



HCI-Informed STEM Mini-Projects for Critical Thinking in Technology-Enhanced Learning

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Abstract

Developing critical thinking in technology-enhanced learning requires more than access to digital platforms; it also depends on how students interact with digital environments while engaging in authentic problem solving. This study examined changes in students' critical thinking following participation in HCI-informed STEM mini-project learning that integrated usability, interactivity, and user experience into Learning Management System (LMS)-supported activities. A quantitative pre-experimental one-group pretest-posttest design was employed with undergraduate Science Education students. Critical thinking was assessed using an essay-based test covering interpretation, analysis, evaluation, inference, and explanation. The findings showed an overall improvement in critical thinking performance following the learning activities, with the magnitude of improvement varying across students. The STEM mini-projects engaged students in problem analysis, solution design, prototyping, testing, evaluation, and scientific explanation, while HCI principles supported their interaction with the digital learning environment. These findings provide preliminary empirical support for integrating HCI considerations into LMS-supported STEM mini-project learning as a promising approach to facilitating critical-thinking processes. However, because the study did not include a comparison group and HCI dimensions were not independently measured, the observed improvement cannot be attributed specifically to the HCI-informed approach. Further controlled studies are needed to establish its effectiveness and clarify the contribution of individual HCI dimensions.

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INTRODUCTION

Technology-enhanced learning has increasingly transformed higher education by providing flexible and digitally mediated environments for teaching and learning (Sailer et al., 2024). Learning Management Systems (LMS) in particular facilitate access to learning resources, communication, collaboration, and learning activities beyond the physical classroom. These capabilities are particularly pertinent to the development of twenty-first-century competencies, such as critical thinking, collaboration, and problem-solving, which necessitate that students actively process information, evaluate alternatives, and apply knowledge to authentic scenarios (AlZahrani & AlOtaibi, 2024). However, the availability of an LMS does not necessarily result in interactive or student-centered learning (Simon et al., 2025). Digital learning activities may remain focused on

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content delivery, while opportunities for meaningful discussion, collaborative problem solving, and active knowledge construction remain limited (Xing et al., 2025). When students primarily access materials and submit assignments without engaging in sustained interaction, they may have fewer opportunities to connect theoretical concepts with authentic problems. Therefore, the effectiveness of technology-enhanced learning depends not only on the availability of digital platforms but also on how learning activities and interactions are designed within those platforms.

STEM (Science, Technology, Engineering, and Mathematics) education provides a potentially suitable approach for addressing these challenges because it engages students in interdisciplinary problem-solving and the application of knowledge to authentic contexts (Alkair et al., 2023; Chang & Yen, 2023; Chen et al., 2024; Zhou et al., 2025). STEM learning requires students to integrate concepts from multiple disciplines, analyze problems, develop solutions, and evaluate the feasibility of their designs (ÖZKUL, 2025; Pinar et al., 2025; Recabarren et al., 2025). Project-based STEM learning, in particular, has been associated with opportunities for students to develop critical thinking and problem-solving skills through iterative processes of investigation, design, testing, and evaluation (Alkair et al., 2023; Chang & Yen, 2023; Chen et al., 2024; Zhou et al., 2025).

Nevertheless, implementing STEM projects in a digital environment presents an additional challenge: students need to interact not only with the learning content and their peers but also with the digital system through which learning activities are organized. Human-Computer Interaction (HCI) offers a useful perspective for addressing this issue by emphasizing the quality of interaction between users and digital systems. In educational settings, principles such as usability, interactivity, and user experience can inform the design of digital learning environments and potentially reduce interaction barriers that interfere with students' engagement in learning activities (da Silva Junior et al., 2026; Lehong et al., 2024; Tomitsch et al., 2021; Womser-Hacker, 2024). Thus, integrating HCI principles into STEM mini-project activities may provide a way to connect the pedagogical affordances of STEM project learning with the interactional requirements of technology-enhanced learning.

