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Online Self-Regulated Learning Assisted by Virtual Labs to Train STEM Student's Critical Thinking Skills

Bahtiar [1], Nevi Ernita [1*], Zulkarnaen [2], Hisbulloh Als Mustofa [3], Rangga Alif Faresta [4]

[1] Department of Physics Education, Universitas Islam Negeri Mataram, Mataram, Indonesia
[2] Department of Physics Education, Universitas Mulawarman, Samarinda, Indonesia
[3] Faculty of Science and Mathematics, Sultan Idris Educations University, Perak, Malaysia
[4] Department of Digital Learning, Monash University, Wellington Rd, Clayton VIC 3800, Australia
*Correspondence: nevi.ernita@uinmataram.ac.id

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Abstract

This study investigated the effectiveness of integrating online self-regulated learning with virtual labs in enhancing critical thinking skills among STEM students. The research adopted a controlled experimental design involving two groups—experimental and control—over a two-month period, employing a mix of interactive virtual labs and structured online self-regulated learning strategies for the former, while maintaining traditional educational methods for the latter. Results indicated significant improvements in the experimental group's critical thinking capabilities across multiple indicators such as interpretation, analysis, evaluation, inference, explanation, and self-regulation, compared to modest improvements in the control group. The experimental group benefited from a dynamic and interactive learning environment that allowed for hands-on experiments and simulations, fostering a deeper understanding and engagement with scientific concepts. This environment, enhanced by the strategic application of self-regulated learning techniques, facilitated a more effective development of critical thinking skills than traditional methods. The study highlighted the potential of virtual labs combined with self-regulated learning to significantly enhance educational outcomes in STEM education, suggesting that such integrative approaches could better prepare students for the complexities of the modern scientific landscape. Additionally, the study underscored the need for future research to explore these strategies across a more diverse and broader educational context to confirm these findings and further refine the educational interventions employed.

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INTRODUCTION

STEM education faced increasing pressure to adapt to community needs, especially in addressing complex issues in the digital age. This highlighted the importance of equipping students with critical thinking (CT) skills (Bilad et al., 2022; Bilad & Doyan, 2023; Salvetti et al., 2023). Although online platforms provided a wealth of learning opportunities, they often struggled to cultivate a stimulating environment that promoted student autonomy. This deficiency led to student disengagement, boredom, and a lack of motivation, which were substantial barriers to the long-term development of critical thinking abilities (Maimun & Bahtiar, 2023; Sarkingobir & Bello, 2024; Suningsih & Juniati, 2022). The intersection of these educational and technological issues underscored the urgent need for adaptive educational strategies that not only leveraged digital tools but also effectively engaged and developed students' critical thinking capacities (Ramadhan et al., 2023).

Previous research emphasized the significance of self-regulated learning strategies in online higher education environments and their impact on academic achievement (Broadbent & Poon, 2015). Additionally, barriers and solutions in online education were discussed, providing insights that could inform the development of online learning environments (O'Doherty et al., 2018). Moreover, research identified key indicators crucial for the perception of online education, including the quality of communication, tool convenience, student motivation, and self-organization abilities (Bogdanova, 2021). Efforts to enhance critical thinking skills across various instructional modalities, including online education, were essential for ensuring effective learning outcomes (Lanz et al., 2022). Furthermore, Bisht et al. (2020) shed light on the challenges faced in online higher education during the COVID-19 era, emphasizing issues such as Internet connectivity and class interactions (Bisht et al., 2022). These insights underscored the significance of addressing barriers to online learning to effectively foster the development of critical thinking skills in students.

Critical thinking skills were pivotal for STEM students aiming to excel in their disciplines. These skills enabled students to tackle complex problems using a logical and systematic approach, foster the generation of innovative solutions, and enhance the ability to analyze and interpret data while collaborating effectively with peers (Verawati et al., 2022). Ennis (2015) succinctly defined critical thinking as "reasonable, reflective thinking that is focused on deciding what to believe or do." Despite the recognized importance of these skills, the optimal methods for cultivating them within online learning environments remained a contentious issue (Wahyudi et al., 2023). Enhancing critical thinking in STEM students through online platforms required a multifaceted approach. It was essential to integrate various educational strategies and teaching methodologies that not only engaged students but also fostered an environment conducive to critical inquiry and independent learning. According to Wang et al. (2013), students who possessed a high degree of technology self-efficacy and who were satisfied with their courses tended to achieve superior academic outcomes. This correlation underscored the importance of designing online learning systems that not only delivered content effectively but also motivated and challenged students to think critically, thus preparing them for the demands of their future careers in STEM fields.

