher, lasted for five days. At the beginning of the training, the researcher explained the purpose of the study, the methods for implementing the intervention, the tasks to be completed during the intervention, and the timetable.

During the training, local knowledge of soil, ecosystems, and natural resource conservation was identified and documented. These pieces of local knowledge were selected based on curriculum objectives and categorised into ecosystem and natural resource conservation. The discussion also covered integrating the identified local knowledge into the school curriculum. For instance, the Awi community traditionally practices terracing and mixed cropping on hilly farmlands to prevent soil erosion and maintain fertility. This practice was linked to the scientific concept of soil conservation and nutrient cycling, helping students understand how controlling runoff and maintaining organic matter supports the nitrogen and carbon cycles in ecosystems. A commonly shared Awi folktale describes how the fox, sheep, and grass depend on one another within the natural order. This story was used to illustrate the food web and trophic relationships, allowing students to connect local ecological stories to the biological concepts of energy flow and interdependence among organisms. The Awi people use small-scale irrigation systems and seasonal water storage pits to conserve water during dry seasons. This practice was connected to lessons on ecosystem sustainability and the water cycle, showing how indigenous methods align with scientific principles of water conservation and ecosystem balance.

Based on this discussion, the researchers developed an instructional package in the form of a lesson plan. This package was designed to guide the experimental teacher in teaching students using IK. It included performance objectives, teaching resources, lesson content, and activities for teachers and students, all aligned with the selected themes. The instructional package was intended for six weeks, with lessons scheduled for four periods per week, each lasting 40 minutes.

Both groups underwent a pretest before the treatment began, and the data collected were recorded and analysed. The pretest utilised the Ecology Achievement Test (EAT), administered by two teachers, to assess the students' prior knowledge. Students were informed about the purpose of the tests and completed the questions independently.

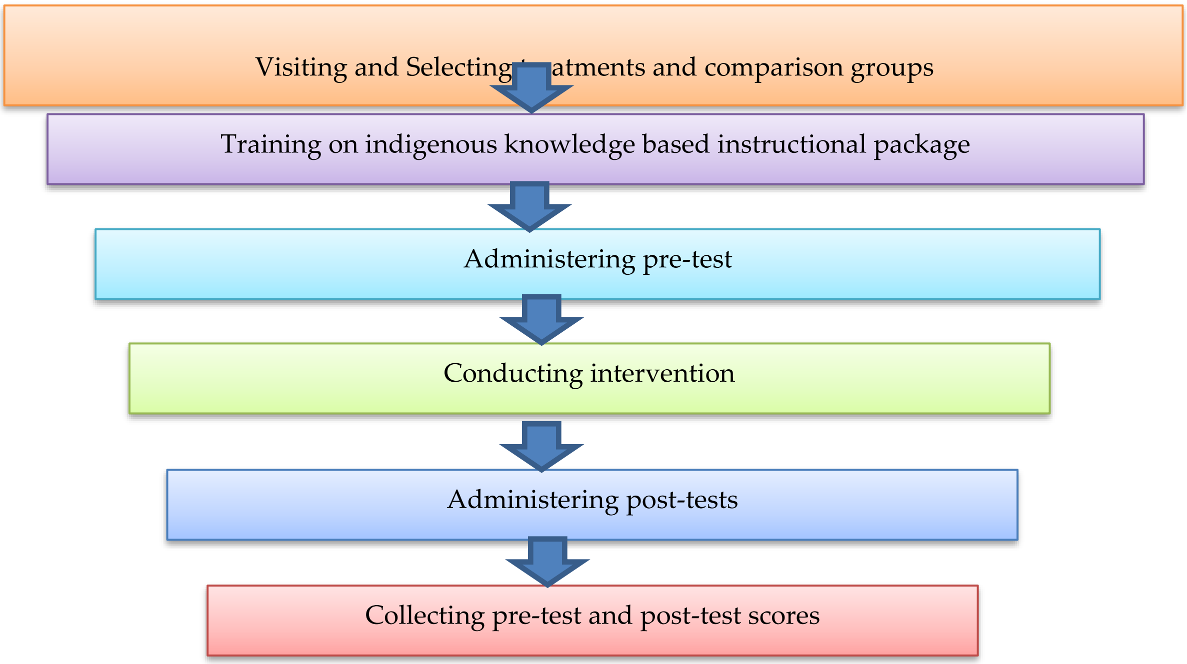
Over the course of six weeks, the topic "Ecosystems and Conservation of Natural Resources" was taught. The treatment group was instructed using an IK-based teaching approach, while the control group followed conventional instructional methods delivered by their regular teachers. For the experimental group, instruction was implemented step by step. Each lesson began with the teacher introducing the topic, followed by an invitation for students to describe and reflect on their cultural beliefs and practices related to the topic, sharing their cultural knowledge with their peers. The teacher then highlighted the differences between the students' cultural perspectives and the topic, establishing connections between the two. The lesson concluded with the teacher sharing additional cultural knowledge related to the topic gained from the students' discussions. In contrast, the control group teacher employed a traditional lecture method, focusing primarily on delivering information for students to listen to and absorb.

To ensure implementation, the researchers periodically visited both the experimental and control classrooms. In the experimental group, we were confirmed that the teacher consistently applied the indigenous knowledge (IK)-based approach, while in the control group, we were verified that the teacher followed the conventional teaching method. In addition to observations, lesson plans, were reviewed to ensure that each teacher adhered to their assigned instructional method. These measures helped confirm that the intervention was implemented as designed, supporting the internal validity of the study.

At the end of the treatment, a post-test was administered by the regular teachers after the instructional program concluded. These tests were administered carefully, with no observable differences between the two groups concerning time allotted, supervision, or the students' willingness to take the tests. Finally, the researcher collected pre-test scores, post-test scores, and questionnaires. Focus group discussions (FGDs) were conducted after the intervention.

Figure 5

Intervention procedures



Data Analysis Methods

This study investigated the effects of an IK-based teaching approach compared to conventional teaching methods on students' achievement in ecology tests before and after the treatment. Additionally, the study examined students' perceptions of the IK-based teaching approach after the treatment and explored gender differences in outcomes. Data were analysed using both qualitative and quantitative methods. The researchers conducted qualitative analyses of Focus Group Discussion (FGD) results, while the achievement tests were analysed quantitatively.

After coding and cleaning the data, it was entered into the Statistical Package for Social Sciences (SPSS) version 26 for recording and analysis. The data were analysed using both descriptive and inferential statistics. Descriptive statistics were summarised, and the results from the experimental and control groups were compared in terms of mean scores and standard deviations.

Inferential statistics, including independent sample t-tests and ANCOVA, were employed to determine mean score differences between the experimental and comparison groups, assessing their respective teaching strategies and different variables. Specifically, the inferential statistics examined the differences in ecology achievement test scores between the experimental and comparison groups before and after treatment and pre- and post-test scores within the experimental group. ANCOVA was also utilised to evaluate the effect of gender on students' achievement.

