Teachers' Perceptions of Critical Thinking Development Through a Microcontroller-Based STEM Innovation Programme

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ABSTRACT

Critical thinking is a core twenty-first-century skill, yet few studies examine how it appears in students' behaviour during hands-on STEM learning from the teacher's perspective. This study examines teachers' perceptions of students' critical thinking development after participation in a microcontroller-based STEM Innovation Programme. The programme progressed from guided Arduino Uno training and a three-junction traffic-light challenge to Micro: bit and artificial intelligence activities, culminating in a group innovation project. In this quantitative descriptive survey, 15 teachers involved in or familiar with the programme completed a 21-item Likert questionnaire. The instrument showed good internal consistency (Cronbach's alpha = 0.836). Teachers rated students highly on analysis and reasoning (mean = 4.45), reflection and evaluation (mean = 4.35), and problem solving (mean = 4.30). One-sample t-tests on all 13 critical thinking items showed that every item was rated significantly above the neutral midpoint of 3.00 (all $p < .001$, Cohen's $d = 1.55–2.97$). Willingness to accept different views was rated highest ($M = 4.60$), whereas re-evaluating ideas given to new information and weighing alternative solutions were rated lowest (both $M = 4.20$), with greater variability. Given the small sample, reliance on teacher perceptions, and absence of a control group, the findings are preliminary. They suggest that progressively open-ended microcontroller projects offer authentic opportunities to practice critical thinking.

Keywords— Arduino, Critical Thinking, Microcontroller, STEM Education, Teachers' perceptions.

INTRODUCTION

The rapid advancement of digital technologies has transformed the competencies required for students to thrive in contemporary education and future careers. Beyond mastering disciplinary knowledge, learners are increasingly expected to analyse information, solve complex problems, evaluate alternative solutions, and make evidence-based decisions. These competencies are closely associated with critical thinking, which is widely regarded as a fundamental twenty-first-century skill. International educational frameworks continue to emphasise the importance of higher-order thinking abilities that enable students to reason critically, assess evidence, and respond effectively to unfamiliar and complex situations [1].

In Malaysia, strengthening higher-order thinking skills remains a key educational priority. Findings from the

Programme for International Student Assessment (PISA) 2022 Creative Thinking assessment revealed that only 54% of Malaysian students achieved at least the baseline proficiency level, while only 12% attained the highest proficiency levels [1]. Although creative thinking is distinct from critical thinking, both require learners to engage in reasoning, evaluation, reflection, and problem-solving processes. These findings highlight the need for learning environments that actively promote higher-order thinking and provide opportunities for authentic knowledge application.

STEM education has emerged as a promising approach for developing critical thinking competencies because it integrates scientific inquiry, technological applications, engineering design, and mathematical reasoning within authentic problem-solving contexts [2]. However, the effectiveness of STEM education depends not only on subject integration but also on the quality of learning experiences that require students to investigate problems, develop solutions, test ideas, and justify decisions. Recent studies have demonstrated that STEM learning approaches incorporating project-based and problem-based activities can significantly enhance students' critical-thinking skills by engaging them in authentic inquiry and decision-making processes [3][4].

Among the various pedagogical approaches, Project-Based Learning (PBL) has attracted considerable attention due to its emphasis on authentic problem solving and product development. In STEM-PBL environments, students are required to identify problems, formulate strategies, construct solutions, test outcomes, and refine their work based on feedback. These iterative processes naturally foster analysis, reasoning, evaluation, and reflection, which are essential components of critical thinking. Empirical evidence indicates that STEM integrated project-based learning can significantly improve students' critical-thinking performance, particularly when learners are engaged in sustained inquiry, collaborative problem solving, and prototype development activities [4] [5].

Microcontroller-based learning provides a particularly effective platform for implementing STEM-PBL because it enables students to integrate programming, electronics, engineering design, and computational thinking within tangible learning tasks [6] [7]. Platforms such as Arduino and Micro:bit allow learners to create functional systems while receiving immediate feedback from their designs. Unlike purely theoretical exercises, microcontroller projects require students to diagnose problems, test alternatives, modify code or hardware configurations, and evaluate outcomes. Such iterative cycles of design, testing, and refinement mirror authentic engineering practice and promote the development of critical-thinking skills through active experimentation and evidence-based decision making.