Although previous studies have examined project-based STEM learning, digital learning environments, and HCI-related principles, these strands of research have largely been investigated separately. Studies on STEM project-based learning have primarily examined students' learning outcomes and problem-solving processes, with recent systematic and meta-analytic evidence indicating that problem- and project-based learning can support higher-order and critical thinking (Loyens et al., 2023; Santhosh et al., 2023; Zhang et al., 2024). In contrast, research on digital learning and HCI has focused more strongly on interaction, usability, engagement, and user experience (Almusharraf, 2024; Grierson et al., 2024; Lehong et al., 2024). Lehong et al. (2024), for example, emphasized the importance of usability requirements and students' needs in the design of learning management systems, suggesting that digital environments should function as interactive components of learning rather than merely as repositories for instructional materials. Consequently, limited empirical evidence is available on how HCI principles can be explicitly incorporated into STEM mini-project activities and how such an integrated learning approach relates to changes in students' critical thinking performance. This gap is particularly relevant in technology-enhanced higher education, where the digital environment is not merely a medium for delivering project instructions but also a space in which students communicate, collaborate, make design decisions, and document their learning processes.

To address this gap, this study implements an HCI-informed STEM mini-project-based learning approach in a technology-enhanced learning environment. The approach integrates usability, interactivity, and user experience into LMS-supported STEM mini-project activities. This study aims to examine changes in students' critical thinking performance following participation in the approach, focusing on pretest-posttest differences and the magnitude of learning improvement.

METHOD

Research Design

This study employed a quantitative pre-experimental approach employing a one-group pretest-posttest design to investigate alterations in students' critical thinking performance following participation in HCI-informed STEM mini project-based learning. The design involved a single cohort

of students who administered a critical thinking pretest prior to the learning intervention and an equivalent posttest following the intervention. The disparities between pretest and posttest scores were subsequently analyzed to ascertain the magnitude of change in students' critical thinking performance. Notably, the absence of a control or comparison group precludes the sole attribution of observed changes to the HCI-informed STEM mini project-based learning approach.

Participant and Learning Context

The participants were 103 undergraduate students enrolled in the Science Education Program during the second semester of the 2025/2026 academic year. The participants were selected from three class groups, consisting of 35 students in Class A, 34 students in Class B, and 34 students in Class C. Purposive sampling was employed to select these class groups based on the following criteria: (1) The classes were enrolled in a foundational science course that serves as a prerequisite for subsequent courses, necessitating students to possess fundamental science concepts. (2) The course was offered at the commencement of the second semester of the 2025/2026 academic year. (3) The students had not previously participated in learning utilizing the HCI-informed STEM mini-project approach.

The learning activities were conducted in a technology-enhanced learning environment utilizing SiDia as the Learning Management System (LMS). The platform facilitated the distribution of learning materials and project guidelines, facilitated group discussions and communication, and collected mini-project assignments. The three class groups were taught by the same instructor and followed the same learning materials, instructional procedures, duration, and LMS implementation. Consequently, the instructional conditions were maintained consistency across the three class groups. The learning activities integrated HCI-informed STEM mini-projects with LMS-supported interaction, discussion, collaboration, project development, and submission.

Research Procedure

The research procedure was conducted over six weeks in six instructional sessions, with each session lasting approximately 100 minutes. The procedure was implemented sequentially across the three class groups, which followed the same learning materials, instructional procedures, duration, and LMS implementation. The activities consisted of four main stages: (1) pretest administration, (2) implementation of HCI-informed STEM mini-projects, (3) project-based learning and interaction activities, and (4) posttest administration. Figure 1 presents the workflow of the HCI-informed STEM mini-project-based learning approach, including the pretest, LMS-supported project activities, collaborative interaction, and posttest administration.