The qualitative data from the FGDs were transcribed and translated from the Awgni language to English. The transcripts were then reduced, coded, categorised, and reported thematically. Subsequently, the qualitative data were manually analysed and triangulated with the quantitative results.

Results

Effects of Integrating IK on the Academic Achievement of Students

Descriptive statistics were generated to evaluate basic statistical assumptions, including independent measurement, regular distribution of dependent variables across each group, and equal variance of the dependent variable (Pallant, 2020). The research design maintained independent measurement by selecting intact classes and testing each group under a single treatment condition. Normal distribution was assessed using skewness, while the Levene's test was employed to analyse the homogeneity of variances among the data sets. The results presented in Table 1 confirmed some of the statistical assumptions, indicating that all variables had skewness values ranging between -1 and 1, which suggests a normal distribution within each group.

Table 1 presents the pre-test and post-test results for a study's experimental and control groups. The control group had a pre-test mean score of 31.04 and a post-test mean score of 36.78, resulting in a mean gain 5.74. In contrast, the experimental group recorded a pre-test mean score of 30.47 and a post-test mean score of 50.33, yielding a mean gain of 19.86. The experimental group's mean gain of 19.86 significantly exceeded the control group's mean gain 5.74, indicating greater performance on the ecology achievement test. However, further inferential statistics are required to reach a definitive conclusion.

Table 1

Mean and standard deviation of students' scores in both experimental and control groups in pre- and post-achievement tests

Group	Variable	N	Mean	SD	Min	Max	Skewness	Kurtosis	Mean Gain
Experimental	Pre-test	43	30.47	12.358	12	64	.344	-.383	
	Post-test	43	50.33	18.273	20	84	.088	-1.261	19.86
Control	Pre-test	46	31.04	12.882	8	60	.392	-.634	
	Post-test	46	36.78	15.586	12	68	.499	-.448	5.74

A pre-test was conducted to determine if the two groups were comparable or homogeneous in achievement, as shown in Table 2. An independent samples t-test was used to assess student achievement differences between the experimental and control groups. No significant difference was found in pre-test scores between the experimental and control groups (t (87) = -.216, $p > .05$, η2 = .0049), indicating that both groups were in the same ecological achievement status before the intervention, suggesting any difference after the intervention can be attributed to the intervention.

Table 2

Independent Samples t-test analysis to compare the experimental and control groups on pretest

Test	Group	N	Mean	SD	SDE	Df	t	P	η^2
Pre-test	Experimental	43	30.47	12.353	1.885	87	-.216	.829	.0049
	Control	46	31.04	12.822	1.890				

Note. Eta squared = $t^2 / t^2 + (N1 + N2 - 2)$; $-.216^2 / -.216^2 + (43 + 46-2) = 0.0014$

As shown in table 3 an independent samples t-test was used to compare the achievement of two groups after the intervention. The Levene's variance equality test was insignificant (p >.05), indicating that the two groups had statistically equal variance. A significant difference was found in mean post-test scores between the two groups (t (87) = 3.77, p < .05), indicating that the experimental group taught by integrating IK had higher achievement scores than the control group.

Table 3

Independent samples t-test analysis to compare the experimental and control groups on the post-test

Test	Group	N	Mean	SD	SDE	Df	t	P
Post-test	Experimental	43	50.33	18.273	2.787	87	3.770	.000 .
	Control	46	36.78	15.586	2.298			

Effects of Integrating IK on the Achievement Scores of Male and Female Students

Table 4 shows the male and female students' mean achievement scores in the experimental and control groups. In the experimental group, male students' mean achievement score was 21.71, whereas female students ' was 18.08. In the control group, the mean achievement scores of the male and female students were 5.34 and 6.18, respectively. As a result, male and female students' mean achievement improvements were greater in the experimental group than in the corresponding control group. This suggests that no relationship exists between gender and teaching strategies and students' ecological achievement. This indicates that IK-based instruction is not gender biased.

Table 4

Comparison of means and standard deviations of achievement scores between male and female students in experimental and control groups (n=89)

Group	Test	Gender							
		Male				Female			
		N	M	SD	Mean gain	N	M	SD	Mean gain
Experimental	Pretest	21	32.19	12.99	21.71	22	28.82	11.78	18.08
	Posttest		53.90	17.96			46.91	18.31	
Control	Pretest	24	33.33	13.27	5.34	22	28.55	12.11	6.18
	Posttest		38.67	15.22			34.73	16.06	

Two-way ANCOVA was used to investigate the impact of instructional strategy and gender on the mean achievement scores of students in ecology. Table 5 presents the analysis results indicating no significant difference in mean achievement scores between male and female students taught ecology and conservation using IK-based instruction. F (1, 88) = 0.103, p > 0.05 indicates that this instruction is not gender biased. Eta for sex was about .001, which is smaller than a typical effect. Sex and group (control and experimental) did not significantly interact with ecology achievement (F (1, 88) = 2.487, p > 0.05). The impact of teaching method on ecological achievement is not significantly different for boys and girls. Therefore, there is no discernible difference in the mean achievement scores for ecology and conservation between the students' gender and the teaching methods.

Table 5

Two-way ANOVA testing the effect of gender and teaching approach on ecology achievement

Source	Sum square	Df	Mean square	F	Sig	Eta Square
Corrected model	24747.493	4	6186.873	121.310	.000	.852
Intercept	454.481	1	454.481	8.911	.004	.096
Pretest achievement	19967.267	1	19967.267	391.510	.000	.823
Teaching method	4500.204	1	4500.204	88.238	.000	.512
Sex	5.231	1	5.231	.103	.750	.001
Group*Sex	126.827	1	126.827	2.487	.119	.029
Error	4284.058	84	51.001			
Total	196096.000	89				
Corrected total	29031.551	88				

The Perceptions of Students on IK-based Teaching Strategy

Following the intervention, Focus Group Discussions (FGDs) were conducted to obtain qualitative insights that complemented the quantitative findings. The objective was to explore students' perceptions of how the integration of Indigenous Knowledge (IK) influenced their learning and academic achievement in biology. A structured set of discussion prompts was developed to encourage reflective and detailed responses. The FGDs involved 12 high-achieving students from the experimental group, six males and six females. Participants were divided into two groups, each consisting of six students, and were coded as S1–S6 for anonymity. The data were organized under two major themes:

Theme 1

Participants expressed overwhelmingly positive views about the integration of Indigenous Knowledge into ecology instruction. Several students (S1 and S4) described it as one of the most effective teaching strategies they had experienced, noting that it simplified complex biological concepts and enhanced understanding. They explained that the approach provided concrete examples drawn from their local environment, making abstract ecological and biodiversity concepts more accessible and meaningful. This connection between local experiences and scientific content led to a more lasting and practical understanding of the subject matter.

