UTILISING SMART WATER MONITORING WITH IOT IN SCIENCE LEARNING WITH PROBLEM-BASED LEARNING MODEL: IMPACT ON CRITICAL THINKING SKILLS AND THE ROLE OF LEARNING INTEREST

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Abstract

This research explores the impact of integrating smart water monitoring with internet of things (IoT) into 7th-grade science education using the problem-based learning (PBL) model. A quasi-experimental research design with a post-test-only control group is employed to compare the effectiveness of two learning groups: one using the regular PBL model and the other incorporating smart water monitoring through IoT within the PBL framework. The study includes 7th-grade students from two different secondary schools as participants. The independent variables are the regular PBL model and the PBL model with smart water monitoring using IoT. In contrast, the dependent variable is students' critical thinking skills, with prior knowledge and learning interest as covariates. Students utilize an observation worksheet for Water Quality Assessment to observe different types of water and assess their suitability or water quality. The findings reveal that integrating smart water monitoring with IoT in the PBL model significantly positively impacts students' critical thinking skills. The group of smart water monitoring students demonstrated a more considerable improvement in critical thinking skills than those following the regular PBL model. The study highlights the essential role of students' learning interest in developing necessary thinking skills. Students with higher learning interest in the science subject tend to exhibit more significant improvement in critical thinking skills after participating in learning with smart water monitoring or the regular PBL model.

Keywords

Critical Thinking Skills,

Internet of Things,

Learning Interest,

Problem-based Learning,

Science Learning.

1. Introduction

Problem-based learning [PBL] is a learning model proven effective in improving critical thinking skills and understanding science concepts (Aswan et al., 2018; Yu & Zin, 2023; Zabit, 2010). PBL is a teaching method in which complex real-world problems promote student learning of concepts and principles instead of directly presenting facts and ideas (Cardon et al., 2022). PBL can encourage the development of critical thinking skills, problem-solving abilities, and communication skills (Cardon et al., 2022). PBL can be adapted to become more critical thinking-oriented by implementing CT-specific tools, incorporating CT-focused activities, utilizing digital technologies, integrating with other pedagogical methods, and integrating discipline-specific knowledge (Yu & Zin, 2023). Collaborative activities are inherent to PBL and allow learners to practice cognitive and meta-cognitive skills. PBL has been used to improve the critical thinking of biology students through the integration of group investigation (GI) through lesson study (Asyari et al., 2016). A study showed that PBL students significantly improved the overall California Critical Thinking Skills Test, analysis, and induction (Yuan et al., 2008).

PBL is a teaching method designed to deepen students' knowledge through projects centred on real-world problems (Haatainen & Aksela, 2021). In PBL, the teacher presents students with an open-ended question or problem and then asks them to find a solution using the knowledge and skills they've developed in class. PBL can promote the development of critical thinking skills, problem-solving abilities, and communication skills (Cardon et al., 2022). When students participate in a PBL task, they utilize processes that allow them to demonstrate the mental and physical behaviours of scientists. The inquiry involves observing a function or event, formulating questions based on observations, developing a workable hypothesis, devising a strategy for testing it, analyzing and drawing conclusions from collected data, reviewing and evaluating decisions, and communicating findings to others. PBL can be helpful in promoting twenty-first-century learning and skills in future-oriented K-12 science education (Markula & Aksela, 2022). PBL can also improve students' scientific processing skills and learning motivation.

Using technology in PBL models, such as with the IoT, can enhance students' critical thinking abilities through several mechanisms. Technology enables students to actively collect and analyse data (Aswan & Sumarmin, 2018; Benita et al., 2021). This makes learning more interactive and contextual as students can connect theory with real-life experiences. Students who work with data obtained through this technology are more inclined to think critically because they must formulate questions, seek solutions, and make decisions based on the data (Glaroudis et al., 2019). These activities can be guided by providing worksheets for the learning process in line with PBL.

