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Enhancing Critical Thinking in Science Education Through STEAM Integration: A Framework for Innovative Pedagogy

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The characteristics of environmental change material are dynamic, so instruction is required to produce innovative solutions through Critical Thinking Skills (CTS) as a key to responding to the complexity of the problem. However, its development in science education is still limited, due to the lack of learning designed to train CTS through scientific processes in exploring phenomena. This limitation impacts the low CTS of students in solving problems systematically and complexly in real life. STEAM (Science, Technology, Engineering, Arts, and Mathematics) is an innovative pedagogical framework to address this gap. The study aimed to determine the effectiveness of STEAM implementation in improving student CTS in science learning. This study used a quasi-experimental method with a non-equivalent control group pretest-posttest design because of the principle of randomization in educational research. 126 students were selected as a sample in a cluster relevant to the research design, which was non-random, so the results reflect contextual realism. The data collection instruments used were test and non-test instruments. Data analysis techniques used descriptive and inferential analysis through ANOVA and n-gain. The results showed a significant difference in CTS between students who studied STEAM and those who did not ($0.001 < 0.050$), with a moderate category ($0.3 \leq g \leq 0.7$). The implication is that STEAM creates a cognitive dissonance that encourages students' CTS habits by questioning assumptions, connecting concepts, and evaluating solutions from multiple perspectives. Supporting data for improving CTS through STEAM is proven by producing products with an average value of 89.33, and the collaboration has an average value of 96.10.

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Introduction

The natural world is undergoing rapid and dynamic changes that reshape ecosystems, economies, and societies on an unprecedented scale. Various natural phenomena are associated with environmental crises, such as climate change, water pollution, and loss of resources. Biodiversity, global warming, illegal logging, limited availability of clean water, and the impact of human activities on the exploitation of natural resources that cause environmental damage (Ahmed, 2022; Erhabor & Don, 2016; Esson & Moss, 2016; Gubasheva, Temirova, & Madaev, 2023; Osmaev, 2023; Sari & Aprilliandari, 2021; Setiawan, 2022). The shortage of clean water and safe drinking water targets is also felt in Indonesia, which has not yet reached the target of around 15% from 2022 to 2024 (Ministry of Health RI, 2023). Another problem occurs because of tin exploitation in Bangka Belitung, Indonesia. Bangka Belitung is one of Indonesia's provinces known for its tin mining. However, over-exploitation resulted in environmental damage by producing 12,607 ex-mining pits covering a total area of 15,579,747 hectares. This exploitation resulted in an ecological disaster with the destruction of coral reefs from 82,259.84 hectares to 5,720.31 hectares, mangrove damage from 273,692.81 hectares to 33,224.83 hectares, resulting in a loss of approximately 240,467.98 hectares (KBO, 2023).

The environmental crisis problem is positioned as an object of study that needs to be identified, and solutions are sought in a complex and comprehensive manner CTS. CTS is the key to responding to the complexity of the problem. However, its development in science education is still limited. There is a lack of instructional designs to train CTS through the scientific process of exploring natural phenomena, causing the lack of stimulation of the scientific process in studying a natural phenomenon, causing students to have difficulty digesting the subject matter and determining the concepts, principles, theories, and laws used to solve problems systematically in life (Lasniroha Sagala & Simanjuntak, 2017). This limitation impacts the low CTS of students in solving problems systematically and complexly in real life, so students cannot contribute to their environment.

CTS is one of the essential competencies for improving human resource quality in the 21st century (Fernando & Drugova, 2023; Naufal et al., 2024) to face future global challenges. However, the percentage of recent college graduates who lack critical thinking skills and are poorly prepared to enter the labour market is a common point of contention for those who criticize the quality of higher education (OECD, 2019; Yusuf, Sutadjİ, & Sugandİ, 2023). Students' low CTS is attributed to a lack of exposure to educational instruction designed to enhance critical thinking skills (Eska, Nasution, Henie, Al, & Sapta, 2023; Nadiroh, Hasanah, & Zulfa, 2019). Students are used to conventional memorization of concepts (Fatimah, Yamtinah, & Shidiq, 2023).

The solution offered in this research is the existence of an innovative pedagogical framework, which serves as a relevant pedagogical paradigm in the era of globalization by optimizing the use of technology that requires creative innovators, critical thinkers, and problem solvers through interdisciplinary learning (Baidal-Bustamante, Mora, & Alvarez-Alvarado, 2023; Bray, Girvan, & Chorcora, 2023; Dotson et al., 2020; Lavi, Tal, & Dori, 2021; Richardo et al., 2023). One is through Science, Technology, Engineering, Art, and Mathematics (STEAM) education that can be implemented in learning. This learning practice involves interdisciplinary and collaborative learning that prioritizes students' hands-on learning experiences, stimulating them to apply knowledge and skills to solve problems in a real-world context. One is science learning, which places natural phenomena as objects that need to be studied through a scientific process that involves science process skills to identify and understand natural phenomena and solve problems (Gizaw & Sota, 2023; Khamhaengpol, Sriprom, & Chuamchaitrakool, 2021) through CTS.

The theoretical basis underlying the implementation of STEAM refers to the theory of constructivism and behaviourism, specifically to improve the cognitive, affective, and skill aspects to achieve learning objectives under the established curriculum (Adesina, 2022). STEAM learn innovation practices to address global challenges, such as improving the quality of human resources and solving complex environmental problems through the development of constructivist thinking (Aguayo, Videla, López-Cortés, Rossel, & Ibacache, 2023; S. Wahyuningsih, Nurjannah, N.E, Rasmani, U.E.E, Hafidah, R, Pudyaningtyas, A.R, Syamsudidin, 2020; Sidekerskienė & Damaševičius, 2023; Sigit, Ristanto, & Mufida, 2022). Constructivism can be considered a mindset that defines learning as forming an integrative and transdisciplinary mindset in constructing frameworks. Trans-disciplinary learning in STEAM involves combining theory and practice (Sidekerskienė & Damaševičius, 2023). The application of theory and practice is used to explore critical ways to generate new ideas in solving real-life context problems through various disciplines and methodologies, and it is viewed from multiple perspectives (Bedewy & Lavicza, 2023; Bertrand & Namukasa, 2023; Pasedan & Nadeak, 2021).

STEAM potential a positive and significant impact on critical and creative thinking skills (Wannapiroon & Pimdee, 2022) necessary to solve complex problems (OECD, 2019). Research shows that STEAM can improve critical thinking and problem-solving skills through learning experiences (Ates & Aktamis, 2024). STEAM learning is implemented at the university level to prepare students to work in this field. The high number of jobs offered in the STEAM field is an opportunity for graduates to compete and achieve economic stability (Ates & Aktamis, 2024). However, to implement STEAM, educators face challenges in instructional design using technology, especially science learning, which needs to pay attention to principles and practices related to ethical considerations so that a value-based learning approach is required (Aguayo et al., 2023; Sigit et al., 2022; Yılmaz, 2021).

Purpose and significance of the study

This study aims to determine the effectiveness of STEAM implementation in improving students' CTS in science learning at Universitas Muhammadiyah Bangka Belitung (Unmuh Babel). In line with the determined purpose, answers to the following questions were sought in this study:

(1) How effective is STEAM learning in improving students' CTS in science learning?
(2) How can STEAM improve students' CTS in science learning?

This research is based on the results of Ilma, Wilujeng, Widowati, Nurtanto, and Kholifah Year 2023, based on the distribution of STEM/STEAM education in Bangka Belitung. Thus, this research needs to be conducted to equalize educational trends in the region. The results of this study can be used as a basis and recommendation to improve the quality of science learning, especially in courses that have the same characteristics as the field of environmental conservation at Unmuh Babel.

Literature Review

STEAM

The development of science and technology in the 21st century encourages changes in various sectors of life by integrating digital technology to support the improvement of the quality of human resources, especially for future educators (Akbariah, Artika, Pada, Safrida, & Abdullah, 2023; Asrizal, Dhanil, & Usmeldi, 2023; Bertrand & Namukasa, 2023; Wijayanti, Wiyanto, Ridlo, & Parmin, 2022; Zayyinah, Erman, Supardi, Hariyono, & Prahani, 2022). The development of science and technology in the 21st century encourages changes in various sectors of life by integrating digital technology to support the improvement of the quality of human resources, especially for future educators (Sidekerskienė & Damaševičius, 2023). STEAM is a learning innovation that offers immersive learning experiences to encourage knowledge such as critical thinking, problem-solving, and teamwork to provide opportunities to face challenges for modern society such as economics, technology, education, and 21st-century work skills (Chan & Nagatomo, 2022; Hasim, Rosli, Halim, Capraro, & Capraro, 2022; Pasedan & Nadeak, 2021; Sidekerskienė & Damaševičius, 2023). STEAM learning positions students and alumni to be ready for the world of work because it develops skills according to their needs and provides innovations (Akbariah et al., 2023; Newell & Ulrich, 2022).

STEAM is a revolutionary form of STEM, the emergence of "A" or "art" in STEAM makes STEAM a complex discipline that includes building students' ability to think logically, objectively, analytically, and intuitively (Bedewy & Lavicza, 2023). STEAM can support constructivist learning in building their knowledge and understanding through active participation in learning activities (Sidekerskienė & Damaševičius, 2023). STEAM education enables trans-disciplinary learning in solving complex problems by combining aesthetic pedagogy with scientific fields (Bedewy & Lavicza, 2023). The pedagogical framework in STEAM implementation requires good TPACK skills of educators to integrate knowledge areas that include pedagogical knowledge, content knowledge, and technological knowledge, and their intersection results in pedagogical content knowledge, pedagogical technological knowledge, and content technological knowledge to build technology integration in STEAM practices. (Akçay & Avcı, 2022; Bedewy & Lavicza, 2023).

