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Integrating Web-Based IoT Learning Media to Enhance Critical Thinking and Problem-Solving Skills in Vocational Education

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Abstract
The integration of Internet of Things (IoT) technology in vocational education is essential for preparing graduates to meet Industry 4.0 demands. Although digital learning technologies have been widely studied, empirical evidence on the effectiveness of web-based IoT learning media integrated with problem-based learning (PBL) in vocational contexts remains limited. This study examines the instructional impact of web-based IoT learning media on vocational students' critical thinking and problem-solving skills. A quasi-experimental non-equivalent control group pretest–posttest design was employed involving 60 eleventh-grade Mechanical Engineering students (30 experimental, 30 control). The experimental group participated in PBL activities supported by a web-based IoT platform for eight weeks, while the control group received conventional instruction. Data were analyzed using Analysis of Covariance (ANCOVA) to compare posttest outcomes while controlling for initial differences in pretest scores. The results indicate statistically significant improvements in critical thinking and problem-solving skills among students in the experimental group compared to the control group ($p < 0.05$). The effect sizes indicate a strong instructional impact within the studied context, though findings should be interpreted cautiously given the sample size. Overall, this study provides empirical support for the pedagogical potential of web-based IoT learning media in fostering 21st-century competencies in vocational education.

Keywords: Website, Internet of Things, Learning Media, Critical Thinking, Problem-Solving Skills

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INTRODUCTION

The integration of advanced digital technologies into vocational education is increasingly essential in addressing the competency demands of Industry 4.0, which emphasize automation, data literacy, and problem-solving skills. While various digital learning technologies such as learning management systems, multimedia modules, and virtual simulations have been widely adopted in vocational education, these tools often function primarily as content delivery or representation media. In contrast, Internet of Things (IoT) based learning introduces a distinct pedagogical approach by enabling real-time interaction between physical devices, learners, and digital systems, thereby situating learning within authentic industrial processes (Khan et al., 2025).

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Pedagogically, IoT-based learning differs from general digital learning technologies in its capacity to support experiential, contextual, and data-driven learning. Through IoT-enabled activities, students engage directly with sensor-generated data, machine communication, and system automation, which require them to analyze real-time information, diagnose system behavior, and propose solutions to practical problems. These characteristics make IoT-based learning particularly relevant for developing critical thinking and problem-solving skills, which are core competencies in vocational education but are not always optimally facilitated by conventional digital platforms (Paucar-Curasma et al., 2024; Prasad et al., 2023). The pedagogical potential of IoT is further strengthened when integrated with Problem-Based Learning (PBL). PBL provides structured problem scenarios that guide learners in investigating, reasoning, and decision-making, while IoT technology supplies authentic data and operational contexts that anchor these problems in real-world practice. However, despite the growing implementation of digital learning in vocational schools, empirical studies examining the combined effect of web-based IoT learning and PBL on vocational students' critical thinking and problem-solving skills remain limited, particularly in developing-country contexts.

Therefore, this study focuses specifically on investigating the instructional impact of web-based IoT learning media integrated with PBL on vocational students' critical thinking and problem-solving skills. By clearly distinguishing IoT-based learning from general digital technologies and aligning it with targeted cognitive outcomes, this study seeks to contribute empirical evidence that supports the pedagogical relevance of IoT as a strategic approach in Industry 4.0–oriented vocational education.

Modern education emphasizes the development of critical thinking and problem-solving skills as core competencies for vocational students, particularly in contexts that require adaptive reasoning and evidence-based decision-making (Facione, 2011; Prayogi et al., 2018). In this study, these constructs are operationalized through the design of a web-based IoT learning environment that embeds authentic industrial tasks requiring students to interpret real-time data, analyze system behavior, and propose practical solutions. Specifically, critical thinking skills—including analysis, evaluation, and inference—are facilitated through IoT features such as real-time sensor data visualization and system simulations, which prompt students to examine causal relationships, assess data validity, and draw reasoned conclusions. Meanwhile, problem-solving skills—such as problem identification, strategy formulation, and solution evaluation—are supported through IoT-based problem scenarios that require students to diagnose system malfunctions, test alternative solutions via simulations, and evaluate outcomes using immediate sensor feedback.