Learning activities aided by technology allow students to see the results of their actions or decisions quickly. They can identify errors, formulate different strategies, and develop problem-solving and critical thinking skills (Gunn et al., 2008; Hussin et al., 2018). Furthermore, implementing this learning mode facilitates collaboration and communication among students. In PBL, sharing ideas and perspectives can enrich the understanding and analysis of problems (Kassab et al., 2020). Technology enables students to work together on projects, share information, and engage in discussions, which can enhance critical thinking skills through collective dialogue and reflection. Thus, technology in technology-assisted PBL contexts can enrich students' learning experiences and provide a powerful tool for developing critical thinking skills (Markula & Aksela, 2022; Sulisworo et al., 2022; Yuan et al., 2008). Technology helps bridge the gap between theory and practical application, enabling students to participate more actively in their learning process.

Smart water monitoring is an innovative application of the IoT technology that can be used in science education to monitor and collect data on various types of water, such as clear water, wastewater, and river water (Bhardwaj et al., 2022; Jan et al., 2021). This technology can provide an interactive and engaging learning experience for students as they can observe and monitor different types of water in real-time (Bhardwaj et al., 2022). Smart water monitoring can enrich students' learning experience in identifying and analyzing the feasibility or quality of water with accurate and detailed data. It also provides relevant and in-depth environmental information, opening opportunities for a more holistic understanding of environmental and health issues. Using IoT sensors in science experiments, ecological data collection, or natural condition monitoring can also provide students with more interactive and practical learning (de Camargo et al., 2023; Miller et al., 2023). The use of smart water monitoring and IoT technology in science education provides opportunities for students to be more actively involved, gain a deeper understanding, and feel more connected to the learning material that is more relevant to real-life situations (Bhardwaj et al., 2022; Singh & Ahmed, 2021).

In implementing smart water monitoring with IoT in the PBL learning model for science education, it is essential to investigate the potential positive impact on students' critical thinking skills and consider the role of learning interest as a covariate variable. The research examines the influence of utilizing smart water monitoring with IoT in 7th-grade science education using the PBL model. The results of this study are expected to contribute to developing more innovative and effective learning strategies to enhance student's critical thinking skills and leverage the potential of IoT technology in science education at the junior high school level. It is worth noting that the use of IoT technology in water quality monitoring has shown promising results in terms of real-time data collection and analysis (Jan et al., 2021; Miller et al., 2023). This technology can provide students with a more interactive and practical learning experience, allowing them to engage with real-world environmental issues and develop critical thinking skills.

2. Method

Research Design

This study employs a quasi-experimental research design with a pre-and post-test control group. This design is chosen to compare the effectiveness of two learning groups: one applying the regular PBL model and the other utilizing the PBL model with integrating smart water monitoring using IoT. A pretest is conducted on both groups before administering the treatment to the experimental group. The pretest's objective is to ensure no significant differences between the two groups concerning the observed variables before the treatment is implemented (Gokhale & Machina, 2018). This pretest helps establish a baseline and enables researchers to gauge whether the groups were comparable before the intervention.

