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Investigating Critical Thinking Skills in Rural Middle School Students through STEM Education: A Qualitative Case Study from Sumedang

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Abstract

Learning plays a crucial role in fostering students' critical thinking skills, enabling them to address the challenges they face in their daily lives. This study was conducted in Sumedang, West Java, where students experience limited water availability. The main water sources are located far from residential areas, requiring students to make long trips each morning to fetch water from a distant river. This qualitative descriptive study aimed to explore how students employ critical thinking skills while engaging in contextual STEM learning through the development of a non-electric water pump project. The project involved seventh-grade students participating in science classes using a contextual STEM approach over one semester. Data were collected and analysed through observation, document analysis, and audio and video recordings using Transcript-Based Lesson Analysis. Indicators of critical thinking such as questioning, articulating assumptions, and demonstrating open-mindedness were observed during the STEM learning process of designing the non-electric water pump. The emergence of these skills varied across learning phases, individual characteristics, and group dynamics. Contextual STEM learning not only promotes critical thinking but also equips students with essential life skills for global competition in the 21st century by preparing them to solve real-world problems. The findings of this study provide insights for educators in designing more meaningful science learning experiences in the future.

Keywords: *Student Critical Thinking Skills, Contextual STEM Learning, Non-Electricity Water Pump Projects*

Introduction

Critical thinking skills serve as a fundamental building blocks for students' future success, providing them with the tools to tackle challenges, make intelligent decisions, and thrive in an ever-changing world (Ellerton & Kelly, 2021; Lipman, 1988). These skills enable students analyse information, consider multiple perspectives, and solve real-world problems creatively (Ellerton & Kelly, 2021). As students' progress through school and enter the workforce, their ability to think critically becomes increasingly essential, shaping their success in education, career growth, and lifelong learning (Tanti et al., 2020). Therefore, developing and refining critical thinking skills are crucial for preparing students to adapt, innovate, and succeed in the future (Yuan & Liao, 2023).

Enhancing critical thinking skills is a central goal in the STEM (Science, Technology, Engineering, and Mathematics) approach, which serves as an essential foundation for achieving this objective (Lacrin, 2021). By integrating these four disciplines, STEM provides a holistic understanding of the natural world and enables students to develop interdisciplinary skills that are essential for problem-solving (Gonzalez & Kuenzi, 2012; Morris et al., 2021). In response to the demand for a skilled and technically proficient workforce, the STEM approach emphasises the integration of knowledge, skills, and problem-solving within contexts relevant to students' daily lives (Corrigan et al., 2021). Consequently, STEM not only prepares students for future workplace success but also empowers them to become competent change-makers in an increasingly complex and globally interconnected society (Morris et al., 2021).

Contextual STEM learning has emerged as a dynamic approach to fostering these essential cognitive abilities. It provides students with immersive experiences that extend beyond theoretical boundaries (Conradty & Bogner, 2020; Lacrin, 2021). By integrating real-world challenges into STEM education, students' understanding of core concepts is deepened, and they acquire the problem-solving skills necessary to navigate the complexities of the modern world effectively (Morris et al., 2021). Through hands-on projects and experiments, students can strengthen their grasp of scientific principles and mathematical concepts while simultaneously honing their problem-solving abilities (Imaduddin et al., 2020).

Although STEM learning approaches have been widely recognized for their effectiveness in enhancing students' critical thinking skills (Moore et al., 2016; Astawan et al., 2023), most previous studies have concentrated on urban contexts with adequate educational facilities, thereby overlooking the complexities of rural education, which often faces infrastructural limitations and restricted access to technology (Hellman et al., 2024; Mueller, 2025). Systematic reviews, such as those by Sungur Gül et al. (2023), highlight the limited incorporation of local contexts in STEM learning designs, despite increasing evidence that community- and place-based approaches can significantly enhance student engagement and the meaningfulness of learning (Quang et al., 2015; Sánchez Milara & Orduña, 2024). Furthermore, many studies remain conceptual or laboratory-based, providing little empirical insight into real-world classroom implementations in rural settings (Jang, 2015). This study addresses these gaps by presenting empirical data drawn from classroom observations and the analysis of learning artifacts in rural Indonesian secondary schools. The findings indicate that integrating local context with problem-based contextual STEM, including e-modules and virtual experiments (Husna et al., 2024), effectively improves students' ability to identify problems, design feasible solutions, and reflect on their reasoning processes. Thus, this research contributes to the development of inclusive, evidence-based, and contextually adaptive STEM learning models (Sungur Gül et al., 2023; Hellman et al., 2024).