The educational value of microcontroller-based STEM learning becomes even more apparent when students engage in open-ended innovation projects. As students move beyond structured instructional activities, they are required to determine project objectives, evaluate alternative solutions, make design decisions, and assess prototype performance [8]. These experiences provide opportunities to practice different dimensions of critical thinking, including analysis and reasoning, problem solving, and reflection and evaluation. Recent research highlights that authentic, interdisciplinary, and technology-supported learning environments are particularly effective in promoting reasoning skills, critical evaluation, and higher-order thinking competencies [1] [9].

Another important factor influencing critical-thinking development is student engagement. Meaningful learning occurs when students actively participate in learning activities rather than passively receiving information. Project-based STEM environments encourage learners to collaborate, communicate ideas, take ownership of their learning, and persist when encountering challenges. Studies have shown that project-based learning is associated with increased engagement, stronger learning experiences, and enhanced critical-thinking development because students assume an active role in constructing knowledge and solving authentic problems [10][11]. Consequently, examining learning engagement alongside critical thinking behaviours provides a more comprehensive understanding of the effectiveness of STEM interventions.

Despite the growing body of research supporting STEM-based project learning, there remains a need to better understand how teachers perceive students' critical-thinking behaviours during technology-rich STEM activities. Existing studies frequently evaluate critical thinking through achievement tests, experimental designs, or pre-test and post-test assessments. While these approaches provide valuable evidence of learning outcomes, they

may not fully capture how students demonstrate critical thinking throughout the learning process. Teachers are uniquely positioned to observe students' behaviours as they analyse information, troubleshoot problems, evaluate alternatives, respond to feedback, and collaborate with peers during project implementation.

This perspective is particularly relevant within the Malaysian secondary-school context, where STEM implementation may be influenced by practical factors such as the availability of resources, facilities, and opportunities for hands-on learning. Previous research involving Malaysian STEM teachers and students identified insufficient equipment and facilities as significant barriers to effective STEM implementation in schools [12]. Consequently, examining teachers' observations of students participating in a structured microcontroller-based STEM programme may provide valuable evidence regarding the potential of such interventions to support critical-thinking development in authentic educational settings.

Therefore, this study investigates teachers' perceptions of students' critical-thinking development following participation in a microcontroller-based STEM Innovation Programme. The programme consisted of Arduino Uno training, a three-junction traffic-light challenge, Micro: bit and artificial intelligence (AI) activities, and a group innovation project themed Technology Innovation Empowers School and Communities. These activities required students to analyse problems, develop and implement solutions, troubleshoot errors, evaluate prototype performance, and refine their ideas. By focusing on teachers' observations, the study contributes to the growing literature on hands-on STEM education and provides empirical evidence of how microcontroller-based project activities may create opportunities for students to practice critical thinking within authentic school and community-oriented innovation contexts.

METHODOLOGY

This study employed a quantitative descriptive survey design to examine teachers' perceptions of students' critical thinking development following participation in a microcontroller-based STEM Innovation Programme. The study focused specifically on teachers' observations of students' thinking and problem-solving behaviors during the programme rather than attempting to directly measure students' critical thinking performance.

The use of a teacher-perception approach was appropriate because teachers were directly involved in or observed the students' participation in the STEM activities and innovation project. Their observations provided an additional perspective on how students approached problems, considered alternative solutions, evaluated their work, and reflected on the outcomes of their projects.

Figure 1 shows a Critical Thinking Framework with how datas are collected and the categories of critical thinking assessment: analysis and reasoning, problem solving and reflection.