Consistent with prior research, the integration of problem-based learning (PBL) with digital platforms enhances students' analytical and solution-oriented abilities by situating learning within meaningful and complex problem contexts (López et al., 2023; Song & Cai, 2024; Syafruddin et al., 2023; Syawaludin et al., 2019). However, unlike conventional web-based learning that primarily delivers static content, the IoT-integrated platform in this study provides dynamic interaction between learners, digital systems, and physical data sources, enabling continuous feedback and iterative reasoning processes. Although previous studies on IoT in education have largely focused on general education settings, this study extends the literature by demonstrating how specific IoT features real-time data streams, simulations, and sensor feedback function as pedagogical mechanisms that align with established indicators of critical thinking and problem-solving in vocational education. These findings reinforce the need for further development and evaluation of web-based IoT learning media to support the digital transformation of vocational education (Prakash et al., 2021).

Observations reveal several major challenges in implementing IoT-based learning media in vocational schools. Inadequate school infrastructure is a significant barrier to adopting this technology. Additionally, teachers' competencies in utilizing IoT require enhancement through continuous training programs. Other obstacles include limited hardware, suboptimal internet connectivity, and insufficient policy and funding support. Addressing these issues requires collaborative efforts to improve infrastructure, build educator capacity, and secure adequate policy backing.

The absence of comparative research analyzing the effectiveness of web-based IoT media on vocational students' cognitive competencies compared to other digital media represents a critical gap in the literature (Joko et al., 2022a; Rio Kudriyanto et al., 2025). Existing studies only examine the effectiveness of IoT media in isolation, without direct comparison to alternative digital platforms. While some findings highlight the potential of IoT media in improving cognitive learning outcomes, empirical evidence comprehensively comparing its effectiveness is lacking.

Critical thinking and problem-solving skills are essential competencies for vocational graduates in the Industry 4.0 era. However, the limited implementation of web-based IoT media in real classroom settings has resulted in insufficient empirical evidence of its impact on students' cognitive skill development. Previous studies have primarily focused on general cognitive learning outcomes without deeply exploring its influence on critical thinking and problem-solving skills in vocational learning contexts (Kedia & Mishra, 2023).

This study employs a quasi-experimental method to evaluate the effectiveness of web-based IoT media designed around contextual problem-solving scenarios. Prior findings indicate that IoT media is more effective in enhancing critical thinking compared to conventional methods, while flipped learning and inquiry-based learning models integrated with IoT significantly improve problem-solving competencies. This study is expected to provide new empirical evidence on the advantages of IoT media in developing 21st-century skills in vocational education. The objectives of this study are: (1) to measure the significant impact of web-based IoT media on improving critical thinking and problem-solving skills among vocational students, and (2) to formulate evidence-based recommendations for integrating this technology into vocational curricula aligned with Industry 4.0 needs. Through a comparative quantitative approach, the results are expected to provide an empirical foundation for developing more effective and relevant vocational education policies in the digital era.

METHODS

This study employed a quasi-experimental research design using a non-equivalent control group pretest–posttest design, which is widely applied in educational research when random assignment of participants is impractical (Creswell, 2014; Shadish, Cook, & Campbell, 2002). This design was selected to examine the causal effect of web-based Internet of Things (IoT) learning integrated with Problem-Based Learning (PBL) on students' critical thinking and problem-solving skills within authentic school settings.

The population of this study consisted of all eleventh-grade Mechanical Engineering students enrolled in vocational high schools in Boyolali, Indonesia. A purposive sampling technique was used to select two intact classes from the same school to ensure comparable curricular exposure and learning conditions. One class (n = 30) was assigned as the experimental group and received web-based IoT learning integrated with PBL, while the other class (n = 30) served as the control group and was taught using conventional lecture-based instruction and textbook materials. To minimize selection bias, both groups were matched based on their pretest scores, ensuring equivalent baseline academic ability prior to the intervention.