In an online learning system, it was essential for students to become independent learners. In other words, it was impossible to achieve progress in learning if students did not self-regulate their learning (Fuchs et al., 2022). Self-regulated learning was crucial in online learning environments, which offered more freedom in terms of space and time, as well as different types of communication and collaboration (Broadbent & Poon, 2015). Therefore, self-regulated learning played a central role in the success of learning in online environments (Fuchs et al., 2022). Innovative studies showed the potential of self-regulated learning in improving critical thinking skills. The multifaceted nature of self-regulated learning encompassed cognitive, metacognitive, behavioral, motivational, and emotional/affective aspects of learning (Panadero, 2017). This comprehensive view of self-regulated learning highlighted its capacity to influence various dimensions of learning, including critical thinking. Implementation of a performance-based assessment platform to support self-regulated learning in primary school students during programming tasks demonstrated the innovative use of technology to enhance self-regulated learning and potentially improve critical thinking skills (Kong & Liu, 2023). Additionally, Anwar and Muti'ah (2022) explored the relationship between critical thinking and self-regulated learning in online learning contexts during the COVID-19 pandemic, emphasizing the importance of self-regulation in fostering critical thinking abilities. Furthermore, Morales (2022) conducted a case study focusing on kinematics graph interpretation to improve students' skills in an online instruction environment using the self-regulated learning framework, indicating the potential of self-regulated learning in enhancing specific cognitive abilities such as graph interpretation. By leveraging self-regulated learning strategies, educators could potentially enhance students' ability to think critically, solve problems effectively, and navigate complex learning tasks with autonomy and self-regulation.

Students' critical thinking skills could develop when online learning provided a learning environment that motivated them to train their critical thinking skills (Oghlu-Sharifov, 2020). One of the learning practices that could provide a motivating online learning environment was through assistive computer technology in the form of simulations. In this study, virtual labs were employed and integrated with online self-regulated learning to train the critical thinking skills of STEM students. Virtual labs were a great tool for learning and understanding complex scientific concepts through computer simulations. These simulations provided an interactive and engaging learning experience that allowed students to explore and experiment with different scenarios to see how different variables affected the outcome. Virtual labs offered a dynamic platform for students, particularly in STEM fields, to engage with complex scientific concepts through interactive simulations (Oghlu-Sharifov, 2020). By integrating virtual labs with online self-regulated learning, students could enhance their critical thinking skills by exploring various scenarios and observing how different variables influenced outcomes. Research showed that the use of virtual labs, when combined with instructional designs such as teacher demonstrations and student critiques, could scaffold the development of scientific literacy and augment the effectiveness of virtual labs in enhancing critical thinking skills (Liu et al., 2022). Additionally, the implementation of guided inquiry lab models had been found to significantly impact students' critical thinking abilities, particularly in subjects like mechanics (Febri et al., 2020). Moreover, the development of high-quality online STEM labs was crucial for providing practical and experiential learning opportunities in virtual environments (Lindsey et al., 2022).

Study Aims

The primary aim of this study was to investigate the effectiveness of integrating online self-regulated learning with virtual labs in enhancing critical thinking skills among STEM students. This research sought to establish whether a combined educational approach, leveraging the interactive capabilities of virtual labs alongside the reflective and strategic components of self-regulated learning, could more effectively develop critical thinking abilities compared to traditional learning methods. The research question was as follows:

- How did the integration of virtual labs with online self-regulated learning influence the development of critical thinking skills in STEM students?

Previous Studies Related to Self-Regulated Learning

Previous studies related to self-regulated learning in the STEM area indicated that this topic had been extensively researched. An initial bibliometric analysis identified a number of studies that implemented self-regulated learning strategies during the period 2023-2024, utilizing the Scopus database for data collection. These studies were summarized and presented in Table 1 that presented a diverse array of studies on self-regulated learning related to STEM education, each exploring different aspects and methodologies to enhance learning outcomes through self-regulation.