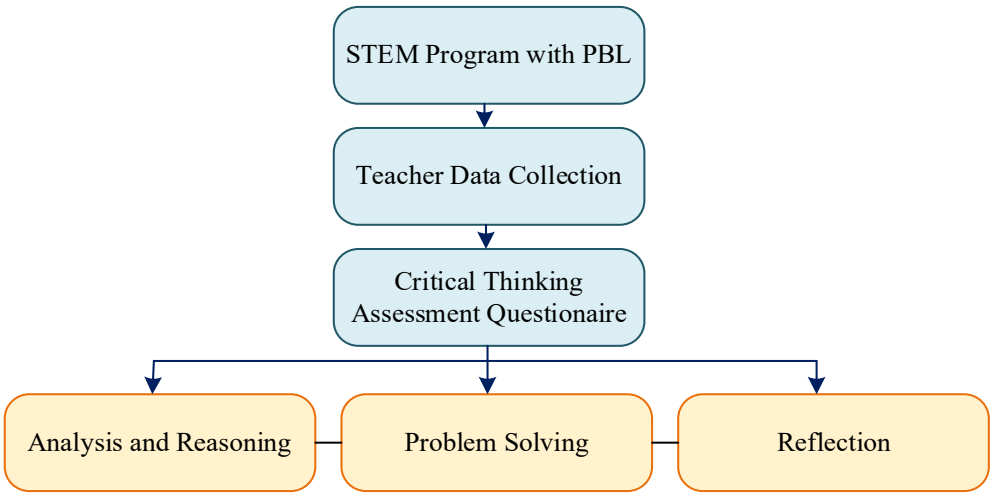

Figure 1. Critical Thinking Framework

A. Participants

The participants were 15 teachers who were involved in or familiar with students participating in the STEM Innovation Programme. The programme was designed to introduce students to microcontroller-based STEM learning through hands-on activities and project development.

The teacher questionnaire gathered basic demographic information, including gender, age group, and school level. Teachers were specifically asked to provide their perceptions of the programme based on students' participation and behaviors throughout its implementation. As the primary aim of this study was to obtain preliminary insights from teachers regarding the programme, all eligible teachers who met the participation criteria were invited to take part in the survey.

B. STEM Innovation Programme

The STEM Innovation Programme was implemented through a series of practical, project-based activities involving programmable microcontrollers. In the first phase, students were first introduced to the fundamental concepts of Arduino programming and electronic components. Students worked with Arduino Uno and completed practical programming and circuit-development activities as shown in Figure 2.