Critical Thinking Skills

Critical thinking skills are one of the targets of achieving 21st-century learning outcomes to face the challenges of global society era 4.0 and society 5.0 (Hidayah, Widiyatmoko, Nurin, & Laksono, 2022). Critical thinking skills as one of the soft skills that need to be developed in the era of globalization to face global challenges, especially to solve real problems studied. The stages of developing soft skills from critical thinking skills are very complex starting from understanding, sketching, deciding, prototyping, and validating (Arce, Suárez-García, López-Vázquez, & Fernández-Ibáñez, 2022). The development of these skills is in line with curriculum developments that demand developing character-building skills that can be transferred to real-life contexts through the fields of education and the world of work (Bertrand & Namukasa, 2020; Pentury, Bu'tu, & Malatuny, 2022; Schmid, Brianza, & Petko, 2020). Skills development is an important aspect of realizing sustainable growth in various sectors to produce fundamental transformative changes by improving the quality of learning (Dhurumraj, Ramaila, Raban, & Ashruf, 2020) through STEAM. Based on the results of the literature review, it is known that critical thinking skills, science literacy, and learning outcomes can be improved by applying STEM / STEAM, so furth21st-century research needs to be done on the potential of STEAM education to improve skills in 21st-century learning (Ilma, Wilujeng, Widowati, Nurtanto, & Kholifah, 2023).

Critical thinking skills are the ability to consider relevant or irrelevant information to be able to make decisions about what to do (Astriani, Martini, Rosdiana, Fauziah, & Purnomo, 2023). Abilities of critical thinking skills are classified under these categories: (1) elementary clarification consists of using a question, analyzing arguments, and asking and answering questions of clarification and or challenge; (2) basic support consists of judging the credibility of a source, observing and judging observation reports; (3) inference consist of deducting and judging deductions, inducting and judging inductions, making and judging value judgment; (4) advanced clarification consists of defining terms and judging definitions, identifying assumptions; (5) strategy and factors consist of deciding on an action and interacting with others (Ennis, 1985).

Method

Research design

This study uses a quasi-experimental method with a non-equivalent control group pretest-posttest design because it considers the relevance to the research and the context of randomization in educational research. However, the intervention's impact is still measured through a pretest-posttest to test its effectiveness as an instructional intervention (Creswell & Creswell, 2018a). The independent variable in this study used STEAM, and the dependent variable used CTS, which included basic clarification, essential support, inference, further clarification, strategy, and tactics. (Ennis, 1985). This research involved PGSD students in a science learning course in the 2023/2024 academic year. The materials used in this study were STEAM learning materials, STEAM-based learning media development, and STEAM-based science learning design for elementary science learning.

Research population and sample

The population of this study included all students of the primary teacher study program at the Faculty of Teacher Training and Education, Unmuh Babel. The sample used in this study consisted of 126 students, with 43 students in the first experimental group, 42 in the second experimental group 2, and 41 in the control group. The sampling technique used was cluster sampling, which is relevant to research designs with non-random allocation, so the results reflect contextual realism. (John W. Creswell, 2014).

Data collection tools

Experts in the field of science learning and evaluation verified 13 critical thinking test items that were utilized in the instrument. The validation process involved empirical tests with 28 primary school teacher-training students. Using SPSS version 22, the reliability test used Cronbach's alpha, and the validity test used Pearson's correlation. The results of the construction validity test based on expert judgment were used to improve the construction aspects of the test items to be tested empirically. They make a validity test decision: if $r_{count} > r_{table}$, the item is declared valid. Determination of the r_{table} with a significance level of 5%, df = 21. The results of the validity test using the Pearson correlation for all test items are displayed in Table 1.

Table 1. Validation test results using Pearson correlation

CTS Dimension	CTS Sub-Dimension	CTS Indicators	Item Number	Pearson Correlation (r_{count})	r_{table}	Decision
Elementary clarification	Focusing on a question	Stay focused on the problem and its context of environmental balance	1 2	0.882 0.565	0.433 0.433	Valid Valid
	Analyzing arguments	Identifies the reasons contained in the argument	3 4	0.605 0.595	0.433 0.433	Valid Valid
Basic support	Considering the credibility of a source	Consider the validity of evidence-seeking procedures	5	0.595	0.433	Valid
Inference	Making observation result	Assess the complexity of the observations that have been made	6	0.881	0.433	Valid
	Conclude by deduction	Using logical condition	7	0.890	0.433	Valid
		Use patterns in tables/graphs to infer	8	0.839	0.433	Valid
	Make a decision	Make a decision based on the result of the formulation or assessment	9	0.930	0.433	Valid
Advanced clarification	Identify terms	Knowing the content validity of a definition	10	0.911	0.433	Valid
	Identifying assumptions	Identify the assumptions that a given condition requires	11	0.618	0.433	Valid
Strategy and tactic	Deciding on an action	Formulate alternative solutions	12 13	0.684 0.604	0.433 0.433	Valid Valid

Table 1 indicates that the question items are valid; nonetheless, ten questions covering the following topics were used in the test: primary clarification, essential support, conclusion, additional clarification, strategy, and tactics (Ennis, 1985). The reliability test result using Cronbach's alpha was 0.933, which is good. Other instruments that support this research use observation sheets and assessment rubrics to assess the design or products developed from STEAM learning, using a rating scale. Supporting aspects to strengthen the research results were also reviewed from the perspective of teamwork through a questionnaire that provides an assessment between friends using a rating scale. Indicators used included willingness to carry out tasks together, tolerance between friends, sharing information between friends, and not dominating the group.

Test Structure

The test questions were in the form of ten essays. Two of the 13 items prepared were not used because they were already represented in the other items. The sample test was performed as follows:

Test No.	: 3
CTS Dimension	: Elementary clarification
CTS Sub-Dimension	: Analyzing arguments
CTS Indicators	: Identifies the reasons contained in the argument
Test Statement	: The Kurau River is one of the rivers in the Central Bangka Regency and has high levels of E.Coli. The cause of these high bacteria levels is dumping water and household waste into river. Some people 1 argue that a high level of bacteria in the river can cause respiratory distress due to the strong odor. Is there anything wrong with this opinion? Explain it!

Data analysis

Descriptive and inferential statistics were used to analyze the data, and then the data was tested with ANOVA and N-Gain Score. ANOVA is used as a data analysis technique in this study because the study involved three sample groups. In line with the theory expressed by Field that when comparing more than two groups simultaneously, the analysis can be done using ANOVA (Field, 2017). In addition, it is useful for controlling the error rate that increases when using repeated t-tests (Creswell & Creswell, 2018b). Meanwhile, N-gain is used to measure the effectiveness of the intervention by normalizing the increase in pretest-posttest scores (Hake, 1999). Before testing the hypothesis, a prerequisite assumption test was conducted to ensure that the data were analyzed using parametric statistics. The N-Gain Category was used for Interactive Engagement, categorizing the effectiveness of educational interventions. A high level of engagement is indicated by an N-gain (g) greater than 0.7, suggesting substantial improvement and a positive impact (Hake, 1999). Medium engagement is represented by an N-Gain between 0.3 and 0.7, indicating moderate improvement. An N-Gain less than or equal to 0.3 signifies low engagement, reflecting minimal improvement. This classification aids in evaluating and making decisions regarding the effectiveness of interactive engagement strategies in educational settings.

Experimental process

This study employed a non-equivalent control group design with a pre-test-post test using a quasi-experiment methodology. This study was conducted for approximately seven weeks during the odd semester of the 2023/2024 academic year. This learning implementation integrates the principles of STEAM learning with Problem-Based Learning (PBL) as the first experimental group (EG 1), STEAM learning with a scientific approach as the second experimental group (EG 2), and direct learning as the control group (CG). This didactic practice represents a pedagogical revolution in the digital transformation era through a framework for innovative pedagogy in science learning. STEAM learning material was created for two meetings by classifying the relevant scope, developing STEAM-based learning media for two sessions, and developing STEAM-based science learning design for elementary science learning for three meetings. Evaluation and reflection are carried out to evaluate innovative products that have been developed, and reflection is used to determine the strengths and weaknesses of the learning process, including communication, cooperation, and innovation products.

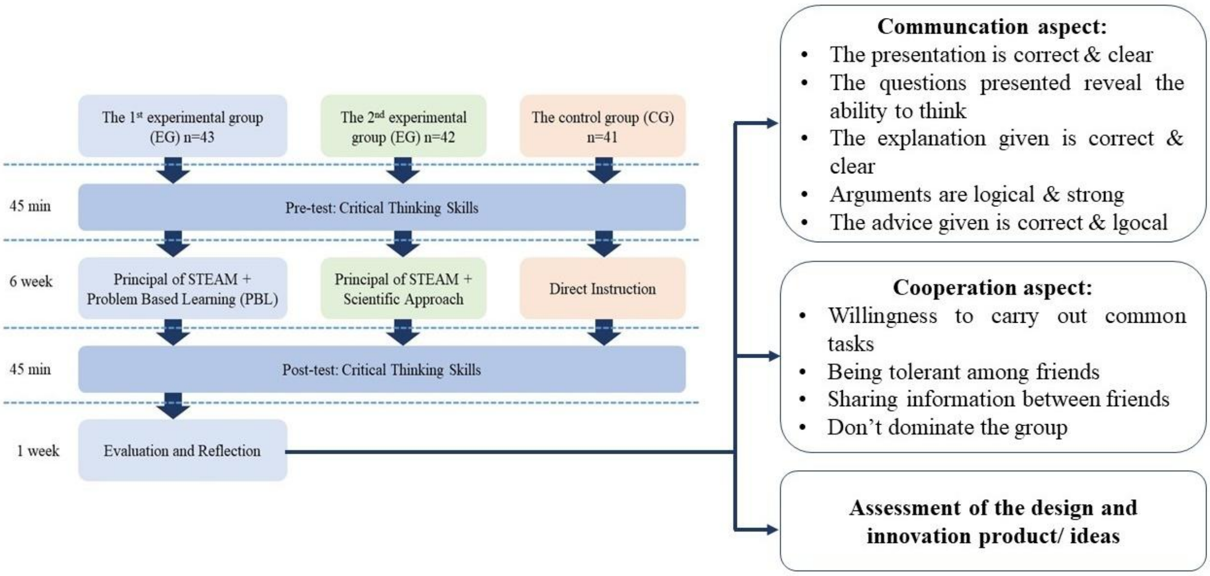


Figure 1. Procedure of Experiment

Teaching environment

STEAM education, as an interdisciplinary comprehensive education, has stages of educational development with different characteristics, starting from 1) STS stage: enlightenment, 2) STSE stage: exploration, 3) STEM stage: prosperity, and 4) STEAM stage: sublimation. STEAM characteristics reflect comprehensiveness, situationality, and practicality (Yu, 2021). STEAM learning reflects collaboration, cooperation, critical thinking/reasoning, reflection, and other characteristics related to working and thinking (Carter et al., 2021).