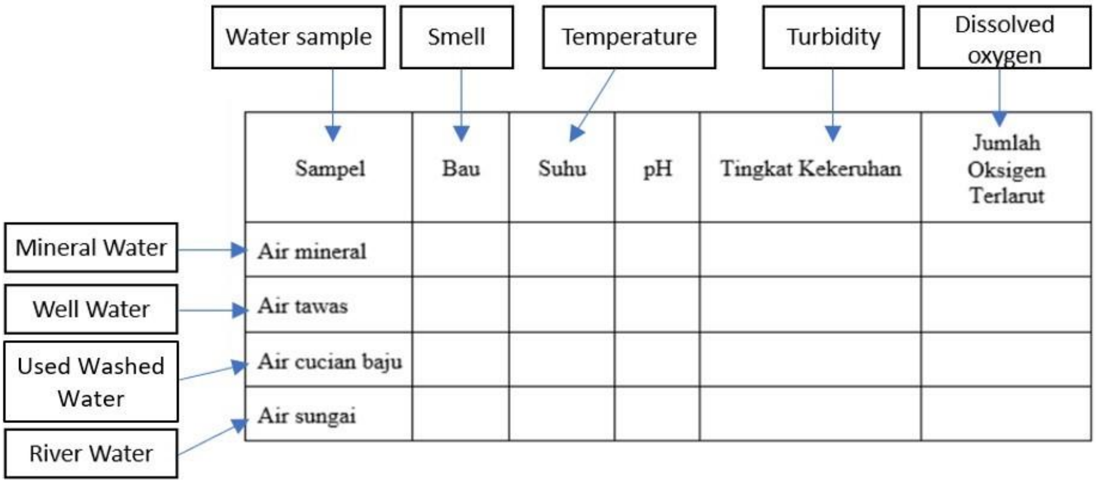
Participants

The subjects of the research are 7th-grade students (57 students) from two different secondary schools. One class acts as the experimental group (32 students), implementing learning with smart water monitoring, while the other class serves as the control group (25 students), following the regular PBL model. Random sampling is conducted to select classes that meet the inclusion criteria.

Instruments

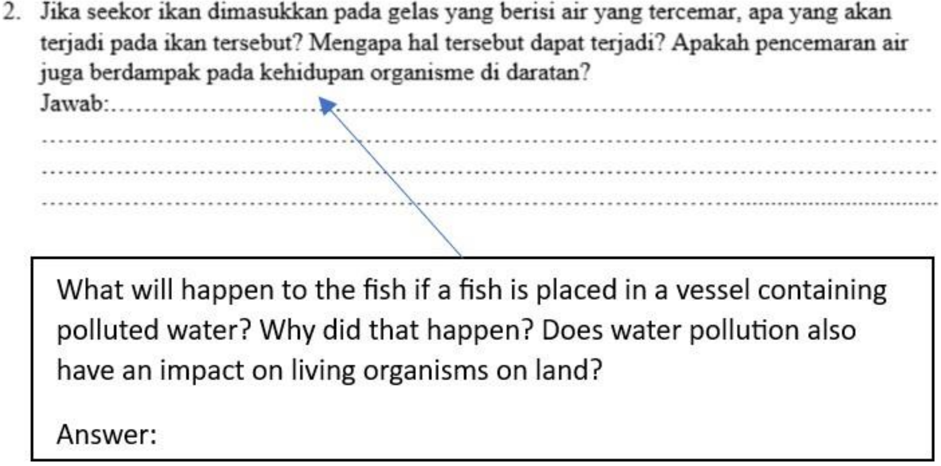
The independent variables in this study are the common PBL model and the PBL model with smart water monitoring using IoT. The dependent variable is the students' critical thinking skills, while the covariate is their Prior Knowledge and Learning Interest. The observation worksheet for Water Quality Assessment guides students in observing various types of water and identifying their suitability or water quality (see Figure 1 for the related worksheet). The instrument measuring prior knowledge was a set of 20 multiple-choice questions (4 optional answers). The instrument measuring critical thinking skills was a set of 5 essay questions (See Figure 2 for the example). Each question was assessed on a scale of 1 to 4. The scores obtained from the assessment were then converted into a scale of 100. The instrument for measuring learning interest was a perception questionnaire consisting of 25 items. Perception was measured on a Likert scale ranging from 1 (Strongly Disagree/ SD) to 5 (Strongly Agree/ SA). Thus, the maximum score attainable was 125.

Figure 1: The example of the observation table (comparing the water quality using IoT app)



Sampel	Bau	Suhu	pH	Tingkat Kekeruhan	Jumlah Oksigen Terlarut
Air mineral					
Air tawas					
Air cucian baju					
Air sungai					

Figure 2: The example of the CTS essay question



2. Jika seekor ikan dimasukkan pada gelas yang berisi air yang tercemar, apa yang akan terjadi pada ikan tersebut? Mengapa hal tersebut dapat terjadi? Apakah pencemaran air juga berdampak pada kehidupan organisme di daratan?

Jawab:...

What will happen to the fish if a fish is placed in a vessel containing polluted water? Why did that happen? Does water pollution also have an impact on living organisms on land?

Answer:

Research Procedure

The pre-test is conducted before the learning process begins. Both groups are given a pre-test to assess the students' initial critical thinking skills. Students in both groups are also requested to complete the Learning Interest Questionnaire. During the learning phase, the experimental group implements the PBL model with smart water monitoring in science learning. In contrast, the control group applies the regular PBL model without smart water monitoring. A post-test is administered after the learning process is completed, wherein both groups are given a post-test to measure the students' critical thinking skills. The stages of PBL with IoT assistance are presented in Table 1. These stages encompass the entire PBL process with IoT integration, allowing students to actively explore, collaborate, and develop critical thinking skills while addressing real-world ecological challenges related to water pollution and its impacts.