Other participants (S2, S3, and S6) highlighted that the method made learning engaging and culturally relevant. They appreciated that the lessons incorporated examples consistent with their community's ecological beliefs and conservation practices. Before each lesson, students were encouraged to explore traditional practices at home and later share their findings in class, which the teacher complemented with scientific explanations. This exchange deepened comprehension and strengthened the bridge between cultural wisdom and formal scientific knowledge.

S6 stated that the approach "made theoretical aspects easy to understand," adding that the traditional lecture method often made biology appear abstract and difficult. Through the IK-based approach, she developed a stronger appreciation for biology, particularly when learning about traditional agricultural practices, such as the use of lupine to improve soil fertility. Similarly, S5 described the lessons as "amazing," noting that they promoted self-directed learning and curiosity. S4 remarked that the experience "cannot be forgotten," as it inspired discussions with family members about ancestral ecological practices, further reinforcing classroom learning through intergenerational knowledge sharing.

Theme 2

Students reported that the IK-based lessons fostered active participation and enthusiasm in class. Several participants (S1, S2, S4, and S6) stated that this approach was more interactive than traditional methods, as it encouraged question-asking, discussion, and sharing of local knowledge. Teachers supported the process by providing contextual examples and guiding inquiry-based activities. Students expressed that these lessons were enjoyable and motivating, creating an inclusive learning environment where every participant contributed.

According to S3, the incorporation of IK "captured students' attention" and maintained engagement throughout the lesson. Participants (S2, S3, and S5) agreed that the method was more appealing and less stressful than conventional teaching. They valued its ability to simplify complex topics and instil confidence in learners, enabling even less confident students to express ideas freely. Students also expressed a strong desire for teachers to apply this approach in other science topics and subjects, as it made learning both relevant and enjoyable.

Furthermore, S2 noted, "I was happy to see ecology presented in a way relevant to my environment," recommending that all teachers use IK-based strategies to connect abstract scientific ideas with familiar contexts. Likewise, S4 emphasized that the lessons were "meaningful," as they allowed students to remember, explain, and apply concepts effectively. The teaching process involved students investigating local practices, sharing their findings, and receiving clarification from the teacher—an approach that reinforced understanding through collaborative and experiential learning.

FGDs revealed that integrating Indigenous Knowledge into biology lessons fostered deeper conceptual understanding, sustained interest, and active student engagement. Participants viewed the approach as culturally relevant, intellectually stimulating, and pedagogically effective. The use of IK-based strategies not only improved comprehension of ecological concepts but also strengthened connections between scientific learning and local environmental realities. These findings underscore the pedagogical value of integrating Indigenous Knowledge into science education as a means of promoting meaningful, participatory, and contextually grounded learning experiences.

Discussion

Based on the overall performance evaluation of the students, the experimental group outperformed the control group on the ecological achievement test. The control group, which was taught similar subjects without incorporating IK, scored significantly lower than the experimental group, which learned about ecology through the lens of IK. Integrating IK into ecological instruction has improved students' understanding and achievement in biology. The likely explanation for this outcome may be connected to the fact that instruction based on IK helped learners integrates their cultural backgrounds and immediate environments with what they learned in the classroom.

The results of this study align with those of Ugwu and Diovu (2016), who stated that integrating IK and practices into chemistry instruction enhances students' understanding of the fundamental principles of the subject and, as a result, improves their academic performance. This finding is further supported by Nwankwo (2021), who discovered that ethno-science education effectively boosts students' achievement in basic science. Additionally, the study's findings reinforce the conclusions of Chongo and Baliga (2019), which indicated that students taught using ethno-physics-based instruction achieved significantly higher scores than those not instructed with this approach. A study conducted by Liyas (2019) examined the influence of IK on pupils' learning outcomes in Basic Science. The findings indicated that incorporating IK practices into biology education results in a more practical and objective approach, which enhances understanding of biology and its applications. This aligns with the findings of the current study. The similarities between this study and other research suggest that IK-based instruction promotes a better understanding of scientific content, thereby enhancing academic achievement. Drawing from Ausubel's theory of meaningful learning, the use of familiar IK concepts could have served as powerful cognitive anchors that facilitated the assimilation of new scientific information. When learners relate new content to their prior cultural and experiential knowledge, they are more likely to construct deeper understanding and retain the material longer. In this study, the incorporation of IK-based instruction may have allowed students to connect abstract scientific principles with real-life experiences and community practices, making learning more relevant and meaningful. Explicitly linking these findings to Ausubel's framework thus reinforces the theoretical grounding of the study and highlights the pedagogical strength of contextualized science instruction.

The present study also showed no statistically significant difference in ecology achievement between genders. Male and female students taught ecology using IK-based instruction did not show significant differences in their academic achievement. There is no notable difference in ecological achievement between male and female students when IK is integrated into ecology instruction. This could be since both genders engage with local customs and are thus familiar with the related processes and knowledge. The selected IK practices and examples reflected shared community experiences, both genders may have had comparable levels of prior exposure and understanding. Additionally, the interactive and participatory nature of IK-based instruction might have provided equal opportunities for engagement, collaboration, and discussion, thereby minimizing any pre-existing differences in interest, confidence, or background knowledge. This suggests that the pedagogy itself, emphasizing inclusivity and shared cultural relevance, could have contributed to the balanced academic performance observed between male and female students.

Furthermore, the results indicate that students' ecological achievement is not affected by the interaction of gender and the teaching approach used. This indicates that incorporating IK and practices into biology teaching is more effective than the traditional lecture approach for enhancing achievement in biology among male and female students, since gender does not interact with the teaching approach to influence students' performance.

This finding is consistent with Oluboyo (2021), who also reported no significant interaction between instructional methods and gender regarding academic performance. Additionally, it supports the work of Ugwu and Diovou (2016), who found no statistically significant difference in the achievements of male and female students. In contrast, this study opposes the results of Mukuka (2019) and Chongo and Baliga (2019), who identified a statistically significant difference in academic achievement between male and female students, concluding that male students performed better than their female counterparts. This study also contradicts the findings of Nbina & Wagbara (2012), who reported that girls performed better than boys using the indigenous knowledge teaching strategy. In conclusion, while the indigenous knowledge-based teaching approach improved students' academic achievement, it exhibited no gender bias, unlike conventional teaching methods.

The result of the qualitative study supports the quantitative findings, indicating improvements in students' academic performance. Focus group discussions revealed that students had a very positive perception of the IK-based teaching strategy. After being exposed to this method, students' perceptions improved significantly. Their interest in IK-based teaching increased because it simplifies complex topics, such as ecological interactions, and accommodates diverse learning styles. During the focus group discussions, all students expressed joy and excitement about their experience with the IK- based teaching approach, particularly in understanding challenging concepts in ecology.

The opinions expressed by the students align with the findings of Mawere (2015), who, through his study of African IK systems, demonstrated that learners can readily appreciate their language, cultural identity, and the wisdom their ancestors contributed to knowledge and technological advancement. Exposure to an IK learning approach has enabled the students to value their culture and recognise its relevance to science and technology for their development. Similarly, Abony (1999) stated that an ethno-science-based instructional package fosters greater interest in science than conventional teaching methods.