Every learning activity on the three materials in EG 1 that implement STEAM is integrated with the main characteristics of PBL, focusing on problem-based learning, integrating various scientific fields, and a centered learning approach; educators act as mentors or facilitators (Chávez, Gamiz-Sanchez, & Vargas, 2020; Smith et al., 2022). The presented are real-world problems that students must understand through their ability to associate new experiences with prior knowledge. PBL incorporates concepts learned into current environmental situations to train students to construct knowledge, conservation attitudes, and skills based on experiences gained in everyday life (Damopolii & Kurniadi, 2019; Doyan, Susilawati, Gunada & Hilfan, 2021; Regala, 2019). The stages of PBL include 1) directing students to the problem, 2) preparing students to learn, 3) assisting independent and group research, 4) developing and presenting artifacts and display objects, and 5) analyzing and evaluating the problem-solving process (R. L. Arends, 2012) through its CTS.

Each learning activity in the three materials in EG 2 implements STEAM integrated with the main characteristics of the specific approach, which focused on observing, questioning, gathering information, associating, and communicating. Observations are made of natural phenomena in the surrounding environment, but mistakes such as bias in observation and interpretation are often shared. So, then questions are carried out using several aspects, for example: a) Rational inference problem: is something true?; b) Criteria for growth: How can we determine which theory is better?; c) Pragmatic action: How can we put what we know into practice?; and d) Intellectual honesty: Why do we science the way we do? (Sagan, 1980).

Students then gather information to dig deeper into the phenomenon studied. Furthermore, connecting and communicating the results of logical analysis is a form of evaluation and reflection.

Learning in the control class adopted direct learning, in which the majority of learning was teacher-centered (Kusumawati et al., 2023). However, in this study, direct learning was supported by multimedia as a medium for science learning. Student involvement in developing thinking skills can be stimulated by direct instruction, for example, by explaining academic content, or by applying active learning methods, such as providing opportunities for students to explore, use, and manipulate content. The implementation of these options is also tailored to learning needs. If delivered directly, learning success depends on students' working memory (Dubinsky & Hamid, 2024). Pedagogy in direct learning can involve students in learning but requires the selection of appropriate methods and approaches to optimize and improve students' CTS in science learning (Jong et al., 2024).

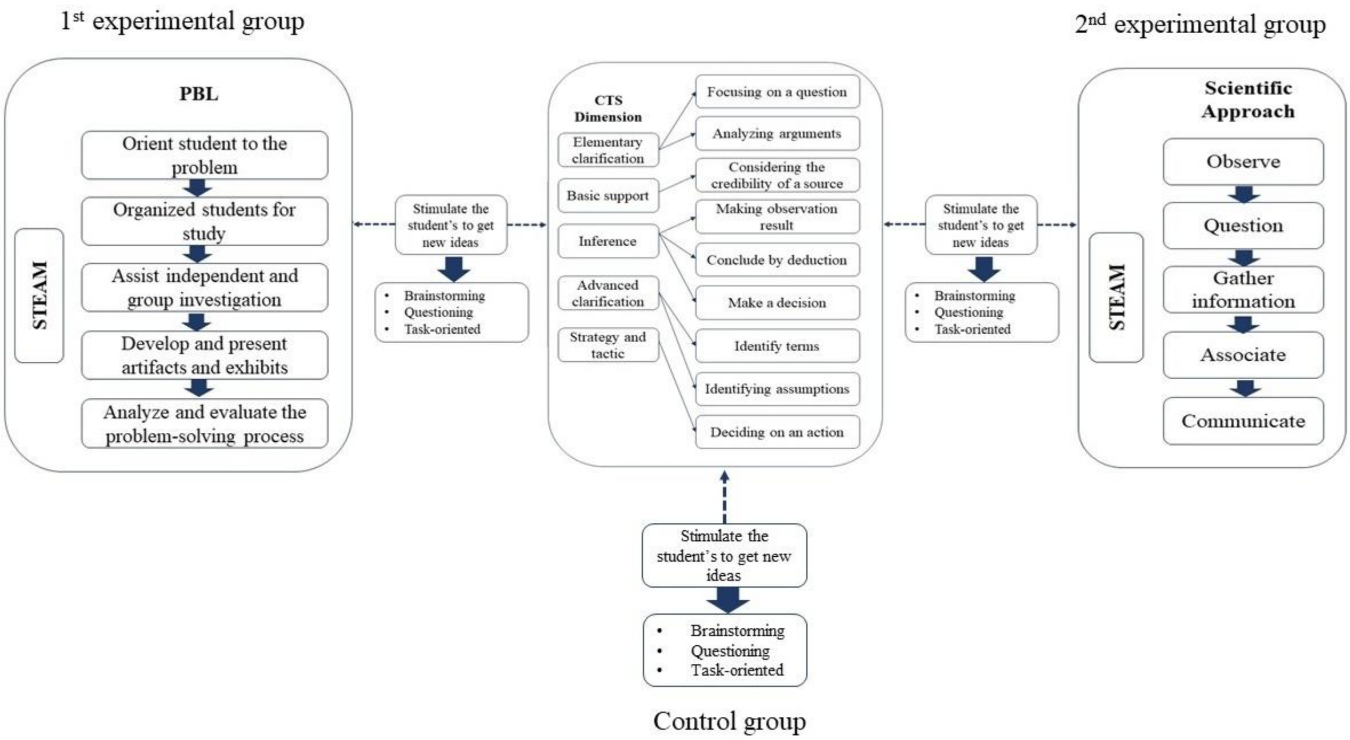


Figure 2. Teaching Environment

Result

The development of science and technology in the 21st century has encouraged changes in various sectors of life by integrating digital technology to improve the quality of human resources, especially for future educators. (Akbariah et al., 2023; Asrizal et al., 2023; Bertrand & Namukasa, 2023; Wijayanti et al., 2022; Zayyinah et al., 2022). Advances in technology and science in the 21st century have encouraged changes in various sectors of life by integrating digital technology to improve the quality of human resources, particularly for future educators (Sidekerskienė & Damaševičius, 2023).

STEAM is a learning innovation that offers immersive learning experiences, such as critical thinking, problem solving, and teamwork, to provide opportunities to face challenges in modern society, such as economics, technology, education, and 21st-century work skills (Chan & Nagatomo, 2022; Hasim et al., 2022; Pasedan & Nadeak, 2021; Sidekerskienė & Damaševičius, 2023). STEAM prepares students and alums for work by developing skills according to their needs and providing innovation (Akbariah et al., 2023; Newell & Ulrich, 2022). STEAM is a revolutionary form of STEM. The appearance of "A" or "art" in STEAM makes STEAM a complex discipline that includes developing students' ability to think logically, objectively, analytically, and intuitively (Bedewy & Lavicza, 2023). STEAM can support constructivist learning in building knowledge and understanding by actively engaging in educational activities (Sidekerskienė & Damaševičius, 2023). STEAM education enables transdisciplinary learning to solve complex problems by combining aesthetic pedagogy with scientific fields (Bedewy & Lavicza, 2023).

CTS is one of the targets of achieving 21st-century learning outcomes to face the challenges of Industrial Revolution 4.0 and Society 5.0 (Hidayah et al., 2022). Critical thinking skills are among the soft skills that need to be developed in the era of globalization to face global challenges, especially to solve real problems learned. The stages of developing soft skills of critical thinking are very complex, starting from understanding, sketching, deciding, prototyping, and validating (Arce et al., 2022). The development of these skills is in line with curriculum development which demands the development of character-building skills that can be transferred into real-life contexts through the fields of education and the world of work (Bertrand & Namukasa, 2023; Pentury, Bu'tu, & Malatuny, 2022; Schmid, Brianza, & Petko, 2020).

Skills development is critical to realizing sustainable growth in various sectors to bring about fundamental transformative change by improving the quality of learning (Dhurumraj et al., 2020) through STEAM. Based on the results of the literature review, it is known that critical thinking skills, science literacy, and learning outcomes can be improved by applying STEM/STEAM; therefore, further research is needed on the capacity of STEAM education to improve 21st-century learning abilities (Ilma et al., 2023).