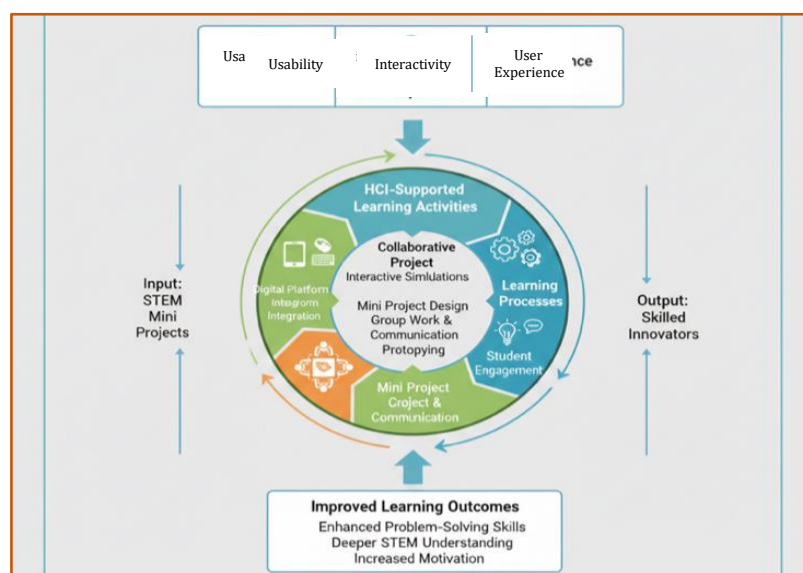


Figure 1. Workflow of HCI-Informed STEM Mini Project-Based Learning in a Technology-Enhanced Learning Environment

Figure 1 illustrates the overall workflow of the HCI-informed STEM mini-project-based learning approach. The framework positions usability, interactivity, and user experience as HCI principles that support the implementation of STEM mini-projects through a digital learning platform. The workflow connects STEM mini-project inputs with HCI-supported learning activities, including collaborative project interaction, project design, group work and communication, digital platform integration, and mini-project development and communication. These activities are intended to support learning processes such as problem solving, student engagement, and collaborative project development, leading to improved learning outcomes.

Stage 1: Pretest Administration. At the beginning of the learning sequence, students completed a critical thinking pretest to establish their baseline performance before participating in the HCI-informed STEM mini-project activities. The pretest measured five critical-thinking skills: interpretation, analysis, evaluation, inference, and explanation.

Stage 2: Implementation of HCI-Informed STEM Mini Projects. Following the pretest, students were organized into project groups. Different groups were assigned different mini-project topics, allowing students to address varied authentic problems while following the same overall project-based learning procedures. The mini-project topics included a water-level indicator, a simple earthquake alarm, electrical energy generation using lime fruit, an automatic plant watering system, a solar-powered fan, a motion-sensor lamp, and a water turbine for lighting an LED. The projects were designed to integrate science, technology, engineering, and mathematics concepts and were implemented according to the principles of usability, interactivity, and user experience. Project guidelines, learning resources, communication, and assignment submission were facilitated through the SiDia LMS.

Stage 3: Project-Based Learning and Interaction Activities. During the project implementation, students worked collaboratively through a sequence of problem identification and analysis, solution planning, design development, prototyping, testing, presentation, and reflection. Although project topics differed among groups, the learning objectives, instructional procedures, project stages, assessment criteria, duration, and LMS-supported learning processes were kept consistent across groups. The SiDia LMS supported interaction among students and between students and the instructor through discussion and communication features, as well as the documentation and submission of project work. HCI principles were incorporated by emphasizing ease of use, opportunities for interaction and feedback, and consideration of users' needs and experiences when developing and refining project solutions.

Stage 4: Posttest Administration. After completion of the mini-project activities, students completed a posttest measuring the same five critical-thinking skills assessed in the pretest. The posttest was designed to be comparable to the pretest in terms of the assessed indicators and level of difficulty. Pretest and posttest scores were subsequently compared to examine changes in students' critical-thinking performance following participation in the learning activities.

Research Instrument

The research instrument was an open-ended critical thinking test designed to assess students' critical thinking skills in the context of STEM mini-projects. The instrument consisted of 10 essay items developed based on five core critical thinking skills adapted from Facione's framework: interpretation, analysis, evaluation, inference, and explanation (Facione, 2013). These five skills were operationalized into the assessment items to measure students' abilities to identify and clarify relevant information, analyze relationships among evidence and variables, evaluate claims or solutions, draw evidence-based conclusions, and provide logical and scientific explanations.

The assessment items were contextualized within STEM mini-project problems, including an automatic plant-watering system, automatic street lighting, an automatic earthquake detector, a solar-powered fan, an automatic door, and a mini hydropower system. The items required students to interpret information, analyze experimental data, evaluate solutions and claims, infer conclusions from data patterns, and explain proposed solutions using scientific reasoning.

Each student response was scored using an item-specific analytic scoring rubric ranging from 0 to 4. The scoring criteria were developed according to the critical thinking skill targeted by each item. A score of 4 represented a complete response that fulfilled the specified criteria, whereas lower scores indicated progressively limited fulfillment of the criteria. A score of 0 was assigned to

responses that were absent, irrelevant, or inconsistent with the information provided. For example, in the inference items, a score of 4 required students to draw an appropriate conclusion and use at least two relevant data points as evidence. The total score was subsequently converted to a 0–100 scale, with higher scores indicating better critical thinking performance. The correspondence between the critical thinking skills and the assessment items is presented in Table 1.