Conclusion and Limitations

Within the context of this quasi-experimental study, the findings strongly suggest that integrating locally relevant Indigenous Knowledge (IK) into Grade 8 biology instruction can be an effective pedagogical strategy for enhancing student achievement in ecology and biodiversity conservation. The results revealed that students taught through IK-based instruction significantly outperformed those in the control group, indicating that contextualized learning experiences grounded in students' cultural backgrounds can lead to deeper understanding and improved academic performance.

Furthermore, the study found no statistically significant difference in achievement between male and female students, suggesting that the IK-based approach benefits both genders equally. This outcome may be attributed to the inclusive and participatory nature of the instruction, which allowed all learners to connect meaningfully with the content regardless of gender.

Students' responses further reinforced these findings, as they expressed enthusiasm and positive attitudes toward the IK-based lessons. They reported that incorporating Indigenous Knowledge made learning more engaging, simplified complex and abstract ecological concepts, and strengthened their appreciation for biodiversity conservation.

Overall, the study underscores the potential of integrating Indigenous Knowledge into science education as a culturally responsive and effective approach to improving learning outcomes, fostering positive attitudes toward science, and promoting environmental awareness among students.

This study acknowledges certain limitations that may influence the interpretation of its findings. The small sample size limited to two classrooms within a single city constrains the generalizability of the results to wider populations or diverse educational settings. Such a restricted scope may not adequately represent variations in students' socio-cultural backgrounds, instructional environments, or regional educational practices. Consequently, the findings should be interpreted with caution when applied to broader contexts. To enhance the robustness and applicability of future research, it is recommended that subsequent studies employ larger, more diverse, and randomized samples, alongside rigorous experimental designs. Such methodological improvements would strengthen the empirical evidence supporting the integration of Indigenous Knowledge into biology education and its broader educational implications.

Implications

The findings of this study indicate that biology teachers should foster classroom environments that deliberately integrate Indigenous Knowledge (IK) into their instructional practices. Incorporating IK across various biology topics promotes active student engagement throughout the learning process, which in turn enhances academic achievement and deepens students' conceptual understanding.

Furthermore, curriculum developers are encouraged to design systematic frameworks that facilitate the integration of local IK within national science curricula. These frameworks should be informed by culturally responsive pedagogical principles and align with existing educational standards to ensure meaningful engagement with indigenous epistemologies.

Finally, pre-service and in-service teacher education programs should incorporate specialized modules on culturally relevant pedagogy. Such modules must equip educators with the theoretical knowledge and practical skills necessary to identify, validate, and respectfully incorporate local IK into classroom practice, thereby fostering culturally inclusive and effective science education.

Competing interests

We declare that there are no competing interests regarding the research and authorship.

Acknowledgements:

We sincerely thank the Federal Ministry of Education of Ethiopia for partially funding this study. We would also like to express our heartfelt gratitude to the grade 8 students and teachers of Bida and Bata Middle Schools who participated in this study.

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Journal of Turkish Science Education, 2025, *22*(4), 822-837.
DOI no: 10.36681/tused.2025.040

Journal of Turkish Science Education
http://www.tused.org
© ISSN: 1304-6020

An international perspective on STEM education: private school teachers' conceptualization – a descriptive survey study

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ABSTRACT
This study explores private school teachers' interpretations of STEM and their awareness of its distinctive features, considering regional differences. The research is descriptive, aiming to outline the general definition and characteristics of STEM education. Of 533 survey respondents, 249 teachers who were familiar with STEM and taught STEM-related subjects in different regions of the world were included. The data were collected through an online survey consisting of two sections: an open-ended question regarding the definition of STEM, and a question asking participants to select from a list of characteristics that are distinctive and non-distinctive of STEM. The results underscore the need for targeted STEM education programmes and teacher training that fit regional and local contexts while upholding global core values. The crucial point of this research is that the geographical variety and private-school teachers' differing perspectives shape conceptualisations of STEM education's nature and characteristics.

RESEARCH ARTICLE

ARTICLE INFORMATION
Received: 04.11.2024
Accepted: 02.09.2025
Available Online: 23.12.2025

KEYWORDS: STEM education, private school teachers, international comparison.

To cite this article: Elmas, R., Cengiz-Keles, N., Adiguzel-Ulutas, M., Akarsu, M., & Canbazoglu-Bilici, S. (2025). An international perspective on STEM education: private school teachers' conceptualization – a descriptive survey study. *Journal of Turkish Science Education*, *22*(4), 822-837. http://doi.org/10.36681/tused.2025.040

Introduction

STEM (Science, Technology, Engineering and Mathematics) education has become more prevalent in the last decade (Fuller et al., 2021; Holmlund et al., 2018; Li et al., 2020). However, there is a conspicuous deficiency of epistemological underpinnings for how educators perceive STEM education in academic endeavours that attempt to define the boundaries of STEM education. The literature needs to provide a consensus on the definition and practices of STEM education (Bybee, 2013; McLoughlin et al., 2020; Li et al., 2022; Ring et al., 2017; Roehrig et al., 2012). Martín-Páez et al. (2019) emphasise the importance of incorporating real-world contexts into STEM learning. Ritz and Fan (2015) state that educational systems still struggle to effectively implement STEM education to solve real-world problems. Ryu et al. (2019) draw attention to the lack of STEM education practices because teachers may not receive or be exposed to integrated STEM education in their previous educational experiences. In this context, investigating how teachers conceptualize STEM education is crucial for supporting more meaningful and integrated STEM practices. Stohlmann et al. (2012) stress that more research is needed on the knowledge, training and experience that teachers need to implement STEM education effectively.

It is significant to understand how teachers in private schools conceptualize and implement the STEM education approach within their unique dynamics. Even within academia, diverse definitions and explanations exist regarding its conceptualization and interpretation (Akarsu et al., 2020). However, there are few comprehensive studies on how educators from different parts of the world with various demographic characteristics conceptualize STEM education and which characteristics they associate with it. Moreover, although real-world challenges, 21st century skills, and STEM occupations' promotion are recognized as essential components of integrated STEM education, teachers' conceptualizations of these elements remain unclear (Dare et al., 2021). Breiner et al. (2012) highlight that the diversity of responses to the inquiry regarding the definition of STEM education is contingent upon the source or academic milieu to which the individual endeavouring to elucidate the matter refers. Hence, exploring how educators across diverse regions worldwide, characterized by a wide range of demographic features, can offer a comprehensive spectrum of perspectives on how STEM education is conceptualized under various circumstances.