Pre and Post Data (n participants =126 students)

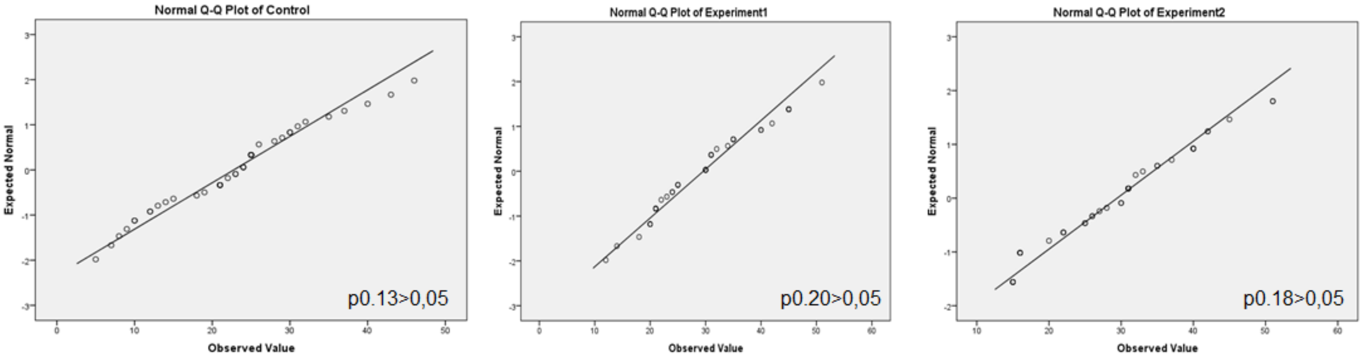
The results presented in Table 3 were obtained from a descriptive analysis involving 126 students: 43 students integrating STEAM learning principles with Problem-Based Learning (PBL) as the first experimental group (EG 1 = 43 students), STEAM learning with a scientific approach as the second experimental group (EG 2 = 42 students), and direct learning as the control group (CG = 41 students).

Table 2. The result of Descriptive Analysis

	1st Experiment		2nd Experiment		Control	
	Pre	Post	Pre	Post	Pre	Post
Min	34	75	33	70	34	54
Max	67	95	63	87	65	87
Mean	52.02	81.74	50.64	80.60	52.73	75.49
STD	6.24	7.06	7.36	6.58	7.75	5.62

Test the prerequisite assumptions of normality and homogeneity

The results of the Kolmogorov-Smirnov normality test showed that the data of the three groups were normally distributed, with a distribution pattern that can be seen in the Normal Probability (Q-Q) plot below.



(a) (b) (c)

Figure 3. Output Normalization Probability Plots of the (a) 1st Experiment-EG 1, (b) 2nd Experiment-EG 2, and (c) control-CG

Figure 3 shows that the data of the three classes are normally distributed because the points around the curve form a curve, the p-value> 0.05, EG 1=0.13, EG 2=0.20, and CG=0.18. A homogeneity test using Levene's statistics obtained sig. 0.63 > 0.05, therefore, it is assumed that the variances are equal.

Hypothesis testing with ANOVA and N-Gain

The results show a significant difference in CTS between students who learn with STEAM and those who do not (0.001 <0.050). It is known that there is a substantial difference in student CTS between learning using STEAM and not utilizing it, according to the results of the analysis test (Table 3).

Table 3. ANOVA Result

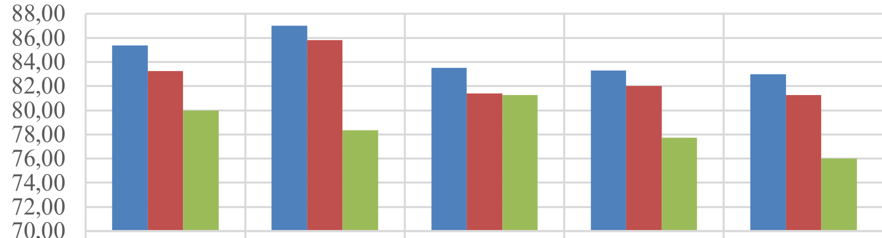
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1387.256	2	693.628	7.348	.001
Within Groups	11610.117	123	94.391		
Total	12997.373	125			

ANOVA testing was also reinforced by the results of the n-gain test, which is used to measure the effectiveness of CTS improvement after learning (Hake, 1999). Based on the results of the implementation of learning in three classes, namely EG 1, EG 2, and CG, the three classes are at the same level of medium, which can be seen in Table 4 in detail.

Table 4. N-Gain analysis test results

Class	N-Gain	Interactive Engagement	Decision
1st Experiment	0.615	$0.3 \leq g \leq 0.7$	Medium
2nd Experiment	0.597	$0.3 \leq g \leq 0.7$	Medium
Control	0.467	$0.3 \leq g \leq 0.7$	Medium

Descriptive analysis of the dimensions of CTS



	Elementary clarification	Basic support	Inference	Advande clarification	Strategi and tactic
1st Experiment	85,35	87,00	83,50	83,31	83,00
2nd Experiment	83,25	85,83	81,40	82,00	81,25
Control	80,00	78,35	81,25	77,75	76,00

Figure 4. Descriptive Analysis of CTS Dimensions

CTS is the ability to consider relevant or irrelevant information to decide what to do (Astriani et al., 2023; Yadi, Sofyan, & Surjono, 2023). The highest CTS was EG 1, whose learning principle uses STEAM with PBL. Although the results showed no significant difference between each measured CTS dimension.

Results of peer assessment of CTS in the discussion process

Figure 5 shows that the learning process involving collaboration and group work can stimulate students to develop their CTS through the learning process. Students identify and analyze natural phenomena in the surrounding environment and utilize STEAM learning to solve these problems. The correct and appropriate presentation aspect has a higher score for students from STEAM classes integrated with the scientific approach, because the scientific approach integrates students' ability to process information by observing, trying, processing, presenting, concluding, and creating (Daga, Wahyudin, & Susilana, 2022; Lieung, Rahayu, & Fredy, 2020; Tanti, Kurniawan, Syefrinando, Daryanto, & Fitriani, 2020), thus improving CTS.

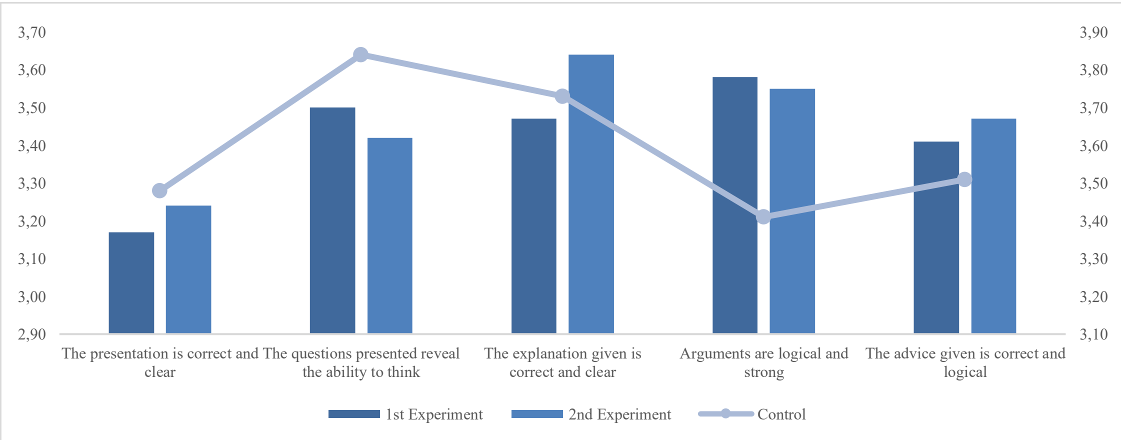


Figure 5. CTS Assessment Results in The Discussion Process Obtained from The Results of Peer Assessment

The highest scores obtained for the aspects of the questions presented revealed the ability to think. Arguments are logical and decisive in students who implement STEAM-integrated problem-based learning because this learning places environmental problem issues as objects of study studied form various points of view, the beauty produced, the technology involved, the tools needed to solve the problem, and mathematical calculations to obtain quantitative and qualitative data. The learning process is based on practice and scientific inquiry, supported by appropriate learning technology, both hard and soft.

The results of the assessment of cooperation in the group

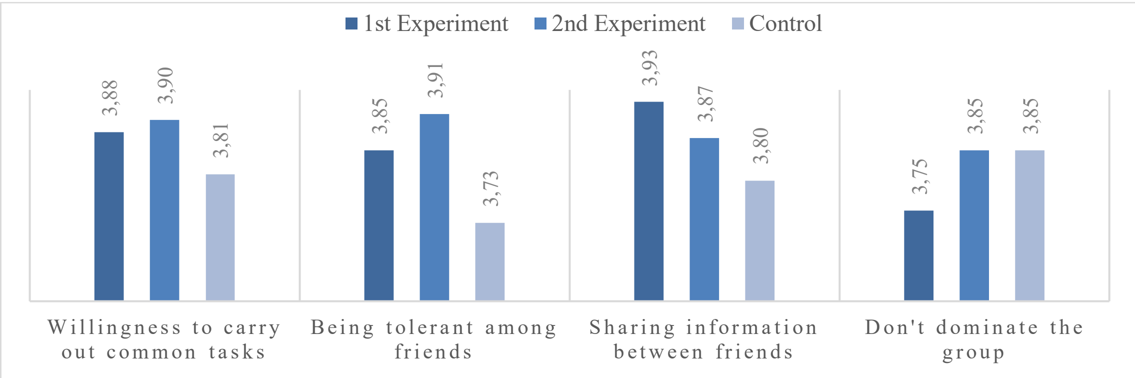


Figure 6. Descriptive Analysis of the Cooperation Aspect

Group learning is a teaching strategy used to stimulate students' CTS abilities. Students critically discuss with each other to solve problems by creating designs using STEAM. Based on Figure 6, it is known that the highest average is in sharing information, with a score of 3.87, and based on these results, it is known that no team members dominate each other in the discussion.

Assessment of the product/innovation idea

The results of the assessment of the design or product produced by STEAM learning are shown in Figure 7.