Table 1. Correspondence between Critical Thinking Skills and Assessment Items

Critical Thinking Skill	Item Numbers	Representative Assessment Focus
Interpretation	1–2	Identifying and clarifying relevant information needed to understand a problem
Analysis	3–4	Analyzing relationships among information, evidence, and variables
Evaluation	5–6	Evaluating the adequacy of evidence and the feasibility of proposed solutions
Inference	7–8	Drawing conclusions based on evidence and patterns in data
Explanation	9–10	Proposing solutions and providing scientific and logical justification

Data Analysis

Data were analyzed using descriptive and inferential statistics. Descriptive statistics were used to summarize students' pretest and posttest scores, including the mean and standard deviation. The normality of the score distributions was examined using the Shapiro–Wilk test. Because the data did not meet the assumption of normality, differences between pretest and posttest scores were examined using the Wilcoxon signed-rank test. The statistical significance level was set at $\alpha = .05$.

Normalized Gain (N-gain)

Normalized gain (N-gain) was calculated to describe the magnitude of improvement achieved by each student relative to the maximum possible improvement from their individual pretest score. Unlike the Wilcoxon signed-rank test, which evaluates whether the paired pretest and posttest scores differ statistically, N-gain provides a descriptive measure of the proportion of the possible score improvement achieved by each student. Rank-biserial correlation was used separately to quantify the magnitude of the paired pretest–posttest difference. Thus, these analyses provide complementary information regarding statistical significance, relative learning gain, and effect size. N-gain was calculated at the individual-student level using the following equation (Hake, 1998) in equation (1):

$$g = \frac{\text{posttest} - \text{pretest}}{\text{maximum score} - \text{pretest}} \quad (1)$$

The interpretation criteria for the normalized gain (N-gain) are as follows:

$g < 0.30$: Low improvement
 $0.30 \leq g < 0.70$: Moderate improvement
 $g \geq 0.70$: Great improvement

Effect Size (Rank-Biserial Correlation)

The effect size was estimated using rank-biserial correlation (r), an appropriate measure for the Wilcoxon signed-rank test (Kerby, 2014) in equation (2):

$$r = 1 - \frac{2W}{n(n+1)} \quad (2)$$

where W is the Wilcoxon test statistic and n is the number of paired observations.

Interpretasi *effect size*:

$r \approx 0.10$: Small effect
 $r \approx 0.30$: Medium effect
 $r \geq 0.50$: Large effect

RESULTS AND DISCUSSION

Changes in Students' Critical Thinking Performance

The descriptive analysis showed an increase in students' critical thinking scores from pretest to posttest. The mean pretest score was 66.93 (SD = 4.82; median = 70.00; IQR = 7.00), whereas the mean posttest score increased to 78.17 (SD = 5.27; median = 80.00; IQR = 5.50). Thus, the mean score increased by 11.24 points between the two assessments. These descriptive results indicate a positive change in students' critical thinking performance following participation in the learning activities. Table 2 presents the descriptive statistics of students' critical thinking scores, including the mean, standard deviation, median, and interquartile range for the pretest and posttest assessments.

Table 2. Descriptive Statistics of Students' Critical Thinking Scores

Assessment	N	Mean	SD	Median	IQR
Pretest	103	66.93	4.82	70.00	7.00
Posttest	103	78.17	5.27	80.00	5.50

Because the Shapiro–Wilk test indicated that the score distributions did not meet the normality assumption, a Wilcoxon signed-rank test was used to examine the difference between pretest and posttest scores. The analysis indicated a statistically significant difference between the two assessments, $W = 4,950$, $z = 8.638$, $p < .001$. The corresponding rank-biserial correlation was $r_{rb} = 1.000$, indicating a very large magnitude of the paired difference. These results indicate that students' critical thinking scores were substantially different at posttest compared with pretest. However, because the study employed a one-group pretest–posttest design without a comparison group, the observed change cannot be attributed solely to the HCI-informed STEM mini-project approach.