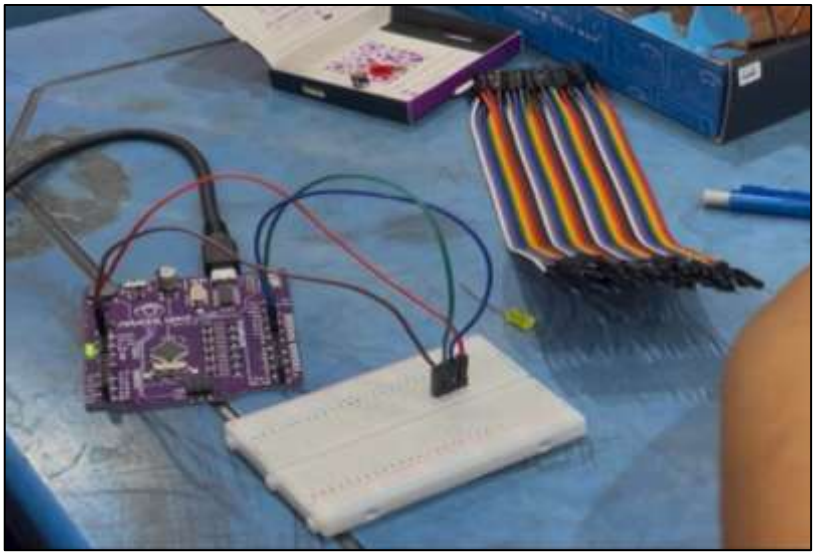

Figure 2: Circuit development activities

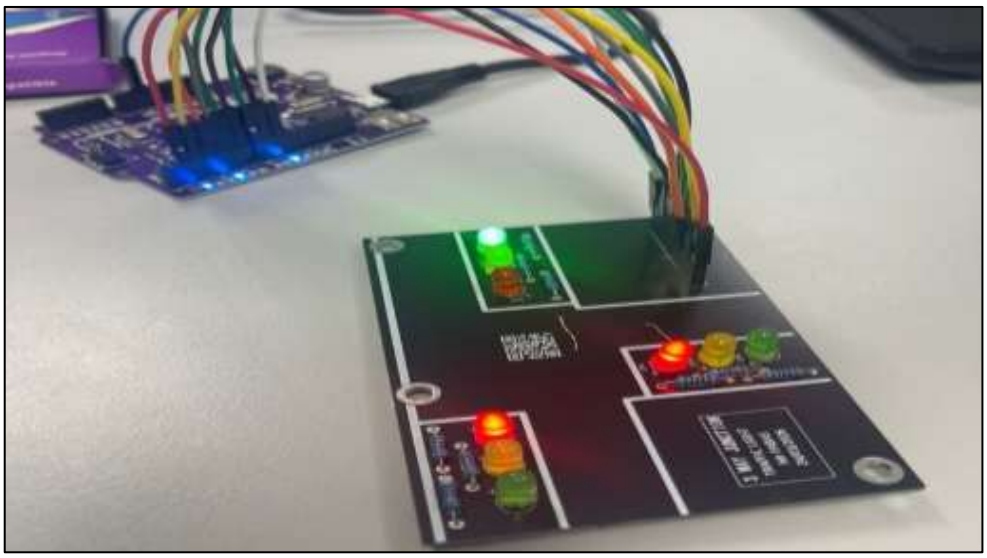

Figure 3: Traffic light system challenge

Then, one of the culminating activities involved a three-junction traffic light challenge, in which students worked

collaboratively to develop and test a functioning traffic light system as shown in Figure 3. The activity required students to understand the sequence and requirements of the traffic light system before developing their solution. They had to plan the programming logic, connect the components, test the system, identify errors, and modify their code when the expected output was not achieved. The questionnaire itself reflects these activities, including students' abilities to identify incorrect system conditions, evaluate system performance, try alternative approaches, and make decisions based on logic.

In the second phase of the programme, students were introduced to Microbit and AI-related activities before working in groups to develop an innovation project based on the theme "Technology Innovation Empowers School and Communities." This project required students to apply knowledge gained from the earlier training to a more open-ended problem. Students were required to discuss ideas, identify problems, consider possible solutions, develop their prototype, test its functionality, and make improvements.

This progression from guided technical activities to open-ended innovation development provided students with increasing opportunities to practice critical thinking. Rather than focusing solely on whether students could successfully program a microcontroller, the programme encouraged them to explain their reasoning, consider alternatives, respond to errors, and make decisions during project development.

Instrument

Data were gathered through a structured questionnaire consisting of 21 items rated on a five-point Likert scale, with response options ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). The instrument was specifically designed to capture teachers' perceptions of students' critical thinking behaviours as well as the effectiveness of the STEM Innovation Programme. To evaluate the critical thinking component, the questionnaire incorporated four key dimensions: Analysis and Reasoning, Problem Solving, and Reflection and Evaluation.

C. One-sample t-test

A one-sample t-test was conducted to determine whether teachers' mean ratings of students' critical-thinking development differed significantly from the neutral midpoint (3.00) of the five-point Likert scale. The test was used to provide inferential support for the descriptive findings, given that the study involved a single group of teachers without a control or pre-intervention comparison group.

RESULT AND DISCUSSIONS

A. Observational findings

Observational findings indicate that the STEM programme successfully enabled students to develop and complete projects aligned with the designated themes. Throughout the programme, students demonstrated active engagement in designing, constructing, testing, and refining solutions using a range of STEM technologies. Most student projects as shown in Figure 4 incorporated Arduino, Micro:bit, and Artificial Intelligence (AI) components, reflecting students' ability to apply knowledge and skills acquired during the workshops to authentic project-based tasks.

Students showed increasing confidence in integrating hardware and software elements to create functional prototypes. Through the use of Arduino and Micro:bit platforms, students were able to develop automated systems, sensor-based applications, and interactive prototypes that addressed the requirements of their selected project themes. In addition, the incorporation of AI elements enabled students to explore emerging technologies and apply data-driven or intelligent features to enhance their project outcomes.

Further observation revealed that students could translate conceptual ideas into practical solutions. They worked collaboratively to identify project objectives, generate ideas, develop prototypes, and troubleshoot technical challenges encountered during the development process. The successful completion of the projects suggests that students were able to apply programming, engineering design, computational thinking, and problem-solving

skills in meaningful contexts.



Figure 4: Project development based on theme "Technology Innovation Empowers School and Communities."

B. Reliability analysis

The reliability of the 21 items instrument was assessed using Cronbach's alpha coefficient to determine the internal consistency of the scale. The analysis yielded a Cronbach's alpha value of 0.836, indicating a good level of internal consistency reliability among the items. According to Nunnally and Bernstein (1994), a Cronbach's alpha coefficient of 0.70 or higher is considered acceptable for social science research, while values exceeding 0.80 indicate good reliability [13].