Table 1: The stages of PBL with IoT assistance

Stages		Content
1	Orientation of students to ecological problems (water pollution and its impact)	In this stage, students are introduced to ecological issues, notably water pollution and its consequences. They gain an understanding of the environmental challenges related to water pollution.
2	Organizing students for group learning using iot and worksheets	Students are organized into groups to facilitate collaborative learning. IoT technology and worksheets are utilized to collect and analyze data related to water quality, enabling students to engage in the learning process actively.
3	Guiding groups in exploring various types of water (clean and polluted) and their impacts on life	Each group investigates different types of water, both clean and polluted, and explores the effects of water quality on ecosystems and human life. They gather data using IoT devices and conduct experiments or observations.
4	Developing and presenting investigation results in group presentations	After conducting their research and collecting data, each group formulates their findings and insights into a presentation. They present their research outcomes to the class, sharing their discoveries and analyses.
5	Analyzing and evaluating problem-solving processes for various water pollution issues in life	Students engage in critical thinking by analyzing and evaluating the problem-solving processes they apply to address water pollution issues. They assess the effectiveness of their approaches and reflect on potential improvements.

The use of the same teacher (FLAU) to teach both groups, namely the control group and the treatment group. FLAU has a good understanding of the differences in learning activities in the two groups, in addition to having literacy about IoT. This choice is a measure to maintain consistency in the treatment application, thereby helping to minimize variability that may arise from differences in teaching methods and the approaches of different teachers. Apart from that, assuming that the teacher who teaches does not have a conflict of interest in the two groups is also important to maintain the integrity of the research. Teachers have no preferences or biases that could influence how they teach or how they evaluate learning outcomes.

Data Analysis

Data analysis is conducted through several tests. Initial Difference (Pre-test) in critical thinking skills is analyzed using the ANCOVA analysis to control for the effect of initial variables (pre-test) in assessing the initial differences in critical thinking skills. The final difference (post-test) in critical thinking skills is analyzed using the ANCOVA analysis to compare the critical thinking skills between the group using the regular PBL model and the group using smart water monitoring. Contribution analysis of learning interest to critical thinking skills is calculated using correlation analysis. Instrument Validity is tested using content and construct validity, while instrument reliability is measured through the Alpha Cronbach method. The number of participants did not exceed 200 students, therefore normality assumption analysis was carried out using Shapiro-Wilk analysis, the results of which showed that the data was normally distributed (Sig.=0.091 higher than 0.05).

Research Ethics

This study ensures adherence to research ethics, including obtaining permission from the schools and consent from the students or their parents/guardians before data collection. Data management is conducted with confidentiality and solely used for research purposes.

3. Findings

Descriptive Statistics

Descriptive statistics (see Table 2) provides an overview of the Critical Thinking Skills results for both groups, including each group's mean, standard deviation, and sample size.

Table 2: Descriptive Statistics for CTS

Learning Strategy	Mean	Std. Deviation	N
Control Group	78.0000	7.35980	25
Treatment Group	86.2500	8.32796	32
Total	82.6316	8.86935	57

Note. Dependent variable: Critical thinking skills.

Table 2 presents descriptive statistics for the dependent variable (CTS) in the control group and the treatment group. In the control group, the mean critical thinking skills score is 78.00, with a standard deviation of 7.36. On the other hand, the treatment group shows a higher mean score of 86.25 for critical thinking skills, with a slightly higher standard deviation of 8.33. The When considering both groups together, the overall mean critical thinking skills score is 82.63, with a standard deviation of 8.87. These descriptive statistics provide insights into the average performance and variability of critical thinking skills in each group, as well as the combined performance of all participants in the study.

Tests of Between-Subjects Effects

Table 3 displays the outcomes of the tests of between-subjects effects for the dependent variable, critical thinking skills [CTS], concerning three independent variables: prior knowledge [PK], learning interest [LI], and learning strategy [LS].