The hallmark of integrated STEM education is a holistic approach that spans several dimensions, creating a vibrant and all-encompassing learning environment Its fundamental tenet is this approach's multidisciplinary character, which smoothly integrates STEM fields. It uses a problem-based learning paradigm, in which learning opportunities are based on actual issues that represent real-world issues and call for innovative and diverse solutions (Anazifa & Djukri, 2017). Additionally, there is a focus on situations with alternative solutions, which motivates learners to investigate other viewpoints and develop creative problem-solving techniques depending on the engineering design process in primary and secondary education (Adiguzel Ulutas et al., 2023).

Regarding integration, STEM education exhibits flexibility, with some research allowing for use within a single field, while others require involvement from at least two STEM disciplines (Dugger, 2010; Ozkan & Topsakal, 2020). Additionally, a process-oriented methodology that incorporates the engineering design process and supports iterative design is a defining characteristic of integrated STEM. This methodology helps learners develop in multiple ways, allowing them to learn through practical experience and facilitating a profound grasp of real-life challenges (Guzey et al., 2016; Hurley et al., 2024; Moore et al., 2014).

The approach is fundamentally skills-based and aims to equip learners with a wide range of abilities necessary for success in the 21st century that meet societal and global expectations (Nazifah & Wang, 2022). Soft skills, seen as an essential foundation of STEM education, are also related to 21st century skills, with a strong emphasis on teaching students to learn from their mistakes and to strengthen their ethical values. The active encouragement of group collaboration fosters collaborative learning opportunities that resemble natural workplace settings. Integrated STEM education, with its emphasis on issues with a variety of solutions, instils an innovative approach, critical thinking skills, and adaptability to the complexity of today's environment (Vasquez et al., 2013). Essentially, the goal is to create learning settings where learners may develop critical evaluation skills and apply evidence-based decision-making techniques (Prastika et al., 2022). One of the most salient characteristics of the STEM education approach is its alignment with the engineering design process, facilitating problem-solving through structured, sequential, and iterative stages (Massachusetts DOE, 2006). This approach allows learners to advance through the solution iteratively, enhancing their understanding of the process and concepts involved and fostering the development of their skills (Hynes et al., 2011; Moore et al., 2014).

Nevertheless, a few naive beliefs continue to exist. A common misunderstanding about STEM is that it can only be predominated by one subject field (Akarsu et al., 2020). However, STEM is interdisciplinary, so it can easily incorporate many disciplines to produce a more comprehensive learning environment. Therefore, this understanding contradicts the nature of STEM education (Erduran, 2020). The notion that laboratory activities predominate in STEM education is the foundation of yet another myth. Practical experiences are essential; at the same time, the STEM education approach emphasizes problem-solving, critical thinking, and real-world applications in a context (Elmas, 2020). It includes a wide range of activities, including laboratory work. Contrary to the myth that it takes a teacher-centred approach, STEM education is learner-centred and frequently involves student directed research, group projects, and teamwork. With the instructor guiding the learning process, this student-centred process encourages active participation and thorough thinking. (Sulaeman et al., 2022). It is a common misconception that STEM is a largely product-oriented field that only considers the final product. STEM education prioritizes process-oriented learning outcomes, encouraging experimentation, iterative design, and problem-based learning to increase understanding (Craig, 2022). The emergence of a tangible product can undoubtedly facilitate the learning process. However, fundamental gains can also be achieved by developing ideas, models and project files (Capobianco et al., 2018; National Research Council [NRC], 2012). In addition, successful STEM initiatives depend on careful planning and the efficient use of available resources, even when certain areas require additional investment. Some studies provide STEM integration with simple materials or recyclable items. According to Ozkan et al. (2024), learners ought to be given the chance to work through open-ended challenges on their own and to develop understanding via trial-and-error processes. Furthermore, including real-world situations with an emphasis on sustainability and economic value can improve the applicability and impact of STEM education.

Finally, it is a limited perspective to associate STEM only with robotics-related activities. Robotics is one aspect of STEM education that can be useful, but a well-rounded educational experience involves a variety of disciplines, technologies and approaches. According to Barrett et al. (2014), the research indicates that many STEM programs have concentrated on disciplines, resulting in a need for more development of best practices for interdisciplinary STEM education. An increasing body of research suggests that more connected and interdisciplinary approaches to learning and improving one's skills are needed in STEM education to deal with issues (Han et al., 2020). The interdisciplinary nature of STEM education aligns with the case of many technical fields collaborating to provide practical solutions to pressing global challenges (Hubbard, 2021).

The idea of integrated STEM education highlights the necessity for a thorough grasp of STEM disciplines while acknowledging the importance of technology as a body of knowledge, skills and practices (Kelley & Knowles, 2016). There are multiple ways to refer to STEM education, including STEM teachers, STEM schools, and STEM projects. Many individuals, institutions, and organizations successfully employ these approaches when the strategies are applied accordingly (Akarsu et al., 2020; Elmas & Adiguzel Ulutas, 2022; Moore et al., 2014; Ulger & Cepni, 2020). STEM education is conceptualized in various ways by teachers depending on the social and cultural context of their region, and different countries have a variety of educational policies for disseminating STEM education (Cogan & Schmidt, 2002; Fang et al., 2013; Hamad et al., 2022).

The following defines the STEM education approach that guided this research. (Akarsu et al., 2020) This definition was chosen because it not only introduces STEM education but also highlights its key characteristics. Addressing these features provides a more comprehensive understanding of the approach.

It is an educational approach that integrates science, technology, engineering, and mathematics disciplines for the solution of real-life problems, facilitates the understanding of real-life problems with engaging and motivating experiences, and is not only product-oriented but also process and skill-oriented.

This study aims to determine private school teachers' definitions of the STEM education approach and to examine their levels of knowledge and awareness regarding the features of a STEM education approach, considering regional variations. Although the definition and characteristics of STEM have been examined in previous studies, our research reveals private school teachers' definitions of STEM and their familiarity with its characteristics using a unique sample. In addition, our study is valuable in that it offers a comparative perspective on geographical diversity. This brings a different and new perspective to the STEM literature that has not been well represented before. The research questions are as follows:

1. What overarching themes emerge in how teachers from STEM-related disciplines in private schools globally conceptualize STEM education?
2. Which attributes of STEM education are predominantly favored by teachers from STEM-related disciplines in private schools on a global scale?

Methods

This descriptive study collected data via a questionnaire validated by experts. Based on the definitions of STEM education by Akarsu et al. (2020), the questionnaire included both relevant and irrelevant characteristics of STEM education. This study makes it feasible for participants to be widely accessible and engaged by utilising the online survey platform, promoting a thorough investigation of their viewpoints on STEM education.