Therefore, the obtained alpha value of 0.836 suggests that the 21 items consistently measure the same underlying construct and that the instrument is sufficiently reliable for subsequent analyses. This result demonstrates that the scale possesses satisfactory internal consistency and can be used with confidence in the study [14].

C. Critical thinking components

(i) Analysis and Reasoning

The Analysis and Reasoning dimension comprised four items that assessed teachers' perceptions of students' abilities to identify problems, evaluate information, differentiate facts from assumptions and opinions, and justify their ideas with logical reasoning. The findings revealed a high level of perceived student performance, with mean scores ranging from 4.40 to 4.53. The overall mean score of approximately 4.45 indicates that teachers generally perceived students as demonstrating strong analytical and reasoning skills following their participation in the programme.

The highest-rated item was "Students demonstrate the ability to critically analyze information before making decisions" with M = 4.53, SD = 0.516. This was followed by the ability to provide logical reasons to support ideas (M = 4.47, SD = 0.516). The ability to identify issues or problems clearly and distinguish facts, assumptions and opinions both recorded M = 4.40, with SD values of 0.632 and 0.507, respectively.

These findings suggest that the programme enabled students to engage in higher order thinking rather than merely following instructions. Throughout the learning process, students were encouraged to think about the reasoning

behind their choices and actions. This was particularly evident in the Arduino and microcontroller activities, where students were required to understand system functionalities before implementing or modifying them. During programming and circuit design tasks, students needed to identify issues, analyse relevant information, and determine the probable causes of incorrect outputs. Furthermore, the relatively low standard deviation values across the items indicate a high degree of agreement among teachers regarding students' analytical and reasoning abilities [15].

The findings are particularly encouraging because analysis and reasoning are widely recognized as core dimensions of critical thinking, enabling learners to evaluate information, interpret evidence, make informed judgments, and justify decisions logically [9]. The hands-on nature of the workshop may have facilitated the development and observation of these skills. Rather than demonstrating critical thinking solely through written assessments, students applied analytical and reasoning processes while constructing circuits, developing programming sequences, and building prototypes. Throughout these activities, students were required to identify problems, examine evidence, evaluate alternative solutions, and justify their decisions based on technical requirements. Furthermore, the innovation project provided authentic opportunities for students to discuss ideas, defend their viewpoints, and make reasoned decisions, thereby strengthening higher-order thinking skills that are fundamental to effective critical thinking [16].

ii. Problem Solving

The problem solving component recorded an overall mean score of approximately 4.30, reflecting a high level of teacher agreement regarding students' problem-solving competencies following participation in the programme. Item mean scores ranged from 4.20 to 4.33, indicating consistently positive evaluations across all indicators. Teachers perceived students as being able to propose alternative solutions (M = 4.33, SD = 0.617), transfer knowledge acquired from previous training to unfamiliar situations (M = 4.33, SD = 0.816), successfully complete challenging project tasks (M = 4.33, SD = 0.488), and independently apply previously learned skills without requiring continuous facilitator support (M = 4.33, SD = 0.617).

The lowest mean score within this dimension was associated with students' ability to evaluate the advantages and disadvantages of alternative solutions before making decisions (M = 4.20, SD = 0.775). Although comparatively lower than the other items, this score remains within the positive range, suggesting that teachers generally agreed that students demonstrated this capability. The relatively higher standard deviation for this item also indicates greater variability in teachers' observations, suggesting that the extent to which students engaged in comparative evaluation differed across learning contexts or project activities.

Overall, the findings suggest that students were able to apply their knowledge and skills when faced with unfamiliar or challenging situations. This outcome is particularly significant because problem solving is widely recognized as a key higher-order thinking skill that requires learners to analyze situations, generate and evaluate solutions, and make informed decisions based on available evidence [1][16]. The progression of activities throughout the programme, beginning with foundational Arduino tasks and a three-junction traffic-light challenge before advancing to Micro:bit and artificial intelligence applications and culminating in a group innovation project, provided students with opportunities to transfer and adapt their learning to increasingly complex and less structured contexts.

iii. Reflection and Evaluation

The Reflection and Evaluation dimension comprised four items and recorded an overall mean of 4.35, indicating that teachers generally agreed that students demonstrated reflective and evaluative behaviours during the programme. Item means ranged from 4.20 to 4.60, showing consistently positive perceptions across all indicators.