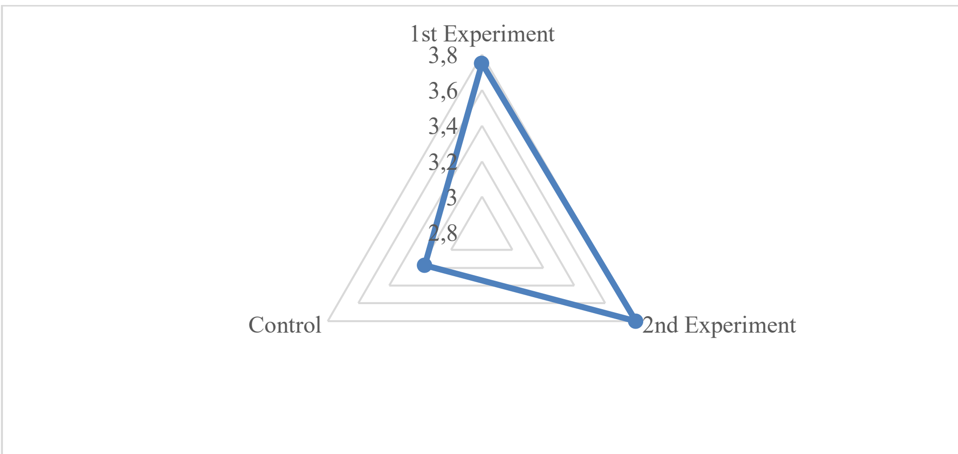


Figure 7. Assessment of the Product

Product assessment in the form of innovation work or ideas includes aspects of planning, processes in substance or technique, and characteristics of usability, as well as the final stage, which consists of an assessment of the form of innovation. The results of the product are shown in Figure 8-10.

Discussion

The results show a significant difference in CTS between students who learn with STEAM and those who do not (0.001 <0.050). It is known that there is a substantial difference in student CTS between learning using STEAM and not utilizing it, according to the results of the analysis test using ANOVA (Table 3-4). The significance value shows that there is a significant difference in increasing students' CTS between learning using STEAM and without. This result is supported by STEAM learning, which can enhance one's capacity for critical thought (Syukri, Ukhaira, Zainuddin, Herliana, & Arsad, 2022) and improve the quality of learning (Baidal-Bustamante et al., 2023). Other studies support the results of this study on the implementation of STEAM to create an engaging and interactive learning environment. Studying phenomena that exist in the surrounding environment so that it can ensure sustainable development in the region through creative thinking, problem solving, innovation (Nguyen, Tien, Nguyen, & Dang, 2024), CTS, and communication skills through activity in STEAM education (Zaqiah, Hasanah, & Heryati, 2024).

The results of the study showed a significant difference in CTS between students who studied STEAM and those who did not (0.001 <0.050), with a moderate category ($0.3 \leq g \leq 0.7$). The implication is that STEAM creates cognitive dissonance that encourages students' CTS habits by questioning assumptions, connecting concepts, and evaluating solutions from various perspectives. Evidenced by supporting data in producing products with an average value of 89.33, and the cooperation aspect has an average value of 96.10. Various efforts have been made to revolutionize pedagogy. Research results show that the distribution of articles examining STEM/STEAM from national and international journals shows that 63% of journals support the publication of STEM/STEAM fields of study (Ilma et al., 2023). Its recommendations offer practical guidance for teachers to improve their teaching and enhance students' life-world competencies, which contribute to the economic and social development of the region (Nguyen et al., 2024).

The highest percentage in the trend of STEM/STEAM research methods is a quantitative approach with an experimental method of 36%, whereas the lowest is in qualitative approaches, including comparative studies (1.6%). Various innovations in learning practices as a form of revolutionary pedagogy include the integration of STEAM learning with other learning strategies. The highest integration results are known to be that STEM/STEAM is mainly integrated with project-based learning, as much as 30.2%, from 2016 to 2021. The highest percentage of the distribution of variables that can be improved through STEM/STEAM learning are critical thinking skills and scientific literacy, with a rate of 18.4% (Ilma et al., 2023). This result shows that STEAM is still relevant for use in developing skills pedagogically, especially in overcoming the problem of the difficulty of developing CTS (Putri, Prasetyo, Purwastuti, Prodjosantoso, & Putranta, 2023). The study's findings support this assertion, because it is well known that students participating in group discussions have attempted to create their modes of thought. Figure 4 illustrates the steps involved in obtaining CTS in detail. These indicators include the presentation's accuracy and clarity, questions asked to demonstrate critical thinking, explanation provided, arguments' strength and logic, and advice offered.

Based on the results listed in Table 2-4, it is known that the experimental class using STEAM with a problem-based learning approach had higher scores than STEAM with a scientific approach, but not significantly. This result shows that the insertion of STEAM in problem-based learning can be an effort to solve problems in real-time (Pérez Torres, Couso Lagarón, & Marquez Bargalló, 2024; Smith et al., 2022). Acquisition of problem-solving efforts through orientation to environmental issues, preparing students to learn, assisting independent and group research, developing and presenting artifacts and display objects, and analyzing and evaluating the problem-solving process (Richard L. Arends, 2012).

CTS is not a product but a process of developing a culture of thinking (Fadli et al., 2024; Gunawardena & Wilson, 2021) to improve the quality of learning at the tertiary level (Li, 2022). However, improving critical thinking requires a long time, and some group discussions affect each individual's debate (Chen, Zhao, Jin, & Li, 2024). Implementing STEAM learning experiences is challenging at the beginning of its application, because it requires instructional design and supportive learning tools. In some tertiary institutions, few educational institutions apply STEAM learning because it is difficult (Hidayah et al., 2022), and 11% of universities implement STEAM learning (Ilma et al., 2023). Example of STEAM learning implementation in science learning on light refraction material by creating products in the form of 3D holograms

Figure 8. STEAM Product on Light Refraction

Students utilized bottle waste to make 3D holograms to explain the light refraction material. The science shown in Figure 8 involves the science of biology to sort waste into innovative products and involves physics materials related to light refraction. YouTube, which supports 3D hologram video media, was used. Engineering is found in the design pattern or 3D hologram design that will be made by considering aspects of mathematics as a basic science to make prism shapes by understanding the geometry and calculating the right size to produce a proportional shape. Thus, the resulting hologram is formed by combining two coherent light rays in microscopic form. The results of this lecture were uploaded to YouTube. An example of STEAM learning implementation by students in utilizing bottle waste as a planting medium is shown in Figure 9.

Figure 9 and 10 show math aspects using the principles of geometry and measuring circles to match the media used. CTS can be improved through STEAM learning by designing varied instructions to stimulate students to think through learning pathways, scenarios, storylines, puzzles, challenges, feedback mechanisms, and concept patterns (Sidekerskienė & Damaševičius, 2023). Group learning can improve communication and add narratives to learning. It can train students to make decisions through critical thinking and student reflection to solve group problems and encourage them to develop the knowledge and skills to solve real-life problems (Angelelli et al., 2023).

Science	The science learned from the science aspect of plastic waste management and how to reuse or reutilize it. In addition. examining how the process of growth and development between plants that live with soil media and without soil media. The selection of kale plants as a test in the project because kale has a transparent stem so it is easy to observe when given treatment.
Technology	Using smartphones and the internet to find references and information on how to utilize waste to be innovated as an economically valuable product. for example growing kale using media that has been innovated from waste into a planting site. Looking for information such as the best time for kale to be exposed to sunlight and whether kale is better to use soil or soil-less planting media
Engineering	Design a project using simple materials from waste. such as plastic cups and plastic bottles. Designing the construction and pattern to be made so that it is easier to use and produces a sturdy product when filled with soil. water. and plants.
Art	The planting media is made by paying attention to the aesthetic aspects to design the pattern and distance used for planting media so that when the kale has grown it is not crowded together. The waste used considers the shape of existing plastic bottles and glasses. if the bottles and glasses are less feasible then they can be modified by adding some accessories to beautify the products made.
Mathematics	Requires mathematical knowledge in designing and making the media. by integrating geometry material from bottles and glasses used. involving circle material in mathematics. besides that in terms of plant growth and development. it requires quantitative and qualitative data collection and analysis. For example. it requires calculations in observing the growth time between plants with soil and water planting media. The results of the observations are known on the 2nd and 3rd days the plants already have small shoots and on the 4th day the shoots grow an average of 2.5 cm.

Figure 9. Reuse Products from Waste as Media and Explanation of each Aspect of STEAM

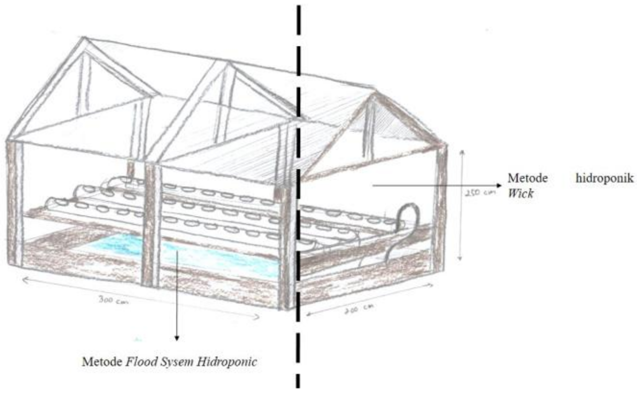


Figure 10. Schematic Design for Aquaponics

Figure 10 shows a simple greenhouse design that can be used to utilize vacant land around a house or at tourist attractions with an edutourism theme. Science covers environmental conservation and growth and development by making aquaponics, and plant parts can be made using pipes or waste bottles that are connected with Styrofoam so that it can be used to grow vegetables and the bottom for fish. Thus, the technology used is appropriate. Engineering is used to design a greenhouse for aquaponics and adjust the channel for sun exposure so that plants can grow. Art by creating visual patterns for farming. Mathematically, the water requirement was calculated based on the volume required.

This concept can improve the economy in a sustainable and environment-friendly manner. The students analyzed the problems that occurred and tried to solve them by thinking complex and interdisciplinary. Improving critical thinking skills can be obtained through learning approaches that cause attitudes and habits in learning mathematics (Mae, Salviejo, Ibañez, &

Pentang, 2024). The solutions to this problem must be studied from various scientific perspectives. For example, understanding natural phenomena as objects that need to be learned requires an interdisciplinary approach (Asrizal et al., 2023).