Table 1. Previous studies on self-regulated learning are closely related to STEM education

Author(s)	Title	Study Context and Findings
(Lin et al., 2023)	• The research on the self-regulation strategies support for virtual interaction	• This study developed and tested four scaffolding tools designed to support self-regulation strategies in virtual learning environments. The experimental results demonstrated that these tools significantly improved self-directed learning performances and behaviors, particularly in enhanced virtual environments. Students using tools like the Learning Task Progress Tree and Panoramic Video Evaluation showed improved time management and self-assessment abilities, respectively.
(Cerón et al., 2024)	• Autorregulate: An Alternative to Support Self-Regulation in MOOCs	• The study introduced a web application named Autorregulate designed to support self-regulated learning in MOOCs. It supports multiple self-regulation strategies and was evaluated for its impact on self-regulation, usability, and usefulness in a Moodle-based MOOC. The results indicated high levels of self-regulation among participants and a positive reception of the tool's usability and usefulness.
(Kong et al., 2024)	• A pedagogical design for self-regulated learning in academic writing using text-based generative artificial intelligence tools: 6-P pedagogy of plan, prompt, preview, produce, peer-review, portfolio-tracking	• This research proposed a pedagogical design called the 6-P pedagogy to integrate self-regulated learning with the use of text-based generative AI tools in academic writing. It emphasizes planning, prompting, previewing, producing, peer-reviewing, and portfolio-tracking to enhance critical thinking and self-regulation. The design aims to mitigate the risks associated with AI tools while fostering a constructive use of these technologies in education.
(Hüseyin-Ateş, 2024)	• Designing a self-regulated flipped learning approach to promote students'	• The study focused on a self-regulated flipped learning approach in science education for middle school students. It found that students in the

Author(s)	Title	Study Context and Findings
	science learning performance	experimental group, who experienced the self-regulated flipped learning, performed better academically and showed higher levels of self-regulation, motivation, and positive attitudes towards learning compared to those in the control group.
(Jiang et al., 2023)	• The Positive Effects of Growth Mindset on Students' Intention toward Self-Regulated Learning during the COVID-19 Pandemic: A PLS-SEM Approach	• The research explored the impact of a growth mindset on students' intention towards self-regulated learning during the COVID-19 pandemic. Findings suggest that a growth mindset enhances students' intentions to engage in self-regulated learning, mediated by perceived behavioral control and behavior attitude, and influenced by perceived teacher support.
(Vargas-Mendoza & Gallardo, 2023)	• Influence of Self-Regulated Learning on the Academic Performance of Engineering Students in a Blended-Learning Environment	• Their study assessed the influence of self-regulated learning on the academic performance of engineering students in a blended learning environment. Results showed that students with higher levels of self-regulation achieved better academic outcomes and demonstrated more effective management of cognitive and organizational strategies.
(Nan-Cenka et al., 2023)	• The Third Wave of Self-Regulated Learning's Measurement and Intervention Tools: Designing 'Diaria' as a New Generation of Learning Diary	• The research introduced 'Diaria', a new learning diary tool intended as part of the third wave of self-regulated learning's measurement and intervention tools. The tool was found to be usable and beneficial in enhancing self-regulation among students, particularly in a linear algebra course.
(Tingting-Wang et al., 2023)	• The Interplay Between Cognitive Load and Self-Regulated Learning in a Technology-Rich Learning Environment	• This study investigated the interplay between cognitive load and self-regulated learning in a technology-rich learning environment, specifically in medical education. It found that high cognitive load negatively affects task performance and is mediated by self-regulated learning behaviors during self-reflection phases.

Author(s)	Title	Study Context and Findings
(Alserhan et al., 2023)	• Personal Learning Environments: Modeling Students' Self-Regulation Enhancement Through a Learning Management System Platform	• Their research focused on enhancing self-regulation through a Personal Learning Environment integrated with a Learning Management System. The study showed that such integration can significantly enhance self-regulated learning, particularly when tailored to active learning strategies and self-reflection
(Ye et al., 2023)	• Analysis of Differences in Self-Regulated Learning Behavior Patterns of Online Learners	• The study analyzed differences in self-regulated learning behavior patterns among online learners. It identified distinct behavior patterns linked to different performance levels, demonstrating that more active and cognitive-oriented behaviors are associated with better academic outcomes.