The highest-rated item was students' willingness to accept different views from peers or teachers (M = 4.60, SD = 0.632). This was the highest mean among all items reported so far. It suggests that the collaborative structure of the programme, particularly the group innovation project, encouraged students to listen to alternative

viewpoints and adjust their thinking. In the traffic-light challenge and the innovation project, students had to discuss design decisions, compare approaches, and accept feedback when their prototypes did not work as expected. Openness to other perspectives is widely regarded as a core disposition of critical thinking and a basis for reflective judgement [1][15].

Teachers also rated students positively on asking quality questions (M = 4.33, SD = 0.488) and on drawing conclusions from the evidence obtained (M = 4.27, SD = 0.458). These two items had the smallest standard deviations in the dimension and minimum ratings of 4. This indicates strong agreement among teachers. Microcontroller activities may have supported these behaviours because the output of a circuit or program gives immediate evidence. Students could observe whether the system behaved as intended, question why it did not, and base their conclusions on test results rather than assumption. This is consistent with the view that reflection and metacognitive awareness are closely linked to critical thinking [16].

The lowest-rated item was students reevaluating their answers or ideas when given new information (M = 4.20, SD = 0.775). Although this mean is still within the positive range, its higher standard deviation and minimum rating of 2 show that teachers' observations varied. Some teachers may have seen students readily revise their ideas, while others observed less revision. Revising one's own thinking considering new evidence is a demanding reflective skill. Students may find it harder to revisit a solution they have already built than to accept a peer's suggestion. This pattern mirrors the Problem Solving dimension, where evaluating the advantages and disadvantages of alternative solutions was also rated lowest (M = 4.20, SD = 0.775). Both results suggest that students' ability to review and revise their own work is the area with the most room for development. Structured reflection prompts, design review sessions, and debugging logs could strengthen it.

D. One sample test of teachers' perception

The one-sample t-test was used as supporting inferential analysis to determine whether the teachers' ratings were significantly more positive than a neutral response (3.00). It was applied to all 13 critical-thinking items, not only a selected subset; the item codes and their wording are listed in Table 1 below.

As shown in Table 2, every one of the 13 items was rated significantly above the neutral midpoint, with t (14) ranging from 6.00 to 11.50 and mean differences from 1.200 to 1.600. None of the 95% confidence intervals included zero, and the lower bounds were all above 0.75 scale points. Effect sizes were large (Cohen's d = 1.55–2.97). The strongest agreement was for AR1 (critically analysing information before making decisions; t = 11.50, mean difference = 1.533) and for RE1 (accepting different views; mean difference = 1.600), and the weakest, though still significant, for PS5 and RE4 (t = 6.00, mean difference = 1.200). The significant results therefore apply to the whole critical-thinking scale and not only to the problem-identification item (AR3: M = 4.40, t = 8.57, 95% CI [1.05, 1.75]). Items with greater variability (PS2, PS5, and RE4) had the widest confidence intervals, in line with the descriptive results above.

Table 1: Item indicator for Critical Thinking Assessment

Question	Item	Indicator
Analysis and Reasoning (AR)	critically analysing information before making decisions	AR1
	providing logical reasons to support ideas	AR2
	identifying issues or problems clearly	AR3
	distinguishing facts, assumptions, and opinions	AR4
Problem Solving (PS)	proposing alternative solutions	PS1
	transferring knowledge to unfamiliar situations	PS2
	completing challenging project tasks	PS3
	applying learned skills without continuous facilitator support	PS4
	evaluating the advantages and disadvantages of alternative solutions	PS5
Reflection and Evaluation (RE)	accepting different views from peers or teachers	RE1
	asking quality questions	RE2

	drawing conclusions from evidence	RE3
	re-evaluating answers or ideas when given new information.	RE4

Table 2. One-sample T-test of Teachers' Ratings against the Neutral Midpoint (3.00), N = 15