Participants

The participants of the study were private school teachers with a probable international curriculum experience and teachers from different regional contexts. Zech (2014) noted that many schools offering project-based STEM education are charter or private. In addition, considering the possibility of innovative pedagogies and interdisciplinary projects being implemented more widely in private schools, it was thought that private school teachers would be suitable participants for the study in terms of providing richer data collection opportunities, but this is also a limitation to be the representativeness of their region. At the beginning, the survey included 533 teachers. Since the aim of the study was to examine teachers' conceptualizations of the STEM education approach, participants who answered “No” to the question “Have you heard of STEM education before?” were excluded from the sample. The final sample consisted of 249 teachers actively working in STEM disciplines in private schools located in different parts of the world (Europe, Africa (Fr), Africa (En), the Middle East, and Asia). The distribution of participants across five distinct regions has been categorized based on their private school locations. The European region encompasses member states of the European Union alongside Eastern European countries. The African Francophone region spans countries within the African continent and is characterized by the adoption of the French educational system and the provision of education predominantly in French.

Conversely, the African Anglophone region comprises nations within Africa that adhere to the British educational system and prioritize English as the medium of instruction. The Asia-Pacific region is confined to Asian countries proximate to the Pacific basin. The Middle East region encompasses nations in Asia and close to the African basin. These geographical differences give a contextual framework for examining participants’ answers and shed light on the various educational environments and methodologies in various geopolitical locations. Table 1 presents the demographic characteristics of the sample.

Table 1

Demographic characteristics of the participants

Variables		Teachers	
		N	%
Heard about STEM education before participating in this study	Yes	249	46.7
	No	284	53.3
Gender	Female	140	56.2
	Male	109	43.8
Region	Europe	32	12.9
	African Francophone	27	10.8
	African Anglophone	50	20.1
	Middle East	51	20.5
	Asia-Pacific	89	35.7
Total teaching experience	1-5 years	78	31.3
	6-10 years	79	31.7
	11-15 years	35	14.1
	16-20 years	25	10.0
	21 and above years	32	12.9

Table 1 indicates that out of the 533 teachers, 46.7% responded "yes" to having heard of STEM education, while 53.3% responded "no." This highlights that more than half of the participants were unfamiliar with the concept of STEM education. Participants with no prior STEM exposure were purposefully excluded from the study, as the research aimed to clarify teachers' conceptualizations of STEM education. In addition to this, the majority of the participants are female, making up 56.2% of the sample, while males represent 43.8%. This indicates a balanced gender distribution, with a slight majority of female teachers.

Asia-Pacific accounted for 35.7% of the 249 participants, demonstrating the region's significant involvement in STEM education. The Middle East demonstrated participation in STEM education, with 20.5% of the participants, closely followed by the African Anglophone region (20.1%). On the other hand, Europe made up 12.9% of the sample, and the African Francophone region made up the lowest percentage (10.8%). This analysis highlights how different regions expose disparities in educational priorities and environmental factors.

The largest group of teachers (31.7%) have 6–10 years of experience, indicating that many are actively honing their teaching techniques. Those with 1–5 years of experience come in second at 31.3%, which includes a sizable portion of more recent teachers who could contribute new viewpoints to STEM teaching. On the other hand, 10.0% of teachers have 16–20 years of experience, while 14.1% have 11–15 years. Lastly, 12.9% of participants have 21 years or more of experience.

Data Collection Tool

An online survey form was used as a data collection tool in the study. The survey consists of two sections. In the first section, participants were asked to express their views on the definition of the STEM education approach through an open-ended question. In the second section, teachers were asked to select items from a list of relevant and irrelevant characteristics of STEM education. For example, “It is a teacher-centred approach” was given as an irrelevant characteristic, while “Based on real-life problems” was given as a relevant characteristic. The survey items were developed based on a literature review, particularly the definitions and characteristics of the STEM education approach presented by Akarsu et al. (2020). The list of relevant and irrelevant characteristics was reviewed by three academics with expertise in STEM education, and the items were revised in line with their feedback. A pilot application was conducted with a small group of teachers for pre-testing, and the comprehensibility and suitability of the items for the measurement purpose were evaluated. As a result of the evaluation, the wording was revised to make the items clear and understandable.

Data Analysis

Pre-existing theories, frameworks or theoretical knowledge are typically the basis for deductive data analysis research (Kyngäs & Kaakinen, 2020). In conceptualizing the definition of STEM education, a word cloud was created by determining the frequency of responses given by the teachers. The word cloud was created using the deductive analysis approach, which focused on the concepts used to define STEM on a regional basis by examining the definition of STEM in the study by Akarsu et al. (2020) and evaluating it.

Apart from the characteristics of STEM education established by Akarsu et al. (2020), the research also includes current misconceptions. As a result, participants had to critically evaluate those characteristics that either matched or deviated from the core ideas of STEM and identify the characteristics of STEM education. Concerning STEM education, this multifaceted approach aimed to elicit a thorough understanding of participants' cognitive structures, thereby explaining regional variations in the process.

Two researchers independently coded participants' responses, identifying common themes through open coding. The researchers created a high-level category for words with similar meanings. After determining the categories, the researchers re-read the participants' responses and coded them separately. The researchers conducted a separate coding procedure, carefully classifying transcripts separately and cross-referencing the results to determine inter-coder reliability. When discrepancies emerged, experts engaged in cooperative discussions to settle disagreements and reached a consensus regarding classification and coding. The study's ethical requirements were emphasized by providing participants with adequate information about the confidentiality safeguards protecting their data. Participants gave their express assent in advance by filling out a consent form, confirming that they were aware of the purpose and methods of the research and that their participation was voluntary. All participant identities were anonymized to respect their right to privacy and confidentiality.

Results

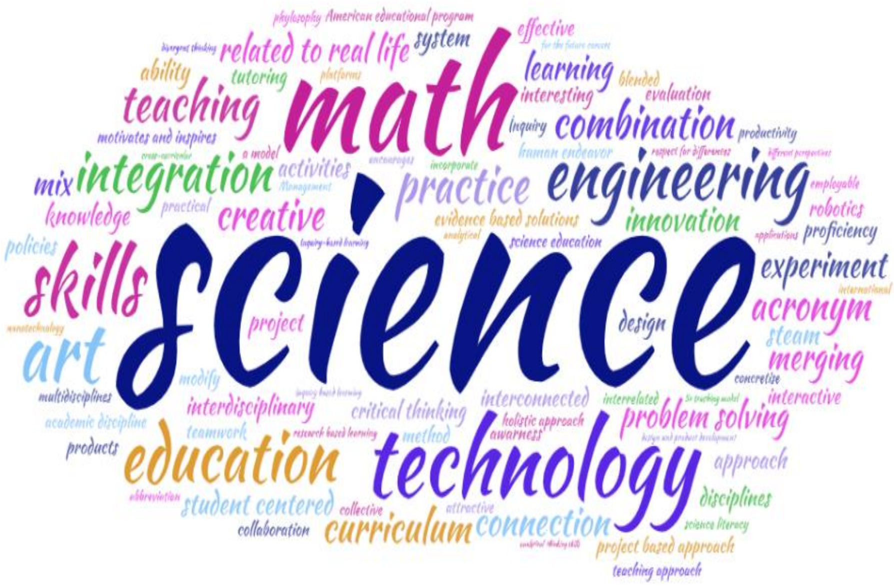
Teachers' opinions are described in the results section, with an emphasis on regional differences and characteristics of the STEM education approach. Key attributes of STEM, according to teachers, are its multidisciplinary nature, its relevance to real-life problems, and the cultivation of 21st-century skills. A general perception that STEM education emphasizes collaborative and process-oriented learning was reinforced by the analysis, which also identified which qualities were deemed unnecessary. Responses varied by region, highlighting the various cultural and educational circumstances that shape teachers' conceptualizations. This highlights the need for methods that account for local differences and needs to enhance the successful integration of STEM education globally.