Lin et al. (2023) explored virtual interaction strategies, developing scaffolding tools that significantly improved self-regulation and learning performances in virtual environments. Cerón et al. (2024) introduced 'Autorregulate,' a tool designed to facilitate self-regulated learning in MOOCs, showing positive effects on self-regulation and tool usability. Kong et al. (2024) proposed the 6-P pedagogy integrating generative AI tools in academic writing to foster critical thinking and self-regulation. Meanwhile, studies like that of Hüseyin-Ateş (2024) and Vargas-Mendoza and Gallardo (2023) investigated the effects of self-regulated learning in flipped and blended learning environments, respectively, demonstrating improved academic performance and effective cognitive strategy management among students.

Further investigations by Jiang et al. (2023) highlighted the positive effects of a growth mindset on self-regulated learning intentions during the COVID-19 pandemic. Nan-Cenka et al. (2023) presented 'Diaria,' a new tool in the realm of self-regulated learning tools, proving its usability and effectiveness in a linear algebra course. Studies by Tingting-Wang et al. (2023) and Alserhan et al. (2023) examined cognitive load and personal learning environments, respectively, showing how self-regulation could be enhanced through technology-rich learning settings and learning management systems. Lastly, Ye et al. (2023) analyzed behavioral patterns in online learning, identifying behaviors that correlated with better academic outcomes, highlighting the critical role of active and cognitive-oriented behaviors in successful self-regulated learning. These studies collectively emphasized the varied approaches and positive impacts of integrating self-regulated learning strategies within different educational frameworks and technologies.

Novelty of Current Research

The novelty of the current study lay in its integrated approach that combined online self-regulated learning with virtual labs to enhance critical thinking skills in STEM students. Prior research had extensively explored the separate impacts of self-regulated learning and virtual lab environments on student learning outcomes (see Table 1); however, few studies specifically investigated the synergistic effects of merging these two approaches within the context of STEM education. This integration was critical as it married the self-paced, reflective aspects of self-regulated learning with the interactive, experimental capabilities of virtual labs, offering a unique platform for students to apply theoretical knowledge in practical scenarios. The focus on both the cognitive strategies involved in self-regulated learning and the hands-on experimental activities facilitated by virtual labs was expected to foster a deeper engagement and understanding among students, which was essential for nurturing critical thinking skills.

Additionally, this study sought to address a gap in the literature by examining how virtual labs could be strategically integrated with self-regulated learning techniques to not only engage students but also effectively develop their critical thinking capabilities. The interactive nature of virtual labs allowed students to experiment with and manipulate variables in simulated environments, which enhanced their ability to analyze and solve complex problems. This approach was particularly relevant given the growing emphasis on digital competencies in education and the need for pedagogical strategies that effectively integrated technology to foster critical thinking and independent learning in an online setting. By leveraging the advantages of both self-regulated learning and virtual labs, this study aimed to investigate the effectiveness of integrating online self-regulated learning with virtual labs in enhancing critical thinking skills among STEM students.

METHOD

Research Design

This study utilized an experimental method approach to comprehensively analyze the effects of online self-regulated learning assisted by virtual labs on the critical thinking skills of STEM students. By adopting a controlled experimental design, the study delineates two distinct groups: an experimental group and a control group. The experimental group participates in a two-month intervention where online self-regulated learning strategies are synergized with interactive virtual labs. This intervention aims to foster critical thinking through active engagement and manipulation of variables within simulated lab environments, reflective learning, and strategic planning. Conversely, the control group continues with traditional instructional methodologies, which typically involve lecture-based teaching without the incorporation of virtual labs or explicit training in self-regulated learning strategies. This dichotomy allows for a clear evaluation of the educational intervention's effectiveness by comparing the critical thinking outcomes between the two groups through pretest and posttest assessments. The design's strength lies in its ability to isolate the specific contributions of online self-regulated learning strategies augmented by virtual labs to student learning outcomes, thereby providing insights into the potential enhancements in critical thinking capabilities.