Data were collected using multiple instruments. Students' critical thinking skills were measured using the *Watson–Glaser Critical Thinking Appraisal II*, while problem-solving skills were assessed using *Heppner's Problem-Solving Inventory (PSI)*. Both instruments were adapted to the vocational education context through expert validation and pilot testing. The reliability analysis indicated high internal consistency, with Cronbach's alpha coefficients exceeding 0.80, which is considered acceptable for educational research (Fraenkel, Wallen, & Hyun, 2019). In addition, student engagement and technical performance during learning activities were assessed using structured observation rubrics. Inter-rater reliability analysis yielded coefficients greater than 0.75, indicating substantial agreement among observers (Cohen, 1960).

The experimental procedure consisted of pretest administration for both groups, followed by an eight-week instructional intervention conducted twice per week. The experimental group engaged in web-based IoT learning activities incorporating real-time simulations, problem scenarios, and collaborative PBL tasks designed to foster 21st-century skills. Meanwhile, the control group received instruction through traditional teaching methods without IoT integration. At the end of the intervention, both groups completed the posttests using the same instruments administered at the pretest stage.

Quantitative data analysis began with descriptive statistics, including means and standard deviations, to describe students' performance before and after the intervention. To determine the effect of the treatment while controlling for initial differences, an Analysis of Covariance (ANCOVA) was conducted using pretest scores as covariates. The magnitude of the treatment effect was calculated using Cohen's d, with values greater than 0.50 interpreted as educationally meaningful effects (Cohen, 1988). All statistical analyses were performed using SPSS version 26, with a significance level set at $\alpha = 0.05$.

RESULTS & DISCUSSION

The effectiveness of web-based IoT learning media in improving critical thinking skills of vocational school students

The experimental results demonstrate compelling evidence regarding the effectiveness of web-based IoT learning media in enhancing critical thinking skills among vocational high school students. Quantitative analysis using ANCOVA revealed statistically significant improvements ($p < 0.05$) across all critical thinking indicators—problem identification, analysis, solution formulation, and conclusion drawing—in the experimental group compared to the control group. Complete data can be seen in table 1.

Table 1. Differences in Critical Thinking Skills

Critical Thinking Indicator	Experimental Group (M ± SD)	Control Group (M ± SD)	p-value	Cohen's d	Effect Interpretation
Problem Identification	84.5 ± 4.2	69.2 ± 5.7	<0.01	2.89	Very Large
Analysis	83.7 ± 4.0	66.8 ± 5.5	<0.01	3.17	Very Large
Problem-Solving	81.9 ± 4.4	65.3 ± 5.9	<0.02	2.88	Very Large
Drawing Conclusions	79.2 ± 4.1	62.7 ± 5.8	<0.01	2.93	Very Large
Total Critical Thinking	82.3 ± 4.1	65.7 ± 5.6	<0.01	3.00	Very Large

a. p-values indicate statistical significance of mean differences between groups using ANCOVA ($\alpha = 0.05$).
b. Cohen's d effect sizes were interpreted per Cohen (1988): 0.2 = small, 0.5 = medium, 0.8 = large. Values > 2.0 indicate very large effects.
c. Results demonstrate significant improvements in all critical thinking indicators for the experimental group using web-based IoT media.

The results of table 1 indicate that the use of IoT-based learning media has a very large and significant impact on improving critical thinking skills of vocational high school students in all aspects of assessment, from problem identification to drawing conclusions. A very small p-value (<0.05) confirms that the difference is not coincidental, while a very large Cohen's d value indicates that this intervention has a strong practical effect in the context of vocational learning. This finding is consistent with the literature stating that the integration of interactive technologies such as IoT can strengthen high-level cognitive skills through contextual learning and problem-based learning.

The effectiveness of web-based IoT learning media in Problem-Solving Abilities of vocational school students

After examining the significant improvements in critical thinking skills, this section presents the analysis of the second core competency evaluated in this study: students' problem-solving abilities. More details can be seen in table 2.

Table 2. Differences in Problem-Solving Abilities

Assessment Criteria	Experimental (M ± SD)	Control (M ± SD)	p-value	Cohen's d
Problem Understanding	4.3 ± 0.5	3.2 ± 0.6	<0.002	1.9
Solution Planning	4.4 ± 0.4	3.4 ± 0.5	<0.001	2.1
Solution Implementation	4.2 ± 0.6	3.3 ± 0.7	<0.004	1.5
Evaluation & Verification	4.0 ± 0.5	3.1 ± 0.6	<0.006	1.6
Total Problem-Solving	16.9 ± 1.2	13.0 ± 1.8	<0.001	2.3

a. p-values < 0.05 indicate significant differences between groups for each indicator.
b. Cohen's d > 0.8 represents large effects; > 2.0 indicates very large effects.
c. The experimental group outperformed the control group in all problem-solving aspects, particularly in solution planning.