Item	M	SD	t	Mean diff.	95% CI	d
AR1	4.53	0.516	11.50	1.533	1.25–1.82	2.97
AR2	4.47	0.516	11.01	1.467	1.18–1.75	2.84
AR3	4.40	0.632	8.57	1.400	1.05–1.75	2.22
AR4	4.40	0.507	10.69	1.400	1.12–1.68	2.76
PS1	4.33	0.617	8.37	1.333	0.99–1.68	2.16
PS2	4.33	0.816	6.33	1.333	0.88–1.79	1.63
PS3	4.33	0.488	10.58	1.333	1.06–1.60	2.73
PS4	4.33	0.617	8.37	1.333	0.99–1.68	2.16
PS5	4.20	0.775	6.00	1.200	0.77–1.63	1.55
RE1	4.60	0.632	9.81	1.600	1.25–1.95	2.53
RE2	4.33	0.488	10.58	1.333	1.06–1.60	2.73
RE3	4.27	0.458	10.71	1.267	1.01–1.52	2.77
RE4	4.20	0.775	6.00	1.200	0.77–1.63	1.55

Note. df = 14 for all items; all two-tailed p values were < .001 (also below the Bonferroni-adjusted threshold of .004). M = mean rating; Mean diff. = M − 3.00; CI = 95% confidence interval of the mean difference; d = Cohen's d.

These results show that teachers' ratings were consistently positive. They do not show that the programme caused students' critical thinking to improve, because the study has no comparison group, no pre-programme measure, and no direct assessment of students. The tests also treat the 15 teachers as a single sample, so the findings should be read as preliminary (see Limitations).

E. Limitations

Four limitations should be considered when interpreting these findings. First, the sample was small (15 teachers) and drawn from teachers who were involved in or familiar with a single programme, so the results cannot be generalized on other schools, teachers, or STEM programmes. Second, the datas are teachers' perceptions only. They show how teachers saw their students' behaviour but are not direct measures of students' critical-thinking ability, and they may be affected by the teachers' own involvement in the programme and by a tendency to rate a programme favorably. Third, the study had no control group and no pre-test or post-test, so it cannot be established that the programme itself produced any change in students' critical thinking; students may have shown these behaviours regardless of the programme. Fourth, the inferential tests compare ratings with a neutral midpoint, and the Likert data are ordinal, so the t-tests describe the strength of agreement among these 15 teachers and not a population effect.

Future studies should therefore involve a larger and more diverse sample of teachers and students from different schools, including a comparison group, and use pre-test and post-test measures of critical thinking. Classroom observations, student performance tasks, and student self-reports would add more objective evidence, and a nonparametric test (for example, the Wilcoxon signed-rank test) could be reported alongside the t-test for ordinal data.

CONCLUSIONS

This study examined teachers' perceptions of students' critical thinking development following a microcontroller-based STEM Innovation Programme that progressed from guided Arduino Uno activities to an

open-ended innovation project. Based on 15 teachers' responses, the findings indicate that the programme was viewed as a meaningful context for practicing critical thinking. The questionnaire showed good internal consistency (Cronbach's alpha = 0.836), and ratings were consistently high for analysis and reasoning (mean = 4.45), reflection and evaluation (mean = 4.35), and problem solving (mean = 4.30). One sample t-test confirmed that ratings for the items tested were significantly above the neutral midpoint.

Teachers' strong agreement on analysis and reasoning suggests students moved beyond following instructions, examining information and tracing the causes of faulty outputs. The highest-rated item across the dimensions reported, willingness to accept different views (M = 4.60), suggests that collaborative project work encouraged openness, while problem-solving ratings indicate students could transfer learning to unfamiliar situations with limited facilitator support.

Two items tied for lowest: reevaluating ideas given new information and weighing the advantages and disadvantages of alternative solutions (both M = 4.20, SD = 0.775). Both showed greater variability, suggesting that revising and comparing ideas may need explicit support, such as structured design reviews, reflection prompts, and trade-off discussions.

For practice, the findings support sequencing STEM learning from guided technical tasks towards open-ended, community-oriented projects, which gives students increasing room for judgement and decision making. Teacher observation may also help schools capture thinking processes that tests alone can miss.

Overall, microcontroller-based STEM projects that move from guided practice to open ended innovation appear to be a promising pedagogical pathway for nurturing critical thinking, if opportunities for reflection and the evaluation of alternatives are deliberately built into the learning design.