Participants

This study was carried out with 70 STEM students at Mandalika University of Education, who were methodically divided into two groups: an experimental group and a control group, each comprising 35 students. The gender composition of the experimental group included 55% male and 45% female students, whereas the control group consisted of 52% male and 48% female students. All participants were within the age range of 18 to 19 years. Random assignment of participants to the experimental and control groups was implemented to foster diversity among the sample and to mitigate potential biases that could affect the outcome of the study. This randomization process is crucial in experimental designs to ensure that any observed effects can be attributed to the experimental intervention rather than pre-existing differences among participants.

Ethical adherence was a cornerstone of this research. Prior to the commencement of the study, all participants provided informed consent, signifying their understanding and agreement to participate under the outlined conditions. The research was conducted in strict accordance with the ethical guidelines set forth by the Mandalika University Institutional Review Board (IRB). The IRB reviewed and approved all research procedures, confirming that they met the necessary ethical standards. This approval was essential to proceed, ensuring that the confidentiality, privacy, and welfare of all participants were safeguarded throughout the research process. Such measures are vital to maintain trust and integrity in academic research, particularly when dealing with human subjects.

Research Procedures

The study was structured over a two-month period, during which critical data were systematically gathered at two pivotal junctures: initially before the interventions commenced (pretest) and subsequently after the completion of the intervention period (posttest). This dual-point collection framework was essential to assess the baseline and the evolved critical thinking skills of the participants. The intervention for the experimental group comprised engagement with virtual labs, designed to provide a hands-on, interactive experience simulating real scientific investigations, coupled with a comprehensive online self-regulated learning curriculum. This learning included activities designed to enhance participants' ability to plan, monitor, and evaluate their learning processes. In contrast, the control group continued with their standard curriculum, receiving traditional lecture-based instruction without the inclusion of virtual labs or structured self-regulatory tasks. This methodological setup was intended to isolate the effect of the innovative educational approach from that of conventional teaching methods.

To ensure the integrity and reliability of the results, data collection was meticulously standardized across both groups. Participants were assessed in similar settings to control for environmental variables that could potentially influence their performance. For example, the same type of classroom was used for both the pretest and posttest for all participants, and the tests were administered under the same conditions regarding time of day and duration. Additionally, the assessment tools were carefully designed to be objective and relevant to the critical thinking skills pertinent to STEM education, thereby ensuring that the evaluation criteria were consistent across both groups. The deliberate control of these variables was crucial for minimizing external influences on the data collected, thus bolstering the study’s findings by ensuring that any differences observed could be attributed with greater confidence to the educational interventions rather than to extraneous factors.

Instruments and Analysis

Quantitative data were collected using a critical thinking skills test administered as both a pretest and a posttest to measure the improvement in students’ abilities. The test consisted of standardized questions designed to assess various dimensions of critical thinking such as interpretation, analysis, evaluation, inference, explanation, and self-regulation (Facione, 2020). Critical thinking skills data is descriptively processed into five scoring scales, where the lowest score is 0 and the highest is +4. They are then converted into criteria ranging from not critical to very critical. Differences in the average score of critical thinking skills between indicators and groups using the ANOVA test. The choice of ANOVA for statistical analysis was due to its efficacy in comparing means among two groups and detecting interaction effects. This method is essential for assessing the differential impact of the learning interventions on the two groups over time, as it allows for a more comprehensive understanding of how the interventions influence the groups differently, accounting for variations within and between the groups and their interactions with the learning interventions across multiple time points.

RESULTS AND DISCUSSION

The results section of the study presents the findings from the analysis of the data collected during the two-month period of the experimental intervention. The results are primarily quantified in terms of changes in critical thinking skills among STEM students participating in online self-regulated learning assisted by virtual labs. Quantitative data from pretests and posttests are supplemented by qualitative insights from interviews, providing a comprehensive understanding of the intervention's impact. The analysis focuses on comparing the experimental group, which engaged in online self-regulated learning and virtual labs, with the control group, which followed traditional instructional methods.