Environmental learning must be understood systematically and applied as a strategic step to solve ecological problems (Aritia & Suyanto, 2019; Megawati, Djulia, & Yus, 2018; Timkina & Mikhaylova, 2023; Tolochko, Bordiug, Mironets, Mozul, & Tanasiichuk, 2023). Various environmental issues that have occurred in multiple regions are related to the ecological crisis in recent years, such as climate change, water pollution, loss of biodiversity, global warming, illegal logging, limited availability of clean water, and the impact of human activities on the exploitation of natural resources that cause environmental damage (Ahmed, 2022; Erhabor & Don, 2016; Esson & Moss, 2016; Gubasheva et al., 2023; Osmaev, 2023; Setiawan, 2022). CTS can be improved if supported by learning tools, such as instruments developed using the HOTS base (Sidiq et al., 2021). Educators need a comprehensive understanding of the hierarchy and its relationship with various pedagogical practices in implementing investigative processes in science learning (Yanto, Subali, & Suyanto, 2019).

The strength of the results of this study is that STEAM can significantly increase CTS for the type of dynamic material characteristics, but clear instructions must support it. This increase is caused by STEAM unique characteristics that integrate multidisciplinary exploration, open inquiry, and creative collaboration, thus creating a learning environment that challenges assumptions, trains systemic analysis, and encourages evaluation of solutions from various perspectives. STEAM learning design places issues of environmental problems as objects of learning assessed from various points of point, beauty produced, technology involved, tools needed to solve problems, and mathematical calculations in obtaining quantitative and qualitative data. CTS can be increased through activities that facilitate students exploring the resolution of authentic problems involving scientific practices and investigations supported by appropriate learning technology in the form of hard and soft technology. The disadvantage is that it requires teachers' and students' time, strategy, skills, and experience to implement effectively and efficiently.

Conclusion

STEAM is a pedagogical revolution in the digital transformation era, which aims to improve the quality of human resources, especially to prepare students to solve real problems transdisciplinary through critical thinking. CTS is necessary to solve various issues in the surrounding environment and ensure sustainability through STEAM learning. The results showed a significant difference in CTS between students who studied STEAM and those (0.001 <0.050) with a medium category ($0.3 \leq g \leq 0.7$). This increase is caused by STEAM unique characteristics that integrate multidisciplinary exploration, open inquiry, and creative collaboration, thus creating a learning environment that challenges assumptions, trains systemic analysis, and encourages evaluation of solutions from various perspectives. The implication, STEAM created a cognitive dissonance that encouraged the customs of students' CTS through questioning assumptions, connecting concepts, and evaluating solutions from various perspectives. Supporting data in producing products of STEAM have an average value of 89.33, and aspects of cooperation during learning have an average value of 96.10.

The limitation of this research is that it is not good in managing the time of learning implementation, so learning requires a long time. In addition, the measured variables are limited to CTS only. Based on these limitations, the recommendation in the future is to prepare instructions that are equipped with careful planning so there is no technical obstacle. In addition, to explore studies by carrying out the Steam learning pedagogy revolution in other forms of innovation and the need to expand or deepen variables that are not only limited to cognitive abilities but other skills that can be a provision for prospective educators in the future. Thus, graduates are ready to face global challenges through learning relevant to the needs of the future.

Declarations

Ethics Statements: This research has followed the ethical standards that are accepted in this journal.

Conflict of Interest: Author declare that there is no conflict of interest in this publication

Informed Consent: All participants have agreed to be involved in this study as stated in the information consent with their real names removed.

Data Availability: All the data collected from the participants test and observation result.

Reference

Adesina, A. E. (2022). Integration of learning management system in basic STEAM education in Nigeria. *International Journal of Contemporary Issues in Education*, *4*(1), 69–75.

Aguayo, C., Videla, R., López-Cortés, F., Rossel, S., & Ibacache, C. (2023). Ethical enactivism for smart and inclusive STEAM learning design. *Heliyon*, *9*(9), 1–15. doi: 10.1016/j.heliyon.2023.e19205

Ahmed, S. (2022). *Identify the problems and needs of Environmental Education .*

Akbariah, N., Artika, W., Pada, A. U. T., Safrida, S., & Abdullah, A. (2023). Stem-Based Learning Process Analysis of Students' Science Process Skills. *Jurnal Penelitian Pendidikan IPA*, *9*(2), 943–951. doi: 10.29303/jppipa.v9i2.2912

Akçay, B., & Avcı, F. (2022). Development of the STEM-Pedagogical Content Knowledge Scale for Pre-service Teachers: Validity and Reliability Study. *Journal of Science Learning*, *5*(1), 79–90. doi: 10.17509/jsl.v5i1.36293

Angelelli, C. V., Ribeiro, G. M. de C., Severino, M. R., Johnstone, E., Borzenkova, G., & da Silva, D. C. O. (2023). Developing critical thinking skills through gamification. *Thinking Skills and Creativity*, *49*(August 2022), 101354. doi: 10.1016/j.tsc.2023.101354

Arce, E., Suárez-García, A., López-Vázquez, J. A., & Fernández-Ibáñez, M. I. (2022). Design Sprint: Enhancing STEAM and engineering education through agile prototyping and testing ideas. *Thinking Skills and Creativity*, *44*(September 2021). doi: 10.1016/j.tsc.2022.101039

Arends, R. L. (2012). *Learning to Teach (9th ed.)*. New York: Mc Graw Hill.

Arends, Richard L. (2012). *Learning to Teach (9th ed.)*. New York: Mc Graw Hill.

Aritia, E., & Suyanto, S. (2019). The Effect of Problem based Learning Model and Concept Map Strategy for Problem Solving and Understanding of the Ecosystem Concept of High School Students. *Journal of Physics: Conference Series*, *1233*(1). doi: 10.1088/1742-6596/1233/1/012005

Asrizal, A., Dhanil, M., & Usmeldi, U. (2023). The Effect of STEAM on Science Learning on Student Learning Achievement: A Meta-Analysis. *Jurnal Penelitian Pendidikan IPA*, *9*(4), 1650–1657. doi: 10.29303/jppipa.v9i4.3108

Astriani, D., Martini, Rosdiana, L., Fauziah, A. N. M., & Purnomo, A. R. (2023). STEAM-Project Based Learning (PjBL): Efforts to Train Critical Thinking Skills for Prospective

Science Teacher. *Jurnal Penelitian Pendidikan IPA*, *9*(10), 7909–7915. doi: 10.29303/jppipa.v9i10.3823

Ates, C. B., & Aktamis, H. (2024). Investigating the effects of creative educational modules blended with Cognitive Research Trust (CoRT) techniques and Problem Based Learning (PBL) on students ' scientific creativity skills and perceptions in science education. *Thinking Skills and Creativity*, *51*(February), 101471. doi: 10.1016/j.tsc.2024.101471

Baidal-Bustamante, E., Mora, C., & Alvarez-Alvarado, M. S. (2023). STEAM Project-Based Learning Approach to Enhance Teaching-Learning Process in the Topic of Pascal's Principle. *IEEE Transactions on Education*, *66*(6), 632–641. doi: 10.1109/TE.2023.3283850

Bedewy, S. El, & Lavicza, Z. (2023). STEAM + X - Extending the transdisciplinary of STEAM-based educational approaches: A theoretical contribution. *Thinking Skills and Creativity*, *48*(January), 101299. doi: 10.1016/j.tsc.2023.101299

Bertrand, M. G., & Namukasa, I. K. (2020). STEAM education: student learning and transferable skills. *Journal of Research in Innovative Teaching & Learning*, *13*(1), 43–56. doi: 10.1108/jrit-01-2020-0003

Bertrand, M. G., & Namukasa, I. K. (2023). A pedagogical model for STEAM education. *Journal of Research in Innovative Teaching and Learning*, *16*(2), 169–191. doi: 10.1108/JRIT-12-2021-0081

Bray, D. A., Girvan, D. C., & Chorcora, E. N. (2023). Students' perceptions of pedagogy for 21st century learning instrument (S-POP-21): Concept, validation, and initial results. *Thinking Skills and Creativity*, *49*(May 2022), 1–14. doi: 10.1016/j.tsc.2023.101319

Carter, C. E., Barnett, H., Burns, K., Cohen, N., Durall, E., Lordick, D., Nack, F., Newman, A., Ussher, S., Dresden, T. U. (2021). Defining STEAM Approaches for Higher Education. *European Journal of STEM Education*, *6*(1), 1–16.

Chan, M. N., & Nagatomo, D. (2022). Study of STEM for sustainability in design education: Framework for student learning and outcomes with design for a disaster project. *Sustainability (Switzerland)*, *14*(1). doi: 10.3390/su14010312

Chávez, D. A., Gamiz-Sanchez, V. M., & Vargas, A. C. (2020). Problem-Based Learning: Effects on Academic Performance and Perceptions of Engineering Students in Computer Sciences. *Journal of Technology and Science Education*, *10*(2), 306–328. doi: 10.3926/jotse.969

Chen, X., Zhao, H., Jin, H., & Li, Y. (2024). Exploring college students' depth and processing patterns of critical thinking skills and their perception in argument map(AM)-supported online group debate activities. *Thinking Skills and Creativity*, *51*(March 2023), 101467. doi: 10.1016/j.tsc.2024.101467

Creswell, J. W., & Creswell, J. D. (2018a). Fifth Edition Research Design Qualiative, Quantitative, and Mixed Methods Approaches. In *Introducing English Language*. California: Sage Publication, Inc. doi: 10.4324/9781315707181-60

Creswell, J. W., & Creswell, J. D. (2018b). Mixed Methods Procedures. In *Research Defign: Qualitative, Quantitative, and Mixed Methods Approaches*. California: Sage Publication, Inc.