These outcomes suggest that integrating programmable microcontrollers and authentic project-based learning into the curriculum may help bridge the gap between theoretical knowledge and practical application. However, the findings are preliminary. They are limited by the small sample of 15 teachers, the reliance on teacher perceptions rather than direct assessment of students, and the absence of a control group and pre-test/post-test comparison, so they cannot show that the programme caused improvements in critical thinking. Future research should involve a larger and more diverse sample of teachers and students from different schools and should combine teacher perceptions with pre-test and post-test assessments, classroom observations, and student performance evaluations to provide more objective evidence of the long-term impact of technology-supported STEM interventions on higher-order thinking.

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REFERENCES

1. Butler, H. A. (2024). Predicting everyday critical thinking: A review of critical thinking assessments. Journal of Intelligence, 12(2), 16. https://doi.org/10.3390/jintelligence12020016
2. Tijani, B. E., & Adeduyigbe, A. M. (2026). Transforming science education: A systematic review of evidence-based strategies for cultivating 21st-century skills in STEM education. Journal of Research in Environmental and Science Education, 3(1), 8-23.
3. Bandjar, B. S., Rindarjono, M. G., & Prihadi, S. (2024). Effectiveness of STEM learning model and project-based learning to enhance critical thinking skills in senior high school. Jambura Geo Education Journal, 5(2), 127-139. https://doi.org/10.37905/jgej.v5i2.26532
4. Rizki, I. A., & Suprapto, N. (2024). Project-oriented problem-based learning through SR-STEM to foster students' critical thinking skills in renewable energy material. Journal of Science Education and Technology, 33(4), 526-541.

5. Rohman, M. H., Marwoto, P., Nugroho, S. E., & Supriyadi, S. (2024). Effectiveness of ethnoecological-STEM project-based learning model to improve critical thinking skills, creativity, and science concept mastery. International Journal of Cognitive Research in Science, Engineering and Education, 12(3), 521-534.
6. Saramati, B., Vidak, A., & Mešić, V. (2026). Learning physics with microcontrollers: A systematic review of empirical research. Eurasia Journal of Mathematics, Science and Technology Education, 22(6), em2848.
7. Rusdiana, D., Said, S., Sanusi, D. K., & Indira, I. (2026). Development of an Integrated Electronics Learning Module Using Sensors and Arduino to Enhance Conceptual Understanding in Physics. Tadris: Jurnal Keguruan dan Ilmu Tarbiyah, 11(1), 119-126.
8. Sánchez-García, R., & Reyes-de-Cózar, S. (2025). Enhancing project-based learning: A framework for optimizing structural design and implementation—A systematic review with a sustainable focus. Sustainability, 17(11), 4978.
9. Hačatrjana, L., & Namsone, D. (2024). Breaking down the concept of students' thinking and reasoning skills for implementation in the classroom. Journal of Intelligence, 12(11), 109. https://doi.org/10.3390/jintelligence12110109
10. Ospankulova, E., Maxutov, S., Lathrop, R., Anuarova, L., & Balta, N. (2025). Science students' attitudes, learning, critical thinking and engagement in project-based learning. Cogent Education, 12(1), 2445358.
11. Maspul, K. A. (2024). Enhancing STEM education through project-based learning: A strategy to engaging secondary school students. Affective Development Journal, 1(1), 1-7. https://doi.org/10.32585/affective.v1i1.12
12. Riduan, M. A., & Othman, Z. S. (2024). Examining challenges and strategies in implementing STEM education in Malaysian secondary schools: perspectives of teachers and students. Jurnal Intelek, 19(2), 96-106.
13. Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. Psychometrika, 16(3), 297-334.
14. Nunnally, J. C., & Bernstein, I. H. (1994). Psychometric Theory (3rd ed.). New York, NY: McGraw-Hill.
15. Hair, J. (2020). Musings on a distinguished methods career and beyond. Advancing Methodological Thought and Practice, Volume 12, 13-114. https://doi.org/10.1108/S1479-838720200000012013
16. Alpindo, O., Istiyono, E., Widihastuti, & Andriyanti, E. (2024). Can critical-thinking skills be measured by analyzing metacognition? Journal of Teaching and Learning, 18(2), 194-211. https://doi.org/10.22329/jtl.v18i2.8813