This study investigates the transformative potential of contextual STEM learning in advancing critical thinking skills, with a specific focus on the creation of non-electric water pump projects. Situated in Sumedang, West Java, this case study examines an educational landscape where students grapple with the tangible issue of water scarcity. By engaging in the design and implementation of non-electric water pump projects, students not only participate in hands-on STEM activities but also confront the socio-economic realities of their local community.

Ultimately, this study seeks to demonstrate the transformative role of contextual STEM learning as a catalyst for cultivating critical thinking skills in students. By presenting empirical evidence from the

Sumedang context, it contributes to the growing discourse on innovative pedagogical approaches and provides insights for educators seeking to harness the potential of contextual STEM learning in nurturing the next generation of critical thinkers.

Methodology

This study employed a qualitative descriptive approach with a single case study design. A single case study was considered appropriate to enable an in-depth, context-specific investigation of students' critical thinking development during the implementation of a contextual STEM-based project. This methodological choice aligns with the exploratory nature of the research, which aimed to uncover nuanced patterns of student interaction, reasoning, and reflective behavior within a naturally occurring classroom environment. Focusing on a single case allowed the study to capture the complexity and richness of the learning process in a real-world setting, thereby providing detailed insights into how and why critical thinking skills emerge in response to authentic problem-solving tasks. Data were collected through observations of verbal interactions and behavioral indicators during the learning sessions and were subsequently analyzed to reveal the dynamics of critical thinking throughout the project-based learning experience.

This study was conducted at a State Junior High School in Sumedang Regency. The participants were 16 seventh-grade students selected through purposive sampling based on their willingness to participate and their availability during the intervention period. Seventh-grade students were chosen because they were in the early stages of learning basic science and technology concepts, which made them suitable for introducing foundational STEM principles. These students engaged in a contextual STEM project to develop a non-electric water pump that addressed the issue of water scarcity in their daily lives. The project employed a science, technology, engineering, and mathematics (STEM) framework to guide students in designing functional, real-life solutions tailored to local environmental challenges. The STEM analysis of Non-Electricity Water Pump Project is shown in Table 1 and the working principle of the non-electric water pump designed by the students is illustrated in Figure 1.

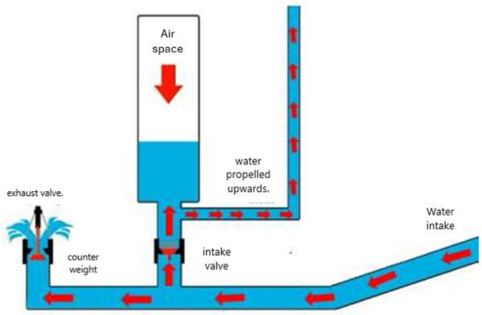

Figure 1. Operational Principle of the Non-Electricity Water Pump Developed by Students in STEM Project.

In the non-electric water pump project, students were challenged to design a prototype using a STEM approach that was adapted to their local environment for practical use in everyday life. The 16 students were divided into six groups, each consisting of two to three members. Each group presented its design, constructed a prototype based on that design, and conducted on-site testing at the school to measure the volume of water flow generated by the non-electric water pump.

The study methodology will consist of three main phases: preparatory, data collection, and data analysis. The preparation phase involved conducting a literature review and designing the research framework. The data collection phase focused on gathering information during STEM learning activities through a project on non-electric water pumps.