Results on Teachers' Conceptualizations of the STEM Education Approach

The first step in the research was to generate a word cloud using the data from examining the teachers' responses to the initial research question (Figure 1). Teachers used 91 different words to describe the STEM education approach.

Figure 1

Word cloud for teachers' definition of STEM education



As expected, the words in the STEM acronym, "science (f=157), technology (f=149), mathematics (f=130), engineering (f=120)," were the most mentioned in all regions. The most often used words across all regions are education (f=50), integration (f=31), relevant to real life (f=21), combination (f=20), problem solving (f=16), teaching (f=16), and practice (f=16). Some words were emphasized more frequently. The distribution of these words by region is as follows: "combination" and "approach" in Europe, "integration" and "problem-solving" in the Middle East, "integration" and "teaching" in Asia, "American Educational Program" and "interdisciplinary" in African Francophone, "experiment," "relevant to real life," "skills" and "integration" in African Anglophone.

Results on Teachers' Preferences for Relevant and Irrelevant Characteristics of STEM Education

In the second step of the research, the data obtained from examining the teachers' answers to the second research question were analyzed (Table 2).

The characteristics of STEM education, presented to participants in random order, were classified into two categories: Relevant (R) and Irrelevant (IR). Attributes categorized as R are marked with the initial "R," while those categorized as IR are marked accordingly.

To enhance interpretability, a color-coding scheme was applied. Features identified as R are displayed in pink, while those identified as IR are displayed in blue. The shade intensity corresponds to the frequency with which an attribute was selected by participants. Specifically:

•5–15% = very light tone
•16–30% = light tone
•31–45% = medium tone

•46–60% = dark tone
•61% and above = darkest tone

In instances where no distribution is observed, white coloration is utilized. This gradation enables a visual comparison of the prevalence of attributes across categories, with darker tones indicating higher frequency and lighter tones indicating lower frequency.

Table 2

Teachers' opinions on the relevant and irrelevant characteristics of STEM education

		1	2	3	4	5
		Europe	African Franco phone	African Anglo phone	Middle East	Asia Pacific
R 1.	It is an interdisciplinary approach.					
R 2.	Based on real-life problems.					
R 3.	It is sufficient to integrate at least two STEM disciplines					
R 4.	It supports the development of 21st century skills.					
R 5.	It is a student-centred approach.					
R 6.	It is a process-oriented approach.					
R 7.	It is a skill-oriented approach.					
R 8.	It facilitates the understanding of real-life problems.					
R 9.	It requires using the engineering design process.					
R 10.	It enables students to learn from their mistakes.					
R 11.	Supports group work.					
R 12.	It requires evidence-based decision-making.					

R 13.	The learning process should be planned step by step.					
R 14.	It allows for iterative design processes.					
R 15.	It focuses on problems that have more than one solution.					
IR 1.	It can be applied with a single discipline.					
IR 2.	It consists of laboratory activity only.					
IR 3.	It is a teacher-centred approach.					
IR 4.	It is a product-oriented approach.					
IR 5.	Supports individual work only.					
IR 6.	It is a costly approach.					
IR 7.	These are activities based on robotics only.					
	Percent frequency of reported Rs	5- 15%	16- 30%	31- 45%	46- 60%	>61%
	Percent frequency of reported IRs	5- 15%	16- 30%	31- 45%	46- 60%	>61%

There are five regions included in the research: Europe, African Anglophone, African Francophone, Middle East, and Asia-Pacific. The features most identified as relevant (R) were:

- R2: Based on real-life problems
- R4: Supports the development of 21st-century skills

Teachers from every region highlighted these qualities, demonstrating a general understanding of the value of contextual and skills-based learning in STEM education. They emphasized the importance of STEM education in developing the critical thinking skills required for today's society and being based on real-life problems.

Conversely, the characteristics most frequently deemed irrelevant (IR) included:

- IR4: Product-oriented approach
- IR5: Supports individual work only

These qualities were uniformly minimized in every location, indicating a widespread agreement that isolated individual projects or product outcomes should not be the main focus of STEM education. Collaborative, process-oriented, and interdisciplinary approaches are clearly preferred instead.

In terms of the selection of irrelevant (IR) features, Although the regions had similar or different preferences for some items, it was observed that teachers' preferences from African Anglophone and Europe had similar distribution rates. The lowest selection of IR features was seen in the Asia-Pacific region. The IR selections by African Francophone teachers were also relatively low. In contrast, Middle Eastern teachers selected IR features at higher distribution rates than other regions.

Interestingly, the distribution rates for selecting relevant (R) features showed that European and African Anglophone countries had similar percentages. Following closely were the African Francophone countries, which had slightly lower but comparable rates. The Asia-Pacific region trailed with marginally lower rates than the African Francophone region. Despite selecting a high proportion of IR features, Middle Eastern teachers also chose R features at higher rates than other regions. This suggests that while certain aspects of STEM education are well understood in the Middle East, the high selection of IR features indicates some conceptual misunderstandings.

In sum, this study reveals both global convergence and regional diversity in the perception and implementation of STEM education. While there is considerable agreement on the essential and important elements as well as irrelevant features of STEM education, certain regional differences suggest that they may be culturally, politically, or economically based.

For example, teachers from the African Anglophone regions of Europe and Africa exhibited similar distribution rates in selecting both relevant (R) and irrelevant (IR) features. In contrast, the Asia-Pacific region showed the lowest selection of IR traits, followed by the African Francophone region with slightly higher rates. Interestingly, Middle Eastern teachers also presented a strong understanding of R attributes, although they selected IR attributes at higher rates.

These results highlight the necessity of targeted STEM education programs appropriate for regional settings. It is imperative to create and carry out educational initiatives that respect and include local educational priorities and cultural diversity, as well as follow international best practices. With this strategy, STEM education will be successful, relevant, and able to accommodate the various needs of students from various geographic areas.