Normalized Gain

Individual normalized gain scores were calculated to further describe the magnitude of improvement in students' critical thinking performance relative to the maximum possible improvement. The mean N-gain was 0.319 (SD = 0.204; median = 0.333), with individual values ranging from 0.000 to 0.750. Based on the classification used in this study, the mean N-gain falls within the moderate-gain category. The distribution of students across the N-gain categories is presented in Table 3.

Table 3. Distribution of Students by N-gain Category

N-gain Category	n	Percentage
Low ($g < 0.30$)	50	48.5%
Moderate ($0.30 \leq g < 0.70$)	46	44.7%
High ($g \geq 0.70$)	7	6.8%
Total	103	100%

The distribution shows that 50 students (48.5%) were classified as having low gain, 46 students (44.7%) as having moderate gain, and 7 students (6.8%) as having high gain. Although the mean individual N-gain was within the moderate category, the distribution indicates considerable variation in the extent of improvement among students.

Figure 2 further illustrates the distribution of individual N-gain scores in relation to students' pretest scores. The variation in gain scores indicates that students did not experience the same magnitude of improvement. Students with higher pretest scores generally had less room for improvement, whereas students with lower initial scores had greater potential for normalized gain. This pattern is also related to the mathematical properties of the normalized-gain calculation, in which the available room for improvement decreases as the pretest score approaches the maximum score. Therefore, the pattern shown in Figure 2 should be interpreted descriptively and should not be taken as evidence that students with lower initial scores necessarily benefited more from the learning approach.

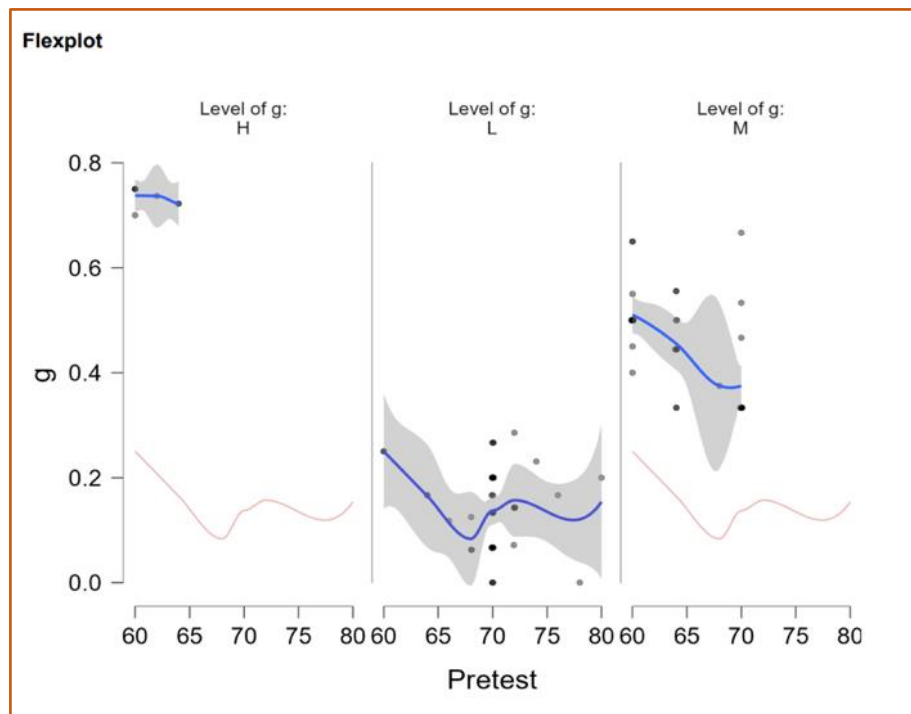


Figure 2. Distribution of Individual Normalized Gain (g) According to Students' Pretest Scores and Gain Categories

The findings indicate an overall improvement in students' critical thinking performance following participation in the HCI-informed STEM mini-project learning activities. The mean score increased from 66.93 in the pretest to 78.17 in the posttest, with a statistically significant difference based on the Wilcoxon signed-rank test ($p < .001$). The mean individual N-gain of 0.319 indicated a moderate level of improvement. However, the distribution of N-gain scores showed variation among students, with 48.5% classified as low gain, 44.7% as moderate gain, and 6.8% as high gain. Thus, the findings indicate an overall improvement in critical thinking performance, although the magnitude of improvement varied across students.