Data were collected and analysed using multiple qualitative techniques, including classroom observations, document analysis (such as lesson plans and student worksheets), and audio or video recordings of classroom activities. To ensure credibility and triangulation of findings, each data source was cross-referenced and analysed using thematic analysis techniques. The analysis procedure in the didactic design study comprised three stages: (1) pre-instructional analysis, which examined the anticipated didactic situation based on lesson plans and teacher intentions; (2) instructional analysis, which focused on real-time classroom interactions, student responses, and teaching strategies during the STEM project; and (3) post-instructional analysis, which evaluated learning outcomes, student reflections, and teacher feedback to identify discrepancies or alignments with the intended design. The instruments included an observation protocol emphasizing critical thinking indicators, which was validated through expert review and pilot-tested to ensure clarity and relevance to the research objectives.

Before analysing students' critical thinking activities, the researcher transcribed all learning recordings using instant transcripts produced by observers on observation sheets, together with audio and video recordings of the lessons. Students' critical thinking activities, based on Paul and Elder's eight essential indicators of thinking (2006), were then analysed using *Transcript-Based Lesson Analysis* (TBLA).

Table 1. STEM Analysis of the Non-Electricity Water Pump Project.

Science	Technology
- Factual (Pressure application in liquid substances) - Conceptual sciences 1. Pressure in substances. 2. Capillarity 3. Gravitational & potential energy 4. Alternative energy 5. Energy transformation	1. Internet for searching information related to non-electricity water pump technology. 2. Computer for creating tables or charts or diagrams of observations and reports on the construction of non-electricity water pump
Engineering	**Mathematics**
1. Designing a prototype of a non-electricity water pump 2. Building a prototype of a non-electricity water pump 3. Conducting testing of the prototype of a non-electricity water pump 4. Evaluating the prototype of a non-electricity water pump	1. Calculating the scale and dimensions of the non-electricity water pump 2. Measuring the height of the water source 3. Creating a graph depicting the relationship of dimensions of the non-electricity water pump

Result

This results section presents an integrated and comprehensive analysis derived from multiple data sources, including systematic observations, document analyses, and detailed audio and video recordings. Quantitative data on the frequency of critical thinking indicators were complemented by qualitative insights that illuminated the processes underlying critical thinking. These converging strands of evidence collectively provided a robust foundation for understanding the complex and dynamic nature of learning outcomes within authentic, contextually grounded STEM education.

A key contextual issue in STEM learning is water scarcity, which is closely connected to the students' environment. In particular, it reflects the challenge of accessing clean water faced by residents living near river streams in Sumedang. This issue is highly relevant for integration with technological applications. Moreover, the topic of pressure intersects with related disciplines such as mathematics, engineering, and technology. Figure 2 shows the STEM project process carried out by students.

Figure 2. Students conducting testing of the non-electricity water pump they have built using the STEM approach.

The critical thinking skills outcomes from STEM learning through the non-electric water pump project are classified according to Paul and Elder's eight indicators, as shown in Figure 3.

The most frequently observed indicator was asking questions, with students posing a total of 203 questions during the learning process. These questions were categorised, based on Paul and Elder's Universal Intellectual Standards (2006), into four sub-indicators: asking questions clearly (2a), asking questions relevantly (2b), asking deep questions (2c), and asking questions from different perspectives (2d). Among these, the most frequent was asking questions clearly (2a), with 79 occurrences, followed by asking questions from different perspectives (2d), which occurred 37 times. Most of the questions posed by students were directed towards their peers during the group discussion phase, particularly when determining the design of the non-electric water pump.

G: *Once you're done, let's chat about how to solve the problems in the workbook, alright? S2: Oh, this one... So, is Sumedang mostly flat or mountainous?*

S3: *Mostly highlands*

S2: *Oh, so if people have difficulty getting water, is it because Sumedang's city. topography is mostly highlands.*

S3: *Yeah, that's right. Write that down.*

S2: *How does it work then? So, the water is pumped from the source using that pump, is*

that the solution?