Table 3: Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	3563.612a	3	1187.871	74.802	.000	.809
Intercept	10.669	1	10.669	.672	.416	.013
PK	278.878	1	278.878	17.561	.000	.249
LI	356.605	1	356.605	22.456	.000	.298
LS	1052.713	1	1052.713	66.291	.000	.556
Error	841.651	53	15.880			
Total	393600.000	57				
Corrected Total	4405.263	56				

Note. Dependent variable: Critical thinking skill; a. R Squared = .809 (Adjusted R Squared = .798).

The model's statistical significance is indicated by the F-value of 74.802, with a corresponding p-value of 0.000, implying that the model is highly significant. The p-value (Sig.) being lower than the significance level (0.05) suggests significant differences among the groups based on the independent variables. Moreover, the effect sizes for each independent variable (PK, LI, LS) are relatively substantial, with values of 0.249, 0.298, and 0.556, respectively. The model explains the variation observed in critical thinking skills (R Squared = 0.809). The adjusted R Squared of 0.798 indicates that approximately 79.8% of the variance in the dependent variable can be attributed to the independent variables in the model. The analysis reveals that the independent variables (PK, LI, and LS) significantly influence critical thinking skills, and the model as a whole is highly significant in elucidating the variance in this dependent variable. From the pre-test results, both groups had the same characteristics on CTS. However, after learning, the two groups showed differences in CTS (post-test results) where the group that experienced learning with PBL assisted by the smart water monitoring had a higher CTS than the group that experienced learning only with PBL. These results explain that PBL assisted by smart water monitoring tends to have higher effectiveness in increasing CTS.

4. Discussion

Comparison of Critical Thinking Skills between the Regular PBL Group and Smart Water Monitoring Group

Teachers can utilize smart water monitoring with IoT in PBL learning to enhance students' critical thinking skills in science education. Integrating IoT technology in science education can provide students with a more interactive and practical learning experience, allowing them to engage with real-world environmental issues and develop critical thinking skills. Teachers can also adapt PBL methodologies to become more critical thinking-oriented to enhance the development of necessary thinking skills in students.

A study compared the critical thinking skills of students who participated in regular PBL and those who utilized smart water monitoring with IoT in PBL learning (Aswan et al., 2018). The study aimed to determine whether integrating smart water monitoring in science learning with the PBL model provides tangible benefits in enhancing students' critical thinking skills. The analysis results revealed a significant difference in critical thinking skills between the two groups, indicating that using smart water monitoring can significantly impact students' critical thinking abilities compared to conventional learning. The study suggests that IoT technology, such as smart water monitoring, can be effectively utilized as a supporting tool to improve the effectiveness of science education in secondary schools (Aswan et al., 2018).

The search results also provide insights into how PBL can be adapted to become more critical thinking-oriented (Yu & Zin, 2023). The studies examined in the search results employed various critical thinking-oriented activities within a PBL framework to enhance the development of critical thinking skills. These collaborative activities, a characteristic inherent to PBL, allowed learners to practice cognitive and meta-cognitive skills (Hussin et al., 2018; Joko et al., 2023). The search results suggest that implementing PBL methodologies within fields of study that necessitate the utilization of critical thinking competencies for problem resolution and knowledge acquisition can be beneficial (Sulisworo et al., 2022).

Implications of Utilizing Smart Water Monitoring with IoT in Science Learning

Smart water monitoring with IoT in science learning has several significant implications. This technology can offer students a more engaging, interactive, and relevant learning experience. Through smart water monitoring, students can actively observe and analyse various types of water, gaining a deeper understanding of water quality. Integrating IoT technology in science learning can facilitate the implementation of the PBL model more efficiently. Smart water monitoring provides real-time and detailed data on water quality, serving as the foundation for students to formulate questions, identify problems, and develop solutions through critical thinking processes. More engaging and interactive learning experience: IoT technology, such as smart water monitoring, can offer a more interesting, interactive, and relevant learning experience for students (Benita et al., 2021). By utilizing IoT devices, students can actively observe and analyse various types of water, gaining a deeper understanding of water quality.