One possible explanation for this improvement is the alignment between the cognitive demands of the STEM mini-project activities and the critical-thinking skills assessed in this study (Duran & Dökme, 2016; Guzey et al., 2016). Students were required to identify relevant information, analyze problems and evidence, evaluate possible solutions, draw inferences from observations or testing results, and explain the reasoning underlying their designs. These activities correspond to the five assessed critical-thinking indicators: interpretation, analysis, evaluation, inference, and explanation (Loyens et al., 2023; Osborne, 2014; Shaw et al., 2020). The mini-project activities therefore provided opportunities for students to practice cognitive processes directly represented in the assessment (Bellaera et al., 2021; Stroupe, 2015).

The findings also provide preliminary support for the practical implementation of the proposed HCI-informed STEM mini-project framework. HCI was incorporated into the technology-enhanced learning environment through the principles of usability, interactivity, and user experience, rather than being treated as a separate instructional activity (Conway-Smith & West, 2025; da Silva Junior et al., 2026; Ogunyemi et al., 2019). SiDia was used to provide project guidelines and learning resources, facilitate communication and discussion, and support project submission and documentation. Thus, the framework connects the pedagogical structure of STEM mini-project learning with considerations of interaction within the digital learning environment (Borck, 2020). Figure 3 illustrates how these HCI considerations were implemented in the LMS-supported learning environment.