S3: *Yep.*

The second most frequently observed indicator was indicator 6, *conveying assumptions to form perspectives*, with a total of 148 instances. Within this indicator, the most frequent sub-indicator was 6a, *clearly conveying assumptions about agreement or disagreement*, which occurred 84 times. The distribution of sub-indicator 6a is presented in the graph below.

Based on the analysis of sub-indicator 6a, it first appeared at learning index 28 and reached its peak at learning index 325. Learning index 28 corresponds to the phase in which the teacher reviewed the design of the non-electricity water pump, while index 325 coincided with the testing of the constructed device. During this phase, group discussions stimulated students to convey more assumptions. This contrasts with the first meeting, where the occurrence of sub-indicator 6a was not tied to the learning phase but rather to opportunities provided by the teacher or peers to express opinions clearly. In the second meeting, however, the frequency of sub-indicator 6a increased during experiment- or testing-related discussions. This pattern suggests that experimental or testing phases encouraged students to think more critically when conveying data from their experiments. An example of sub-indicator 6a can be seen in the dialogue from Group Discussion 1 during the testing of the non-electricity water pump.

S2: *So, it's 'cause the load was too heavy and the air tank sprung a leak.*

S3: *Yeah, spot on. It leaked 'cause I messed up installing the gear. Should've done it right* *to avoid leaks. Made a mistake with it this morning.*

S3: That's why the pump didn't work.

S2: Yeah, wrong installation.

Based on the analysis of critical thinking skills across the indicators in STEM learning through the construction of a non-electricity water pump, the least frequently observed indicator was *setting goals*.

This indicator comprises two sub-indicators from the Universal Intellectual Standards: (1a) clearly stating learning objectives and (1b) stating objectives relevant to the problem. Clear communication of objectives refers to articulating the overall project aim, namely solving the water problem, whereas relevant communication denotes students expressing the objectives of specific learning activities in relation to the problem presented by the teacher during the learning process.

Analysis of the occurrence of the *communicating goals* indicator revealed that students paid limited attention to articulating objectives. They rarely expressed either the general project goals or the specific activity objectives unless explicitly prompted during group discussions. Descriptive analysis of the STEM learning project on constructing a non-electricity water pump further indicated that the most frequently demonstrated critical thinking skills were posing questions, presenting assumptions, and open-mindedness, whereas the least frequently observed was communicating learning objectives or project completion goals.

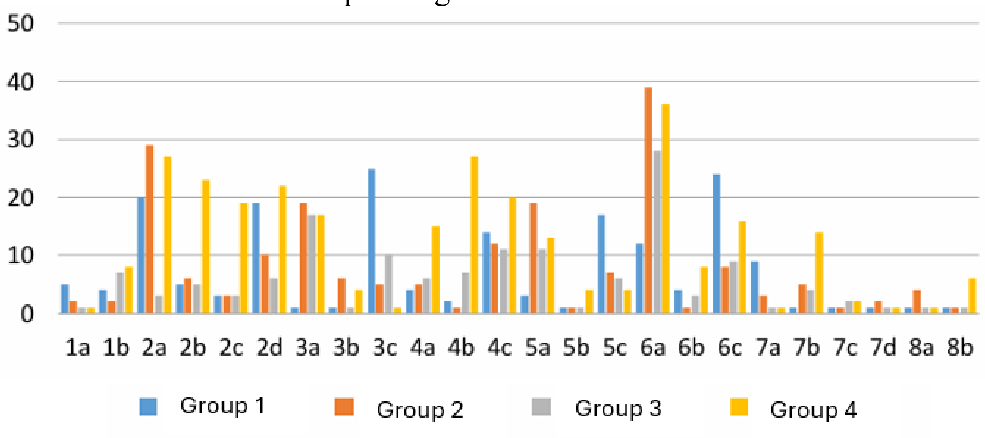

Figure 3. Graph of students' critical thinking skills outcomes over 1 semester of project work.