The Table 2, Table 3, and Figure 1 delineates various indicators of critical thinking—interpretation, analysis, evaluation, inference, explanation, and self-regulation. These indicators were measured at two intervals: before the intervention (pretest) and after the intervention (posttest), with the parameters of average score of students' critical thinking skills (Table 4). Additionally, statistical tools such as ANOVA were used to determine the significance of the differences observed between the groups over time, as shows in Table 5.

Table 2 presents the pre-test results of critical thinking skills among STEM students, comparing the experimental group with the control group across various critical thinking indicators: interpretation, analysis, evaluation, inference, explanation, and self-regulation. Initially, both groups showed comparable results, with mean scores roughly around 2.2 for most indicators, suggesting a moderate level of critical thinking skills prior to the intervention. The experimental group exhibited slightly higher means in the interpretation, evaluation, and explanation aspects, whereas the control group performed better in analysis and had similar scores in self-regulation. These findings illustrate a baseline equivalence between the two groups, setting a foundation for assessing the impact of the intervention on enhancing these critical faculties.

Table 2. Pre-test results of students critical thinking skills

CT indicators	Group	Valid	Mean	SE	SD	Coeff. of var.
Interpretation	Control	35	2.162	0.079	0.468	0.216
	Experimental	35	2.196	0.062	0.366	0.167
Analysis	Control	35	2.464	0.125	0.739	0.300
	Experimental	35	2.143	0.088	0.521	0.243
Evaluation	Control	35	2.233	0.074	0.436	0.195
	Experimental	35	2.291	0.097	0.575	0.251
Inference	Control	35	2.155	0.082	0.486	0.226
	Experimental	35	2.057	0.079	0.468	0.227
Explanation	Control	35	2.051	0.077	0.454	0.221
	Experimental	35	2.205	0.111	0.654	0.297
Self-regulation	Control	35	2.166	0.076	0.448	0.207
	Experimental	35	2.164	0.091	0.538	0.249

Table 3 outlines the post-test results, indicating significant improvement in the experimental group’s critical thinking skills across all indicators after engaging with the online self-regulated learning and virtual labs. The mean scores for the experimental group saw substantial increases, with interpretation jumping from approximately 2.2 to 3.6, and other indicators like analysis and inference reaching beyond 4.0. Conversely, the control group's improvements were modest, with scores in all categories remaining under 3.0. This pronounced difference underscores the effectiveness of the integrated self-regulated learning and virtual lab approach in fostering critical thinking, compared to traditional methods used with the control group.

Table 3. Post-test results of students critical thinking skills

CT indicators	Group	Valid	Mean	SE	SD	Coeff. of var.
Interpretation	Control	35	2.291	0.091	0.540	0.236
	Experimental	35	3.586	0.134	0.796	0.222
Analysis	Control	35	2.836	0.115	0.680	0.240
	Experimental	35	4.110	0.118	0.697	0.170
Evaluation	Control	35	2.696	0.112	0.664	0.246
	Experimental	35	4.011	0.133	0.786	0.196
Inference	Control	35	2.531	0.098	0.580	0.229
	Experimental	35	4.395	0.100	0.589	0.134
Explanation	Control	35	2.679	0.108	0.638	0.238
	Experimental	35	4.184	0.131	0.777	0.186
Self-regulation	Control	35	2.612	0.105	0.618	0.237
	Experimental	35	4.183	0.116	0.687	0.164

Table 4 consolidates these findings into average scores of students' critical thinking skills both pre- and post-test. Initially, both groups started at similar levels, with means around 2.2. After the intervention, the experimental group’s average score significantly increased to approximately 4.1, far surpassing the control group’s average of 2.6. This highlights the substantial impact of combining virtual labs with self-regulated learning strategies on enhancing critical thinking skills in STEM education. The notable improvement in the experimental group underscores the effectiveness of these innovative educational approaches.