The results of table 2 show that the experimental group using IoT-based learning media has significantly better problem-solving skills than the control group using conventional methods. The greatest improvement was seen in the indicator of planning problem solving, which is a crucial stage in the problem-solving process. The significantly higher total score in the experimental group indicates the effectiveness of IoT media in improving the problem-solving skills of vocational high school students comprehensively.

Correlation of IoT Interaction with Learning Outcomes Problem solving and critical thinking

This section presents the correlation analysis between the frequency of IoT media engagement and students' performance in problem-solving and critical thinking assessments. More details can be seen in table 3.

Table 3. Correlation Between IoT Interaction and Learning Outcomes

Correlation Statistic	Value	Description
Pearson's r	0.78	Strong positive correlation between IoT interaction and learning outcomes
p-value	<0.001	Statistically significant correlation
Mean Interaction Frequency (log)	5.1 ± 2.4	Average student interaction with IoT media
Mean Post-test Score (0-100)	77.6 ± 12.3	Average problem-solving & critical thinking scores
Linear Regression (slope/intercept)	5.2 / 50.1	Each 1-log increase in interaction raises scores by 5.2 points
Sample Size (n)	30	Number of participants

Active interaction with IoT media significantly contributed to improved problem-solving and critical thinking skills. Higher interaction frequencies correlated with higher post-test scores, consistent with meta-analyses confirming IoT-based learning models' effectiveness ($r = 0.764$; $p < 0.001$).

Discussion

This study provides empirical support for the pedagogical potential of web-based IoT learning integrated with problem-based learning (PBL) in enhancing vocational students' critical thinking and problem-solving skills, which are essential competencies in the Industry 4.0 era. In contrast to prior studies that predominantly emphasize the technical implementation of IoT systems, this research extends the literature by empirically examining cognitive learning outcomes within a vocational education context (Paucar-Curasma et al., 2024; Prasad et al., 2023). The findings align with constructivist and experiential learning perspectives, suggesting that IoT-based learning environments, which engage students with real-time data, system feedback, and authentic problem scenarios, can effectively foster higher-order thinking skills when combined with PBL (Hmelo-Silver, 2004; Khan et al., 2025).

Despite these contributions, the findings should be interpreted with caution due to several methodological limitations. The relatively small sample size and the focus on a single vocational school and disciplinary context may constrain the generalizability of the results (Fraenkel et al., 2019). Moreover, the study compared IoT-based learning only with conventional instruction, without including other digital learning platforms such as virtual laboratories or augmented reality, limiting conclusions regarding the comparative effectiveness of IoT-based learning (Creswell, 2014). Additionally, contextual factors including school infrastructure readiness and teacher technological competence—which have been identified as critical determinants of successful technology integration—were not systematically examined (Ertmer & Ottenbreit-Leftwich, 2010). These limitations underscore the need for future research employing larger, multi-site samples, comparative experimental designs, and mixed-method approaches to strengthen external validity and deepen understanding of IoT-based learning implementation in vocational education.

Results demonstrate that web-based IoT learning media significantly improves vocational students' critical thinking skills in mechanical engineering compared to conventional methods. ANCOVA analysis yielded significant p-values ($p < 0.05$) for all critical thinking indicators, with very large effect sizes (Cohen's $d > 2.0$). All assessment aspects, from problem identification to conclusion-drawing, showed meaningful improvements in the experimental group. These findings align with literature affirming that interactive technologies like IoT, especially when combined with problem-based learning (PBL), effectively develop higher-order cognitive skills relevant to contemporary industry needs.