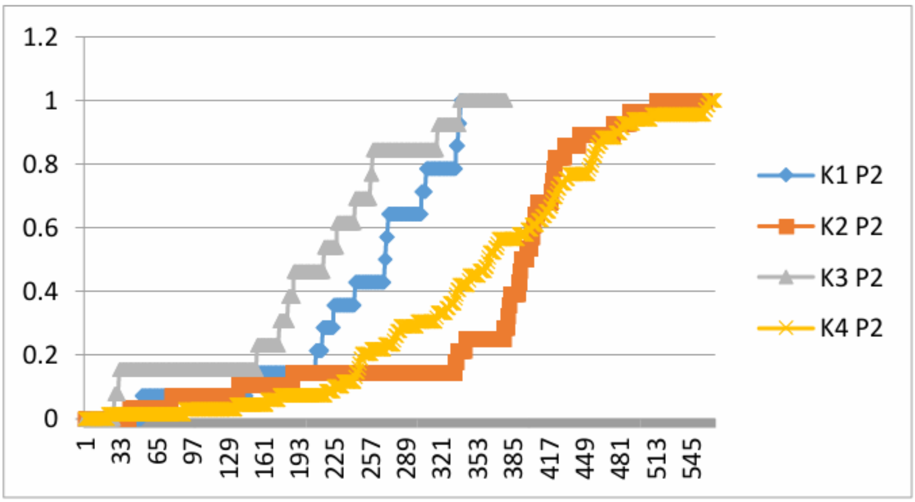

Figure 4. The Frequency of Sub-indicator "Conveying Assumptions" in the Learning Index.

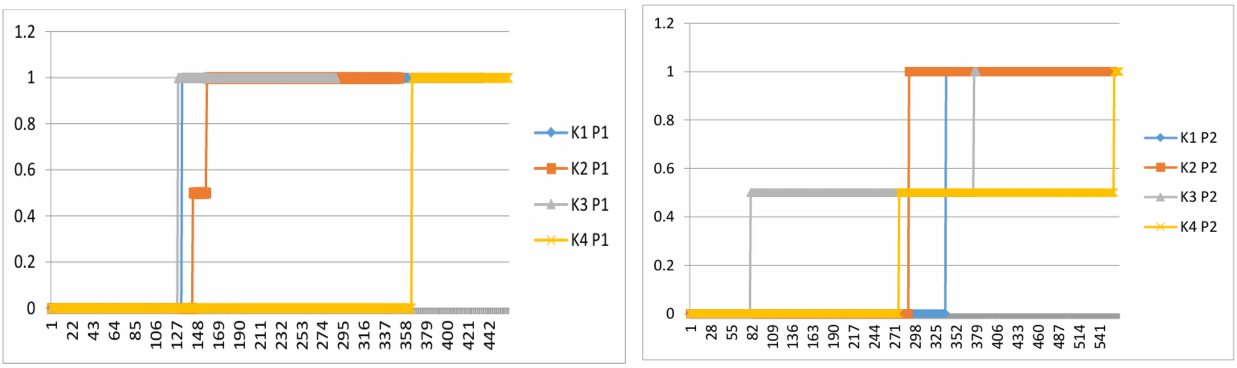

Figure 5. The Occurrence of Sub-indicators Communicating Problem-Solving Goals and Communicating Learning Objectives.

Discussion

An analysis of the frequency and distribution of critical thinking indicators in the STEM learning project on constructing a non-electric water pump revealed that their occurrence was influenced by the stages of STEM activities. In the initial meeting, when students identified fundamental questions related to real-life issues such as water scarcity in Sumedang Regency, there was a marked increase in questioning, with this indicator appearing 203 times—significantly more than any other. During subsequent group discussions on designing a non-electric water pump to address water scarcity, the indicator *identifying and explaining concepts* occurred 124 times, reflecting students' efforts to discuss and clarify relevant operational principles.

This frequent occurrence highlights students' active involvement in conceptualising and clarifying technical aspects of the project. Document analyses of group notes and design sketches revealed iterative refinements of understanding, corroborating the quantitative data and demonstrating cognitive engagement beyond simple indicator counts. Triangulating findings across multiple data sources thus enriches interpretation, offering a more holistic account of how students' critical thinking skills develop in authentic STEM learning contexts.