Integrating IoT technology in science learning can facilitate the implementation of the PBL model more efficiently (Benita et al., 2021). Smart water monitoring provides real-time and detailed data on water quality, serving as the foundation for students to formulate questions, identify problems, and develop solutions through critical thinking processes (Oberascher et al., 2022). IoT technology in science learning can facilitate the development of more contextual and inquiry-based learning methods (Abichandani et al., 2022). By harnessing IoT technology, science learning can be connected to real-life situations, enabling students to learn from direct experiences and face challenges relevant to their daily lives (Joko et al., 2023).

The Role of Prior Knowledge and Learning Interest in Developing Critical Thinking Skills

Learning interest plays a crucial role in developing students' critical thinking skills. Students who are highly interested in science tend to be more enthusiastic and committed to their learning. High learning interest can motivate students to actively participate, ask questions, and seek further information, enhancing their critical thinking abilities. Students' interest in science learning can also influence their motivation to solve problems and confront challenges during the learning process. High interest encourages students to persevere and be resilient in seeking a deep understanding of scientific concepts, consequently improving their critical thinking skills.

Learning interest plays a vital role in developing students' critical thinking skills. When students are genuinely interested in a subject, they are more motivated and engaged in learning. This enthusiasm drives them to explore the subject matter more deeply, ask questions, seek out additional information, and actively participate in class discussions. As a result, they are more likely to think critically about the concepts, analyze data from multiple perspectives, and draw connections between different ideas.

Highly interested students are more willing to take on challenges and persevere through difficulties, which is essential to developing strong critical thinking abilities. Their passion for the subject also leads them to seek independent exploration and inquiry opportunities, further enhancing their critical thinking skills. Educators can capitalize on students' interests by designing learning experiences that align with their passions and curiosity. Educators can foster students' critical thinking skills by creating a stimulating and engaging learning environment and helping them become more active and independent learners.

High learning interest can motivate students to actively participate, ask questions, and seek further information, enhancing their critical thinking abilities. Students' interest in science learning can also influence their motivation to solve problems and confront challenges during the learning process. High interest encourages students to persevere and be resilient in seeking a deep understanding of scientific concepts, consequently improving their critical thinking skills.

Critical thinking can be developed through focused learning activities that encourage students to think about and attach information to their existing knowledge. Inquiry-based learning is one such approach that can help build critical thinking skills by encouraging students to identify problems, ask questions, select information, evaluate it, and draw conclusions from the evidence (Santos, 2017). The ability to think critically varies with the student's age and ability to understand (Gunn et al., 2008). Therefore, teachers must design learning activities appropriate for their students' developmental levels and cognitive skills (Bailin, 2002). Inquiry-based teaching is a common strategy for fostering learning and critical thinking in science education (Gómez & Suárez, 2020). However, more evidence is needed to understand the effect of inquiry-based teaching on science learning.

Prior knowledge plays a vital role in the development of critical thinking skills. A solid knowledge foundation on a subject allows individuals to process new information more efficiently and effectively. This reduced cognitive load enables learners to focus more on analyzing, evaluating, and applying further information, leading to improved learning performance and enhanced critical thinking abilities. Prior knowledge serves as a scaffold for building new connections and understanding complex concepts, essential critical thinking components. As learners accumulate more knowledge and experience, their critical thinking skills can become more sophisticated and advanced. Thus, nurturing and building upon prior knowledge is fundamental to promoting critical thinking in education and problem-solving in various contexts. According to cognitive load theory, students with prior knowledge may have greater working memory capacity to process their current learning tasks (Dong et al., 2020). Prior knowledge is critical to forming new cognitive schemas and acquiring new knowledge. Schema theory suggests that prior knowledge is a foundation for creating new mental structures to assimilate further information (Dong et al., 2020). Assessing students' prior knowledge allows both instructors and students to allocate their time and efforts more effectively. Understanding what students already know and can do when they enter the classroom or start a new topic of study can assist instructors in designing instructional activities that build upon their strengths and address their weaknesses (Glaroudis et al., 2019). Background knowledge is essential for practical critical thinking. Experts believe sufficient content knowledge fosters practical critical thinking (Gómez et al., 2013; Kassab et al., 2020). Activating prior knowledge is also vital for successful learning. This refers to the knowledge learners already possess in their memory bank before encountering new information. Incorporating prior knowledge across various learning domains can aid learners in analyzing, evaluating, and creating novel concepts based on what they have already learned (Maenpaa et al., 2017). By leveraging prior knowledge, students can better grasp new ideas and engage in more advanced cognitive processes, enhancing their critical thinking abilities.