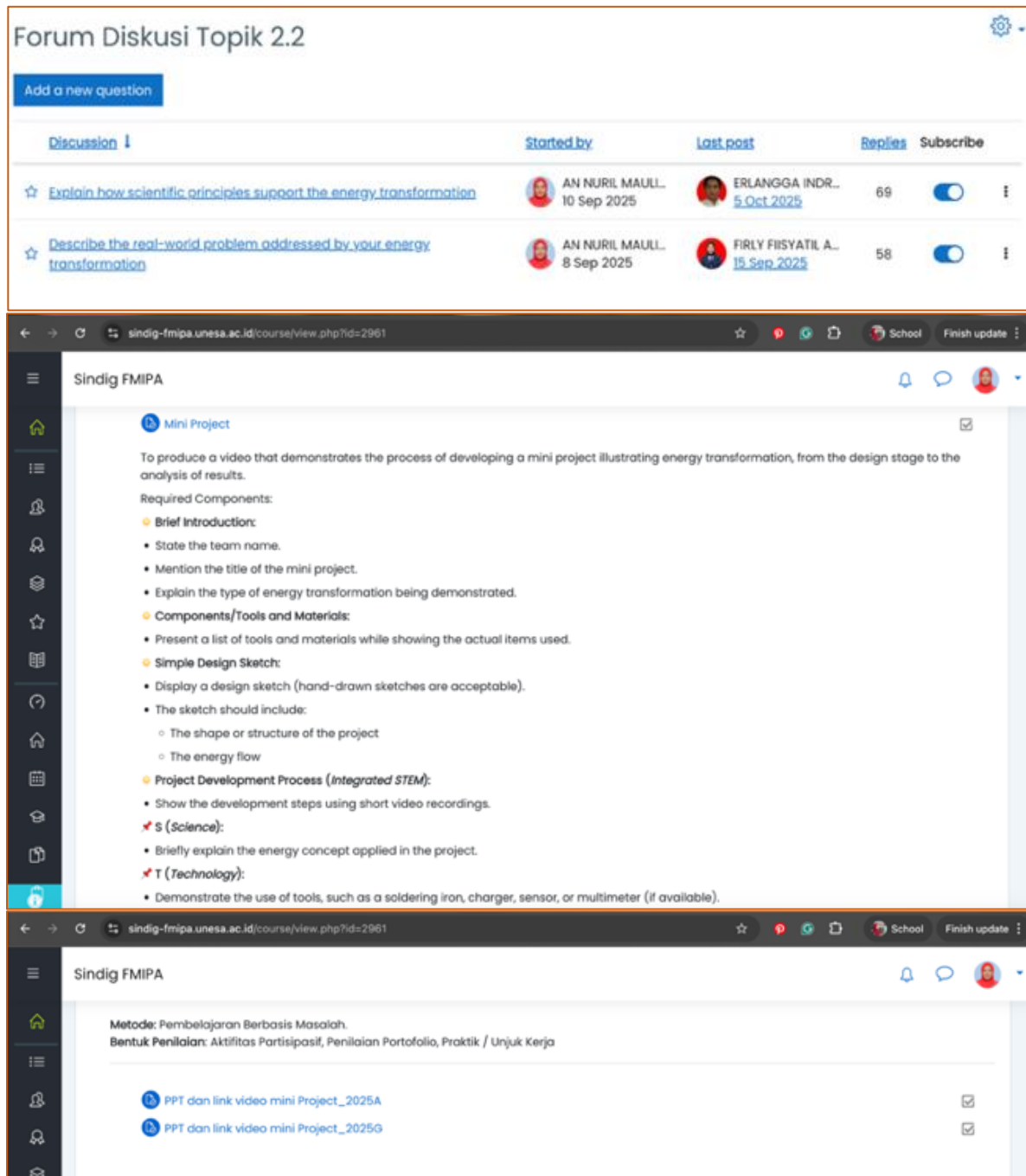


Figure 3. HCI Principles, Particularly Usability, Interactivity, and User Experience in SiDia

Figure 3 illustrates how the three HCI principles were incorporated into the LMS-supported STEM mini-project process. Usability was represented through access to learning materials, project guidelines, and assignment submission features, which enabled students to access and manage project-related information within the LMS. Interactivity was represented through discussion and communication features that supported the exchange of ideas and coordination during project development (Cooksey & McDonald, 2019). User experience was addressed by integrating project guidelines, communication, documentation, and submission within a connected digital workflow (Rajaram, 2023).

The mini-project design sketch shown in Figure 4 illustrates the application of these learning activities in the development of STEM solutions. Students worked collaboratively through problem analysis, conceptual design, prototyping, testing, and refinement (Kim, 2021). Thus, the LMS served not only as a repository for learning materials but also as a digital environment that supported interaction and project-based learning activities (Tsai & Tang, 2017).

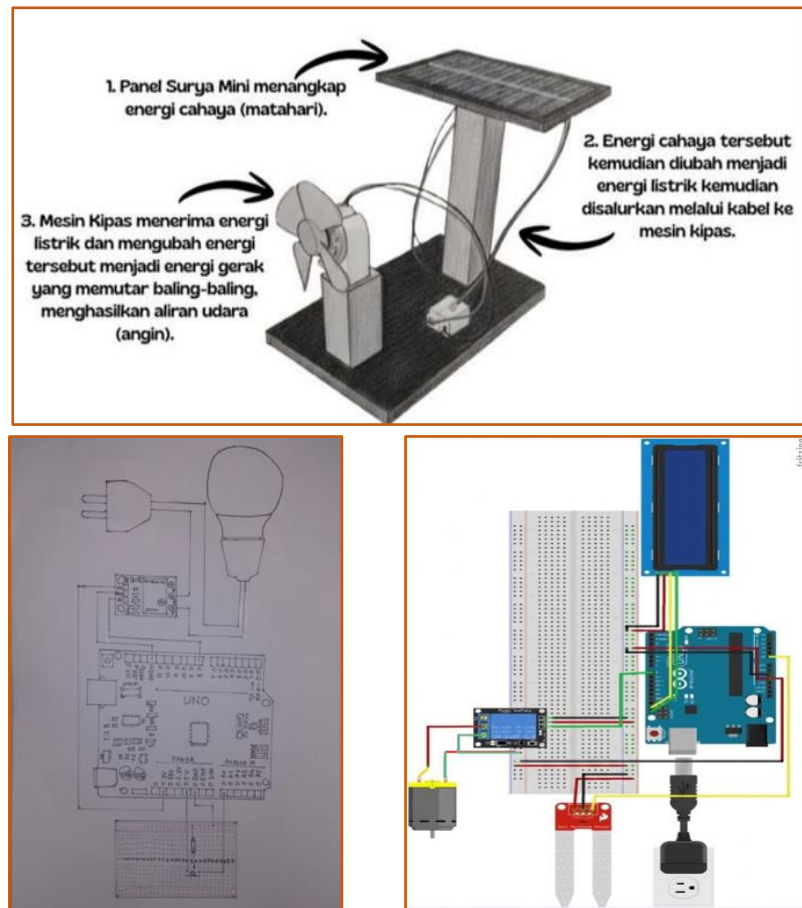


Figure 4. Example of a STEM Mini-Project Design Developed by Students

Figure 4 shows an example of the mini-project design developed by students. The design process involved problem analysis, conceptual design, prototyping, testing, and refinement. These activities provided opportunities for students to apply science, technology, engineering, and mathematics concepts while engaging in critical-thinking processes such as analysis, evaluation, inference, and explanation (Septiyanto et al., 2025).