The initial stages of the non-electric water pump project demonstrated promising outcomes in the development of students' critical thinking skills. As they addressed the real-world issue of water scarcity and engaged in the design and implementation of prototypes, students not only applied STEM knowledge but also refined their critical thinking abilities (Stembridge Labs, 2023). Beyond the high frequency of questioning and concept clarification, their engagement in the project also led to frequent demonstrations of problem-solving and decision-making skills (Husain, 2023). The collaborative nature of the project, in which students worked in groups to present designs and conduct on-site testing, provided multiple opportunities to analyse problems, evaluate alternatives, and make informed decisions (Golden, 2023; Nguyen & Habók, 2023)

In addition, students' immersion in the socio-economic realities of their local community encouraged them to reflect on the ethical and environmental implications of their designs (Golden, 2023). This holistic approach to STEM learning not only deepened their understanding of the practical applications of STEM concepts but also fostered a sense of responsibility and awareness of the broader consequences of their work, aligning with the objectives of contextual STEM education (Castle et al., 2024). As the project progresses, it will be important to continue monitoring the development of students' critical thinking skills and to investigate how these are translated into their problem-solving approaches (Karampelas, 2023). Such monitoring can provide valuable insights into the transformative potential of contextual STEM learning in cultivating well-rounded, socially conscious individuals with strong critical thinking abilities (Asher et al., 2023).

The iterative process of testing and redesigning the non-electric water pump project actively engaged students in systematically collecting and analysing experimental data. This engagement extended beyond data gathering to encompass higher-order cognitive activities such as hypothesis formulation, developing assumptions, and reflective evaluation of observed results (Totten et al., 2020). Tasks such as observing, recording data, and repeatedly evaluating test outcomes provided students with opportunities to strengthen their data interpretation and causal reasoning skills, which are key indicators of critical thinking ability.

Observational data from the first and second sessions demonstrated a consistent frequency of these activities, revealing a clear pattern closely aligned with the structured sequence of learning tasks. This indicates that the emergence of critical thinking indicators was not incidental but was strongly shaped by the design and sequencing of authentic learning experiences (Kamarrudin et al., 2023). In other words, critical thinking skills developed through dynamic interactions between learners and a well-structured, contextually relevant learning environment.

The teacher's role in this context was pivotal, functioning as both facilitator and scaffold provider (Patel & Johnson, 2023). Through structured guidance, the teacher supported students in managing complex information and directed their thought processes from basic data collection towards deeper analysis and evidence-based decision-making (Vance et al., 2016). The observed pattern of critical thinking development further highlights the importance of sustained, inquiry-based, and contextually grounded learning experiences (Lacrin, 2021). The emergence of these skills varied according to the learning phase, individual characteristics, and group dynamics (Karampelas, 2023). Contextual STEM learning is specifically designed to strengthen students' life skills for global competition in the twenty-first century by equipping them to solve everyday problems effectively (Saleh et al., 2023). Findings from this study's STEM learning project may therefore offer valuable guidance for teachers in developing a more meaningful science education curriculum for the future.

Conclusion

The design of STEM learning with the theme of non-electric water pumps is characterised by the use of contextual problems drawn from students' daily lives, particularly the issue of water scarcity in Sumedang Regency. This approach fosters a deeper understanding and application of knowledge gained in classroom discussions. The stages of prototype design and experimentation further promote active engagement in practical problem-solving, enabling students to achieve a more comprehensive grasp of concepts. Frequent group discussions also create opportunities for the emergence of critical thinking indicators essential to students' holistic development. The development of these skills is influenced by learning phases, individual characteristics, and group dynamics, all of which are integral aspects of STEM education. Moreover, teacher instructional practices play a crucial role; the findings and discussions arising from this project should encourage teachers to reflect on their methods and to train students more effectively to solve everyday problems critically and innovatively.

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