Daga, A. T., Wahyudin, D., & Susilana, R. (2022). An Investigation of Developing Indonesian Elementary School Students' Critical Thinking Skills: A Literature Review. *International Journal of Curriculum and Instruction*, *14*(3), 1752–1766. Retrieved from http://ijci.wcci-international.org/index.php/IJCI/article/view/931

Damopolii, I., & Kurniadi, B. (2019). The Development Of Android-Based Mobile Learning Supported By Problem-Based Learning Strategy For Students ' Learning Success. *International Journal of Scientific & Technology Research*, *8*(07), 8–11.

Dhurumraj, T., Ramaila, S., Raban, F., & Ashruf, A. (2020). Broadening educational pathways to stem education through online teaching and learning during covid-19: Teachers' perspectives. *Journal of Baltic Science Education*, *19*(6), 1055–1067. doi: 10.33225/JBSE/20.19.1055

Dotson, M. E., Alvarez, V., Tackett, M., Asturias, G., Leon, I., & Ramanujam, N. (2020). Design Thinking-Based STEM Learning : Preliminary Results on Achieving Scale and Sustainability Through the IGNITE Model. *Curriculum, Instruction, and Pedagogy*, *5*(February), 1–10. doi: 10.3389/feduc.2020.00014

Doyan, A., Susilawati, Gunada, I. W., & Hilfan. (2021). The Effect of Problem-Based and Discovery Learning Models with the Science Approach to the Understanding Concept and Science Process Skills of the Student. *Proceedings of the 5th Asian Education Symposium 2020 (AES 2020)*, *566*(Aes 2020), 274–280. doi: 10.2991/assehr.k.210715.058

Dubinsky, J. M., & Hamid, A. A. (2024). Neuroscience and Biobehavioral Reviews The neuroscience of active learning and direct instruction. *Neuroscience and Biobehavioral Reviews*, *163*(December 2023), 105737. doi: 10.1016/j.neubiorev.2024.105737

Ennis, R. H. (1985). *A logical basis for measuring critical thinking skills*. Retrieved from https://pdfs.semanticscholar.org/80a7/c7d4a98987590751df4b1bd9adf747fd7aaa.pdf

Erhabor, N. I., & Don, J. U. (2016). Impact of environmental education on the knowledge and attitude of students towards the environment. *International Journal of Environmental and Science Education*, *11*(12), 5367–5375. doi: 10.25073/0866-773x/68

Eska, N., Nasution, A., Henie, M., Al, I., & Sapta, M. (2023). Relationship between Critical and Creative Thinking Skills and Learning Achievement in Biology with Reference to Educational Level and Gender. *Journal of Turkish Science Education*, *20*(1), 66–83.

Esson, M., & Moss, A. (2016). The challenges of evaluating conservation education across cultures. *International Zoo Yearbook*, *50*(1), 61–67. doi: 10.1111/izy.12113

Fadli, R., Surjono, H. D., Sari, R. C., Eliza, F., Hakiki, M., Hidayah, Y., Triyono, M.B., Samala, A. D. (2024). Effectiveness of Mobile Virtual Laboratory Based on Project-Based Learning to Build Constructivism Thinking. *International Journal of Interactive Mobile Technologies (IJIM)*, *18*(06), 40–55. doi: 10.3991/ijim.v18i06.47643

Fatimah, H., Yamtinah, S., & Shidiq, A. S. (2023). Study of Ecology and Biodiversity Learning Based on Project Based Learning-Science Technology Engineering Mathematics (PjBL-STEM) in Empowering Students ' Critical Thinking. *Jurnal Penelitian Pendidikan IPA*, *9*(9), 729–736. doi: 10.29303/jppipa.v9i9.3688

Fernando, S.-M. L., & Drugova, E. A. (2023). Trends in critical thinking instruction in 21st-century research and practice: Upgrading instruction in digital environments. *Thinking Skills and Creativity*, *49*. doi: https://doi.org/10.1016/j.tsc.2023.101383

Field, A. (2017). Discovering Statistic Using IBM SPSS Statistic 5th. In *Sage Edge* (Vol. 53).

Gizaw, G. G., & Sota, S. S. (2023). Improving Science Process Skills of Students: A Review of Literature. *Science Education International*, *34*(3), 216–224. doi: 10.33828/sei.v34.i3.5

Gubasheva, K. A., Temirova, A. B., & Madaev, S. M. (2023). Modern Technologies as Important Tools for Environmental Education During the Environmental Crisis. *SHS Web of Conferences*, *172*, 1–8. doi: 10.1051/shsconf/202317201039

Gunawardena, M., & Wilson, K. (2021). Scaffolding students' critical thinking: A process not an end game. *Thinking Skills and Creativity*, *41*(July 2020), 100848. doi: 10.1016/j.tsc.2021.100848

Hake, R. R. (1999). Analyzing change/gain scores. *Unpublished.[Online] URL: Http://Www. Physics. Indiana. Edu/\~ Sdi/AnalyzingChange-Gain. Pdf*, *16*(7), 1073–1080. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/22025883%5Cnhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:ANALYZING+CHANGE/GAIN+SCORES#0%5Cnhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Analyzing+change/gain+scores#0

Hasim, S. M., Rosli, R., Halim, L., Capraro, M. M., & Capraro, R. M. (2022). STEM Professional Development Activities and Their Impact on Teacher Knowledge and Instructional Practices. *Mathematics*, *10*(7), 1–20. doi: 10.3390/math10071109

Hidayah, I., Widiyatmoko, A., Nurin, N. S., & Laksono, A. (2022). An Implementation of STEAM Approach: Junior High School Mathematics and Science Teachers' Perceptions and Obstacles. *International Conference on Science, Education and Technology*, (February 2023), 92–95. Retrieved from https://proceeding.unnes.ac.id/index.php/ISET/article/view/1734%0Ahttps://proceeding.unnes.ac.id/index.php/ISET/article/download/1734/1220

Ilma, A. Z., Wilujeng, I., Widowati, A., Nurtanto, M., & Kholifah, N. (2023). A Systematic Literature Review of STEM Education in Indonesia (2016-2021): Contribution to Improving Skills in 21st Century Learning. *Pegem Egitim ve Ogretim Dergisi*, *13*(2), 134–146. doi: 10.47750/pegegog.13.02.17

John W. Creswell. (2014). *Research Design: Qualitative, Quantitative and Mixed Methods Approaches (4th ed.)*. London: Sage Publication Ltd.

Jong, T. De, Lazonder, A. W., Chinn, C. A., Fischer, F., Gobert, J., Hmelo-silver, C. E., Kodinger, K.R., Krajcik, J.S., Kyza, E.A., Linn, M.C., Pedaste, M., Scheiter, K., Zacharia, Z. C. (2024). Beyond inquiry or direct instruction : Pressing issues for designing impactful science learning opportunities. *Educational Research Review*, *44*(July), 1–8. doi: 10.1016/j.edurev.2024.100623

KBO. (2023). Tragedi Tambang Timah di Bangka Belitung: Lebih dari 80 Orang Tewas dan Kerusakan Lingkungan yang Mengkhawatirkan. (Tin Mining Tragedy in Bangka Belitung: More than 80 Dead and Worrisome Environmental Damage). *Detik Babel*. Retrieved from https://detikbabel.com/tragedi-tambang-timah-di-bangka-belitung-lebih-dari-80-orang-tewas-dan-kerusakan-lingkungan-yang-mengkhawatirkan/

Khamhaengpol, A., Sriprom, M., & Chuamchaitrakool, P. (2021). Development of STEAM activity on nanotechnology to determine basic science process skills and engineering design process for high school students. *Thinking Skills and Creativity*, *39*(April 2020), 100796. doi: 10.1016/j.tsc.2021.100796

Kusumawati, Y., Winarno, S., Ariansyah, M. H., Fitri, E. N., Studi, P., Informasi, S., & Dian, U. (2023). Design and Implementation mDPBL Teaching Approach to Improve Students ' Creative Thinking Skill. *JET: Journal of Education and Teaching*, *4*(1), 119–127. doi: 10.51454/jet.v4i1.221

Lasniroha Sagala, N., & Simanjuntak, M. P. (2017). The Influence of Problem Based Learning Model on Scientific Process Skill and Problem Solving Ability of Student. *IOSR Journal of Research & Method in Education (IOSR-JRME)* , *7*(4), 1–09. doi: 10.9790/7388-0704040109

Lavi, R., Tal, M., & Dori, Y. J. (2021). Perceptions of STEM alumni and students on developing 21st century skills through methods of teaching and learning. *Studies in Educational Evaluation*, *70*, 1–11. doi: 10.1016/j.stueduc.2021.101002

Li, W. (2022). Studying creativity and critical thinking skills at university and students` future income. *Thinking Skills and Creativity*, *43*, 100980. doi: 10.1016/j.tsc.2021.100980

Lieung, K. W., Rahayu, D. P., & Fredy. (2020). Scientific Approach to Improve the Critical Thinking Skills. *Proceedings of the 3rd International Conference on Social Sciences (ICSS 2020) Scientific*, *473*(Icss), 480–483. doi: 10.2991/assehr.k.201014.105

Mae, K., Salviejo, A., Ibañez, E. D., & Pentang, J. T. (2024). Critical thinking disposition and learning approach as predictors of mathematics performance. *Journal of Education and Learning (EduLearn)*, *18*(4), 1107–1116. doi: 10.11591/edulearn.v18i4.21386

Megawati, Djulia, E., & Yus, A. (2018). Development Of Student Worksheets Based On Science Process Skills To Improve High Order Thinking On The Environment Theme Of Our Friend In Elementary School In 15 Sub District Percut Sei Tuan. *3rd Annual International Seminar on Transformative Education and Educational Leadership*, *200*(Aisteel), 345–351.

Ministry Health RI. (2023). Annual Report of Drinking Water Quality Monitoring in 2022. In *Ministry Health RI*.