This integration suggests that HCI can serve as a complementary design perspective for implementing STEM mini-project learning in a technology-enhanced environment. However, the observed improvement cannot be attributed specifically to HCI because the intervention simultaneously involved STEM mini-project learning, LMS-supported interaction, collaborative activities, and HCI-informed design principles. Furthermore, usability, interactivity, and user experience were not directly measured using dedicated instruments. Therefore, the findings support the feasibility and pedagogical rationale of the proposed framework, but do not establish the independent contribution of HCI to changes in critical thinking.

Overall, the findings suggest that the HCI-informed STEM mini-project approach has potential as an integrated instructional approach for technology-enhanced learning. The observed improvement in critical thinking, together with the implementation of usability, interactivity, and user-experience considerations within the LMS-supported project process, provides preliminary empirical and practical support for the proposed approach. However, the contribution of HCI itself cannot be determined from the present study because the HCI dimensions were not directly measured and no comparison group was included. Future research should employ comparison groups and direct measures of usability, interactivity, and user experience to examine the specific contribution of HCI and determine whether the approach provides benefits beyond conventional STEM project-based learning.

LIMITATIONS

This study has several limitations that should be considered when interpreting the findings. First, the study employed a *one-group pretest–posttest* design without a control group. Therefore, the observed improvement in students' critical thinking cannot be directly attributed solely to the implementation of *HCI-informed STEM mini-project-based learning*. The design only allows the study to describe changes in students' critical thinking performance before and after the learning intervention. Second, the study focused primarily on students' critical thinking performance and did not empirically examine other potentially relevant variables, such as learning engagement, motivation, or collaboration. In addition, the research instrument was limited to an essay-based critical-thinking test.

Most importantly, although usability, interactivity, and user experience constituted the central HCI dimensions incorporated into the proposed learning approach, these dimensions were not directly measured using dedicated empirical instruments. Consequently, the study demonstrates how HCI principles were incorporated into the LMS-supported learning activities. Still, it does not provide empirical evidence regarding the level or change of students' usability perceptions, interactivity, or user experience. Third, the study was conducted with students from the Science Education Program at a single higher-education institution with a relatively limited number of participants, which may restrict the transferability of the findings to students with different characteristics and educational contexts. Other factors, such as students' initial abilities, prior experience with LMS use, and digital technology skills, may also have influenced the learning process during the STEM mini-project implementation. Therefore, future research should employ experimental or quasi-experimental designs with comparison groups, involve larger and more diverse participant populations, and include dedicated instruments to measure usability, interactivity, and user experience empirically. Future studies could also examine additional variables, such as learning engagement, motivation, and collaboration, to provide a more comprehensive understanding of the implementation and contribution of the *HCI-informed STEM mini-project-based learning* approach in technology-enhanced learning environments.

CONCLUSION

This study indicates that the HCI-informed STEM mini-project-based learning approach has the potential to support students' critical thinking in a technology-enhanced learning environment. The findings showed an increase in students' critical thinking performance from pretest to posttest, with a statistically significant difference between the two assessments and a moderate mean individual normalized gain. The approach incorporated the HCI principles of usability, interactivity, and user experience into LMS-supported STEM mini-project activities, including access to learning resources, communication and discussion, project documentation, and assignment submission. These findings provide preliminary empirical and practical support for the implementation of the proposed HCI-informed STEM mini-project approach. However, because the study did not include a comparison group and did not directly measure usability, interactivity, or user experience, the observed improvement in critical thinking cannot be attributed specifically to HCI. Future research should employ comparison groups and dedicated instruments for measuring HCI dimensions to examine the specific contribution of HCI and the applicability of the approach across different educational contexts.

AUTHOR CONTRIBUTIONS

ANMF designed the study and led the implementation of the HCI-informed STEM mini project-based learning. TN and DA contributed to learning material development, project implementation, and data collection. MAM conducted data analysis and interpretation of the results. K provided input on instructional design and STEM–technology integration. AB critically reviewed and refined the manuscript. All authors approved the final version of the manuscript.

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