The study also reveals significant differences in problem-solving abilities between students using web-based IoT media and those using conventional methods, after controlling for pretest factors. The experimental group exhibited substantially higher problem-solving scores, particularly in solution planning, with p-values < 0.05 and Cohen's $d > 2.0$. This proves that IoT media not only enhances problem identification but also optimizes systematic solution design and implementation. These improvements demonstrate IoT's effectiveness in training analytical and systematic thinking among vocational students.

IoT platform interactivity significantly contributes to 21st-century competency development, particularly critical thinking and problem-solving skills (Purnamawati et al., 2021). Correlation analysis shows that active interaction with IoT media strongly correlates ($r > 0.7$) with higher post-test scores. Increased interaction frequencies corresponded to higher achievement, confirming that IoT's interactive features—real-time feedback, data visualization, and realistic industrial simulations—create contextual and applicative learning experiences that support workplace-relevant competency development (Gao, 2022).

The experimental group outperformed the control group in all problem-solving indicators, especially solution planning. Very large Cohen's d effect sizes indicate the efficacy of web-based IoT media in training systematic and analytical thinking for real-world problem-solving. These results align with prior research proving that IoT-integrated problem-based learning significantly enhances vocational students' problem-solving abilities (Alani et al., 2021; Filantropie et al., 2023).

The combination of IoT media and problem-based scenarios effectively addresses conventional IoT implementation limitations, which often focus narrowly on technical aspects. Qualitative analysis revealed that 82% of students successfully designed functional IoT system prototypes post-intervention, surpassing 65% experimental group achievement (Paganelli et al., 2019). This demonstrates that holistic approaches integrating technology and innovative pedagogy yield optimal learning outcomes.

IoT sensor implementation in realistic industrial simulations created a multidisciplinary learning ecosystem. Results show students' ability to combine mechanical engineering knowledge with real-time IoT data analysis, a core competency aligned with Industry 4.0 demands. These findings support on the importance of contextualizing learning through wearable technology, though their study did not measure specific impacts on higher-order cognitive skills (Akil, n.d.; Joko et al., 2022b).

This study findings on the effectiveness of project-based and problem-based learning enhanced by digital technology (Kumar et al., 2024). However, it adds value by empirically proving the superiority of web-based IoT media over conventional methods in under-researched Indonesian vocational contexts. Furthermore, it reveals crucial synergies between IoT technology and innovative pedagogies like PBL in creating industry-relevant learning experiences.

CONCLUSION

This study examines the significant impact of IoT-based learning media on developing vocational students' critical thinking and problem-solving skills while formulating evidence-based recommendations for integrating this technology into Industry 4.0-aligned vocational curricula. Analytical results show that web-based IoT media implementation statistically significantly improves all indicators of critical thinking and problem-solving abilities. Statistical significance ($p < 0.05$) supported by large effect sizes (Cohen's $d > 2.0$) indicates strong practical impacts in vocational education. These findings align with prior research confirming that interactive technologies like IoT, especially when combined with problem-based learning (PBL), effectively develop higher-order cognitive skills relevant to contemporary industry needs.

This study contributes three key advancements to scientific knowledge. First, it provides new empirical evidence on the effectiveness of problem-solving contextualized IoT learning media in developing 21st-century vocational competencies. Second, it addresses literature gaps through comprehensive analysis of IoT-PBL integration impacts on vocational students' critical thinking and problem-solving skills, previously understudied. Third, it generates data-driven policy recommendations for structured IoT implementation in vocational curricula.

Despite these contributions, several limitations should be acknowledged and provide directions for future research. This study focused solely on comparing IoT-based learning media with conventional instructional methods, without examining other emerging digital learning platforms. Future studies are therefore recommended to pursue several research avenues. First, future research should involve larger and more diverse samples across multiple vocational institutions and regions to enhance the generalizability of findings. Second, comparative experimental studies should be conducted to examine the relative effectiveness of IoT-based learning against other digital learning approaches, such as virtual laboratories, augmented reality, or AI-assisted learning systems. Third, future research should explore longitudinal implementations to investigate the sustainability of cognitive skill development over time and its transfer to workplace performance. Finally, subsequent studies should test IoT-based learning models across different vocational subjects, learning modalities (online, blended, and hybrid), and levels of industry collaboration, enabling a more holistic understanding of IoT's role in transforming vocational education for the digital era.

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