Nadiroh, N., Hasanah, U., & Zulfa, V. (2019). Behavioral Geography : an Ecoliteracy Perspective and Critical Thinking Skills in Men and Women. *Indonesian Journal of Geography*, *51*(2).

Naufal, M. A., Ramdhani, N., Syahid, N. K., Zahrah, F., Nurfadya, M., Hafid, N. A., Dassa, A., Ihsan, H., Ahmad, A. (2024). STEAM learning implementation in Makassar : SWOT analysis. *Journal of Education and Learning (EduLearn)*, *18*(3), 794–803. doi: 10.11591/edulearn.v18i3.21353

Newell, M. K. J., & Ulrich, P. N. (2022). Competent and employed: STEM alumni perspectives on undergraduate research and NACE career-readiness competencies. *Journal of Teaching and Learning for Graduate Employability*, *13*(1), 79–93. doi: 10.21153/jtlge2022vol13no1art1534

Nguyen, Tien, Nguyen, D., & Dang, T. (2024). Educational Status of High School Biology Teachers to Develop Living World Understanding Competency in Students: A Case Study in the Mekong Delta, Vietnam. *The International Journal of Interdisciplinary Social and Community Studies*, *19*(2), 63–83. doi: 10.18848/2324-7576/CGP/v19i02/63-83.

OECD. (2019). Skills for 2030. *OECD Future of Education and Skills 2030*, 16. Retrieved from https://www.oecd.org/education/2030-project/teaching-and-learning/learning/skills/Skills_for_2030_concept_note.pdf

Osmaev, M. (2023). Experience and Problems of Environmental Education, Education and Upbringing. *SHS Web of Conferences*, *172*, 1–6. doi: 10.1051/shsconf/202317201040

Pasedan, D. D., & Nadeak, B. (2021). STEAM learning approach: realizing 21st century skills through increasing compound intelligence of class x students. *JPPI (Jurnal Penelitian Pendidikan Indonesia)*, *7*(1), 65–71. doi: 10.29210/02021815

Pentury, J. W., Bu'tu, D., & Malatuny, Y. G. (2022). Profile of Students' Critical Thinking Skills in 21st Century Skills-Based Learning. *ICOPE*, 218–225. Atlantis Press SARL. doi: 10.2991/978-2-38476-060-2_22

Pérez Torres, M., Couso Lagarón, D., & Marquez Bargalló, C. (2024). Evaluation of STEAM Project-Based Learning (STEAM PBL) Instructional Designs from the STEM Practices Perspective. *Education Sciences*, *14*(1). doi: 10.3390/educsci14010053

Putri, A. S., Prasetyo, Z. K., Purwastuti, L. A., Prodjosantoso, A. K., & Putranta, H. (2023). Effectiveness of STEAM-based blended learning on students' critical and creative thinking skills. *International Journal of Evaluation and Research in Education*, *12*(1), 44–52. doi: 10.11591/ijere.v12i1.22506

Regala, G. Z. (2019). Problem-Based Learning Module in the Conservation of Ecosystem. *4th International Congress on Action Research, Action Learning*, (March), 108. Retrieved from https://www.researchgate.net/publication/369542640

Richardo, R., Dwiningrum, S. I. A., Wijaya, A., Retnawati, H., Wahyudi, A., Sholihah, D. A., & Hidayah, K. N. (2023). The impact of STEM attitudes and computational thinking on 21st-century via structural equation modelling. *International Journal of Evaluation and Research in Education (IJERE)*, *12*(2), 571. doi: 10.11591/ijere.v12i2.24232

S. Wahyuningsih, Nurjannah, N.E, Rasmani, U.E.E, Hafidah, R, Pudyaningtyas, A.R, Syamsudidin, M. M. (2020). International Journal of Pedagogy and Teacher Education (IJPTE). *International Journal of Pedagogy and Teacher Education (IJPTE)*, *4*(1), 33–44.

Sagan, C. (1980). The Scientific Approach. In *Cosmos* (pp. 31–57). New York: Random House.

Sari, W. P., & Aprilliandari, D. I. (2021). The Development of PBL Integrated Bioenvironmentalscience App (BES App) for Environmental Learning. *Bioeduscience*, *5*(3), 264–271. doi: 10.22236/j.bes/537799

Schmid, M., Brianza, E., & Petko, D. (2020). Developing a short assessment instrument for Technological Pedagogical Content Knowledge (TPACK.xs) and comparing the factor structure of an integrative and a transformative model. *Computers and Education*, *157*(July), 103967. doi: 10.1016/j.compedu.2020.103967

Setiawan, A. (2022). Keanekaragaman Hayati Indonesia: Masalah dan Upaya Konservasinya. (Indonesia's Biodiversity: Problems and Conservation Efforts). *Indonesian Journal of Conservation*, *11*(01), 13–21. doi: 10.15294/ijc.v11i1.34532

Sidekerskienė, T., & Damaševičius, R. (2023). Out-of-the-Box Learning: Digital Escape Rooms as a Metaphor for Breaking Down Barriers in STEM Education. *Sustainability (Switzerland)*, *15*(9). doi: 10.3390/su15097393

Sidiq, Y., Ishartono, N., Desstya, A., Prayitno, H. J., Anif, S., & Hidayat, M. L. (2021). Improving elementary school students' critical thinking skill in science through hots-based science questions: A quasi-experimental study. *Jurnal Pendidikan IPA Indonesia*, *10*(3), 378–386. doi: 10.15294/JPII.V10I3.30891

Sigit, D. V., Ristanto, R. H., & Mufida, S. N. (2022). Integration of Project-Based E-Learning with STEAM: An Innovative Solution to Learn Ecological Concept. *International Journal of Instruction*, *15*(3), 23–40. doi: 10.29333/iji.2022.1532a

Smith, K., Maynard, N., Berry, A., Stephenson, T., Spiteri, T., Corrigan, D., Mansfield, J., Ellerton, P., Ellerton, P., Smith, T. (2022). Principles of Problem-Based Learning (PBL) in STEM Education: Using Expert Wisdom and Research to Frame Educational Practice. *Education Sciences*, *12*(10), 1–20. doi: 10.3390/educsci12100728

Syukri, M., Ukhaira, Z., Zainuddin, Z., Herliana, F., & Arsad, N. M. (2022). The Influence of STEAM-Based Learning Application on Students' Critical Thinking Ability. *Asian Journal of Science Education*, *4*(2), 37–45. doi: 10.24815/ajse.v4i2.28272

Tanti, T., Kurniawan, D. A., Syefrinando, B., Daryanto, M., & Fitriani, R. S. (2020). Identification of students attitudes towards natural sciences at Adhyaksa 1 Junior High School, Jambi City. *Journal of Education and Learning (EduLearn)*, *15*(1), 19–26. doi: 10.11591/edulearn.v15i1.16377

Timkina, Y., & Mikhaylova, Y. (2023). Assessment of university students ' need to acquire knowledge about ecology. *E3S Web of Conferences*, *05008*, 1–5.

Tolochko, S., Bordiug, N., Mironets, L., Mozul, I., & Tanasiichuk, I. (2023). Forming ecological culture in educational applicants within the context of modern education. *Revista Amazonia Investiga*, *12*(61), 41–50. doi: 10.34069/ai/2023.61.01.5

Wannapiroon, N., & Pimdee, P. (2022). Thai undergraduate science, technology, engineering, arts, and math (STEAM) creative thinking and innovation skill development: a conceptual model using a digital virtual classroom learning environment. *Education and Information Technologies*, *27*(4), 5689–5716. doi: 10.1007/s10639-021-10849-w

Wijayanti, A., Wiyanto, W., Ridlo, S., & Parmin, P. (2022). Implementation of STEAM in Science Learning: A Systematic Literature Review. *Technology*, 238–245. Retrieved from https://proceeding.unnes.ac.id/index.php/iset

Yadi, F., Sofyan, H., & Surjono, H. D. (2023). Enhancement of critical thinking skills vocational students in indonesia using problem-based learning-stem by e-learning. *Jurnal Pendidikan Teknik Mesin*, *10*(1).

Yanto, B. E., Subali, B., & Suyanto, S. (2019). Improving Students' Scientific Reasoning Skills through the Three Levels of Inquiry. *International Journal of Instruction*, *12*(4), 689–704. doi: 10.29333/iji.2019.12444a

Yılmaz, A. (2021). The effect of technology integration in education on prospective teachers' critical and creative thinking, multidimensional 21st century skills and academic achievements. *Participatory Educational Research*, *8*(2), 163–199. doi: 10.17275/per.21.35.8.2

Yu, P. (2021). Development , Characteristic and Enlightenment of STEAM Education in the United States. *Frontiers in Educational Research*, *4*(10), 96–99. doi: 10.25236/FER.2021.041019

Yusuf, A. R., Sutadjİ, E., & Sugandİ, M. (2023). Hacettepe Üniversitesi Eğitim Fakültesi Dergisi Hacettepe University Journal of Education Integration of STEM Project-Based Learning into 21st Century Learning and Innovation Skills (4Cs) in Vocational Education Using SEM Model Analysis. *Hacettepe University Journal of Education*, *38*(4), 454–469. doi: 10.16986/HUJE.2023.499

Zaqiah, Q. Y., Hasanah, A., & Heryati, Y. (2024). the Role of Steam Education in Improving Student Collaboration and Creativity: a Case Study in Madrasah. *Jurnal Pendidikan Islam*, *10*(1), 101–112. doi: 10.15575/jpi.v10i1.35207

Zayyinah, Z., Erman, E., Supardi, Z. A. I., Hariyono, E., & Prahani, B. K. (2022). STEAM-Integrated Project Based Learning Models: Alternative to Improve 21st Century Skills. *Proceedings of the Eighth Southeast Asia Design Research (SEA-DR) & the Second Science, Technology, Education, Arts, Culture, and Humanity (STEACH) International Conference (SEADR-STEACH 2021)*, *627*, 251–258. doi: 10.2991/assehr.k.211229.039