Discussion

This study argues that it is essential to correctly understand the concept of STEM education when implementing the STEM education approach. Unsurprisingly, in conceptualizing the STEM education approach, the first thought turns to the words represented by the acronym STEM. This is primarily because the acronym itself is derived from the initial letters of the related disciplines, thereby creating a memorable association. STEM, which stands for "science, technology, engineering, and mathematics," was the most mentioned by teachers in all regions. Similarly, Bartels, Rupe and Lederman (2019) noted that STEM stands for science, technology, engineering, and mathematics as determined by all participating teachers. Furthermore, the most often used words across all regions are education, integration, relevant to real life, combination, teaching, problem-solving, practice and skills. This finding is supported by Breiner, Harkness, Johnson and Koehler (2012), who noted that teachers' conceptualisation of STEM education differs in understanding. The findings of Haddad et al. (2022) highlights the idea that educators should be prepared to think of STEM education as a complex and practical strategy that develops 21st century skills rather than just an acronym.

Radloff and Guzey (2016) identified varying perspectives on STEM education among pre-service teachers. In their study, participants conceptualized STEM education through lenses such as pedagogy, discipline, exclusion, and integration. The study also highlighted regional differences in the frequency of STEM-related terminology used by pre-service teachers. Despite numerous efforts to enhance STEM education within educational systems (Akon-Yamga et al., 2024), teachers' conceptualizations of STEM often diverge, influenced by their instructional methods and interpretations. These differences may result in misunderstandings or misapplications of STEM's theoretical principles in practice. Notably, teachers consistently stress the interdisciplinary nature of STEM education as central to both teaching and learning. The results of this study are congruent with the predefined characteristics of the STEM education approach (Akarsu et al., 2020). Teachers in many regions focus on providing experiences that allow students to apply STEM concepts in real-world contexts (Elmas, 2020). Depending on their instructional approaches and level of knowledge, private school science instructors worldwide have different conceptualizations of STEM education (Thibaut et al., 2017).

Ring, Dare, Crotty and Roehrig (2017) found that teachers' STEM integration models were related to real-world problem-solving as context, STEM as separate disciplines, and STEM as an acronym. According to Zhan, Shen, Xu, Niu, and You (2022), STEM education is influenced by different nations' social, cultural and economic issues. Although Western countries emphasized 'educational equity' and 'disciplinary integration,' Eastern countries emphasized 'humanistic leadership' and 'cultural integration' in STEM education. To successfully incorporate STEM education in the classroom, instructors must have a solid understanding of STEM disciplines and their approaches to integration (Fathy, & Malkawi, 2022).

The study further revealed that while teachers from different regions commonly describe STEM education as being "based on real-life problems" and emphasizing "the development of 21st-century skills," these are seen as relevant features. However, there is a widespread misconception that STEM education is predominantly a "product-oriented approach" and "supports individual work only," considered the most prominent irrelevant features. STEM education may be perceived by teachers as a product-oriented approach, as it is often associated with project competitions, robotics tournaments, or engineering prototypes.

Similarly, the lack of emphasis on teamwork and collaboration in the context of STEM education may have created the perception among teachers that they are supporting students' individual success ultimately, students get a score or grade on their personal report cards. In this context, pre-service training can be provided to teachers and prospective teachers to support the effective implementation of STEM education in classrooms. In their study, Khuyen et al. (2024) provided STEM training to pre-service teachers and found that, as a result, the lesson plans developed by the pre-service teachers shifted from a product-oriented to a process-oriented approach. Although the multidimensional structure of STEM education makes it difficult to define for practice (Dare et al., 2022), there are some essential characteristics on which STEM education is curated. The characteristics of the STEM education approach include being based on real-life problems, supporting skill development, being process-oriented rather than product-oriented, and supporting group work and peer solidarity (Elmas & Adiguzel Ulutas, 2022). Roehrig, Dare, Ellis, and Ring-Whalen (2021) stated that one of the seven features of integrated STEM education is the development of 21st century skills. Besides, numerous studies demonstrate that the STEM education approach fosters the development of skills such as problem-solving, effective communication, collaboration, leadership, creativity, and analytical and critical thinking, which are essential components of 21st century skills (Elmas & Gül, 2020; Stehle & Peters-Burton, 2019; Uttal & Cohen, 2012). In this context, teachers appear to establish appropriate associations with the key characteristics of the STEM education approach. Their views on integrated STEM teaching are positively linked to both their professional development and the personal value they attribute to science (Thibaut et al., 2017). Dare, Keratithamkul, Hiwatig and Li (2021) further noted that all participating teachers viewed STEM education through an integrated lens, recognizing its potential to develop 21st century skills and motivate students by engaging them with real-world challenges.

Conclusion

The findings of this research offer insightful data about teachers' understanding and attributes surrounding STEM education, which can help schools implement an integrated STEM education approach (Chaya, 2023; Nayem & Hossain, 2023; Permanasari et al., 2021; Said et al., 2023). These divergent interpretations of the STEM education approach highlight the need for further research to raise awareness and promote the widespread adoption of its core and well-established characteristics.

Moreover, given the widespread misconceptions about the characteristics of STEM, teacher training programs should place greater emphasis on process-oriented, collaborative, and interdisciplinary learning approaches. Professional development programs should ensure that teacher candidates gain competence in planning, implementing, and evaluating STEM applications. Achieving a consensus on a unified understanding of STEM education and advancing based on these shared principles will ensure effective skill acquisition among students.

Further research in STEM education could explore several critical areas to enhance both the understanding and practical application of the STEM education approach. One potential focus is conducting longitudinal studies that examine teachers' professional development and classroom practices over extended periods of time. Such research would provide valuable insights into how educators conceptualize and implement STEM education, allowing for a deeper understanding of how these practices evolve. Additionally, exploring the specific challenges and opportunities teachers face in different educational settings is crucial. While the current study involved participants from multiple nations, future research could benefit from comparative studies investigating differences between various educational contexts, such as urban versus rural schools or public versus private institutions. These comparisons would yield a more nuanced and comprehensive perspective on how STEM education is adopted and applied in diverse environments. Furthermore, examining the influence of teachers' backgrounds, resources, and student demographics on STEM education outcomes could reveal important variables that shape instructional strategies and inform effective teaching practices. By expanding research in these areas, scholars and policymakers can work towards more effective and equitable STEM education practices, ensuring that students from all regions and institutions gain access to the skills and knowledge necessary for success in the 21st century.

In addition, it would be beneficial to explore how technological advancements, such as artificial intelligence and machine learning, can further support STEM education. Integrating emerging technologies into the curriculum not only reflects the interdisciplinary nature of STEM but also equips students with the tools to address complex real-life problems. Similarly, investigating the role of collaboration between schools, industries, and communities in fostering innovation in STEM education would provide insights into how external partnerships can enhance the learning experience. Ultimately, striving for a more unified and comprehensive approach to STEM education, supported by rigorous research and practical applications, will be vital in advancing both teacher professional development and student academic success in the evolving educational landscape.

Limitations

The coding process was conducted independently by two researchers, followed by discussions to reach consensus. However, no quantitative measure of inter-rater reliability was calculated, which constitutes a limitation of this study. Only teachers with experience in STEM education were included in the sample for this study. This situation may introduce potential selection bias, as the findings do not represent teachers who are unfamiliar with STEM.

Declaration of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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