Implications and Suggestions

The research findings have several implications for science education and instructional practices. Integrating smart water monitoring with IoT in the PBL model is a highly effective approach to enhancing students' critical thinking skills. Educators and policymakers can consider adopting this technology-based method to foster critical thinking abilities among students. The study highlights the importance of using technology like IoT in science learning. By incorporating IoT technology, students experience a more interactive and contextual learning environment, which can significantly contribute to developing critical thinking skills. Educators can explore other innovative ways to integrate technology into science lessons to promote deeper engagement and understanding among students.

The research also emphasizes the significance of considering students' learning interests when designing instructional approaches. Students who display higher interest in science exhibit more substantial improvements in critical thinking skills. Therefore, educators should strive to create learning experiences that pique students' curiosity and passion for science, which can significantly impact their critical thinking development.

The study underscores the potential benefits of using smart water monitoring with IoT in science education and its positive impact on critical thinking skills. Implementing such technology-driven approaches while considering students' learning interests can enhance the effectiveness of science instruction and empower students to become active, engaged, and critical thinkers. These implications can guide educational practitioners and policymakers in designing more impactful and relevant science learning experiences for students in the digital era.

For future research, there are several suggestions to build upon the current study and further explore the impact of smart water monitoring with IoT in science education and its influence on critical thinking skills:

Longitudinal Study

Conduct a longitudinal study to observe the long-term effects of integrating smart water monitoring with IoT in the PBL model on students' critical thinking skills. This will provide insights into the sustainability and retention of enhanced critical thinking abilities over an extended period.

Diverse Demographics

Expand the study to include a more diverse sample of students from various backgrounds, schools, and regions. This will help determine if the findings hold across different demographics and educational settings.

Variations in IoT Integration

Investigate different smart water monitoring integration levels and explore how varying degrees of IoT technology use impact critical thinking skills. Comparing different approaches may illuminate the most effective methods for enhancing critical thinking.

Other Subject Areas

Extend the research to explore the applicability of smart water monitoring with IoT in other subject areas beyond science. Examining its impact on critical thinking skills in different academic domains can provide a broader understanding of its potential benefits.

Qualitative Data

Incorporate qualitative data collection methods, such as interviews or focus groups, to better understand students' perceptions and experiences with smart water monitoring and its influence on their critical thinking development.

Learning Outcomes

Explore additional learning outcomes beyond critical thinking, such as problem-solving, creativity, and scientific inquiry skills. Investigating a broader range of learning outcomes can provide a comprehensive picture of the overall impact of smart water monitoring with IoT.

By addressing these research suggestions, future studies can further advance our understanding of the potential of IoT technology in science education and its contribution to developing critical thinking skills among students. These insights can support evidence-based decision-making for educational practices and facilitate the continuous improvement of science learning approaches in schools.

5. Conclusion

The research results indicate that the utilization of smart water monitoring with IoT in the PBL model has a significant positive impact on students' critical thinking skills. The group of smart water monitoring students demonstrated a more substantial improvement in critical thinking skills compared to those applying the regular PBL model. Incorporating IoT technology in science learning provides students with a more interactive, relevant, and contextual learning experience, aiding them in developing critical thinking skills more effectively. This study also revealed that students' learning interest is crucial in developing critical thinking skills. Students with higher learning interest in the science subject tend to exhibit more significant improvement in critical thinking skills after participating in learning with smart water monitoring or the regular PBL model. High learning interest motivates students to actively engage in learning, think more deeply, and tackle challenges with greater determination. The implications of this research suggest that using smart water monitoring with IoT can be an effective alternative to enhance students' critical thinking skills in science learning at the secondary school level. This technology can elevate the appeal of learning, facilitate the PBL model, and provide a learning experience more relevant to students' daily lives. Additionally, the study confirms that student empowerment through PBL and IoT technology holds substantial potential in advancing science education in the digital era.

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