Table 4. Average score of students' critical thinking skills

Testing	Group	Valid	Mean	SE	SD	Coeff. of var.
Pretes	Control	35	2.205	0.041	0.242	0.110
	Experimental	35	2.176	0.041	0.244	0.112
Posttest	Control	35	2.607	0.052	0.309	0.119
	Experimental	35	4.129	0.083	0.493	0.119

The results from Tables 2, 3, and 4 collectively demonstrate that the integration of virtual labs with online self-regulated learning significantly enhances critical thinking skills among STEM students. The experimental group, equipped with innovative digital tools and learning strategies, showed marked improvements across all critical thinking indicators compared to the control group, which followed more conventional educational methods. This supports the hypothesis that more interactive and engaging learning environments, which allow students to experiment and regulate their learning pace, are crucial for developing higher-order thinking skills. These findings provide strong empirical support for the effectiveness of combining self-regulated learning frameworks with virtual lab environments in STEM education, paving the way for further research and implementation of such pedagogical strategies. The significant improvement in the experimental group's scores demonstrates the potential of these methods to enhance critical thinking skills. Furthermore, the scatter plots of students' critical thinking skills, illustrating the average scores from pre-test and post-test assessments, are presented in Figure 1. This visual representation further emphasizes the impact of the interventions, highlighting the clear distinctions between the experimental and control groups.

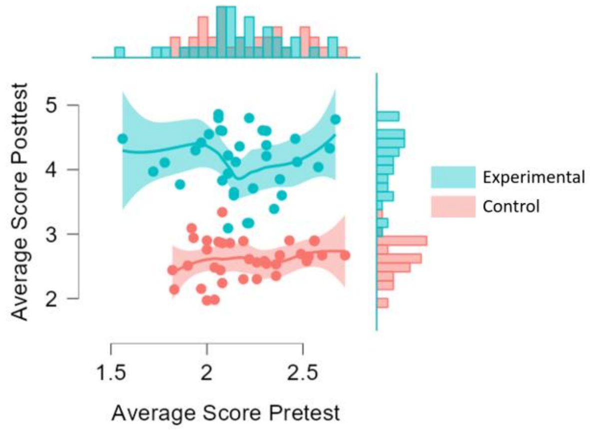

Figure 1. Scatter plots of students' critical thinking skills from the average score of pre-test and post-test

The scatter plots and trend lines in Figure 1 clearly illustrate that the experimental group demonstrates a significant upward shift in post-test scores compared to their pre-test scores. The trend line for this group shows a steep incline, suggesting a strong positive correlation between the intervention and improvements in critical thinking skills. Most points for the experimental group are clustered around higher post-test scores, particularly noticeable in the range above 3.5, reaching up to 5. This starkly contrasts with the control group (shown in pink), where the post-test scores show a flatter trend line, indicating minimal improvement. The control group's scatter plot points are densely packed around the lower range of the post-test score axis, mainly between 2 and 3, demonstrating that traditional teaching methods did not significantly enhance critical thinking skills. This observation aligns with the histograms, where the control group's post-test scores remain clustered around the lower end, while the experimental group's scores are visibly spread over a higher range.

Tables 5 and 6 in the study provide a statistical analysis of the intervention's impact on critical thinking skills, employing ANOVA and post hoc tests to analyze the differences between the control and experimental groups before and after the intervention.

Table 5. The results of ANOVA

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Within Subjects Effects						
RM Factor	48.534	1	48.534	450.209	< .001	0.464
RM Factor ✻ Group	21.037	1	21.037	195.148	< .001	0.201
Residuals	7.331	68	0.108			
Between Subjects Effects						
Group	19.500	1	19.500	161.623	< .001	0.186
Residuals	8.204	68	0.121			

Note: RM Factor = repeat measure factor (pretest – posttest)

Table 5 details the results of the ANOVA, which evaluates the effects of the intervention on critical thinking skills using within-subjects and between-subjects effects. The within subject effects section shows a significant repeat measure factor (pretest to posttest) with an F value of 450.209 and a p-value of less than 0.001, indicating a substantial improvement in critical thinking over time across all participants. The interaction between the repeat measure factor and group is also significant (F = 195.148, p < 0.001), demonstrating that the change in critical thinking skills varied significantly between the experimental and control groups. The partial eta squared (η^2) values of 0.464 and 0.201 suggest a large effect size for both the time factor alone and the interaction effect, respectively. In the between subject effects, the analysis shows that the group factor alone (comparing overall scores between control and experimental groups without considering time) also results in significant differences (F = 161.623, p < 0.001) with an effect size of 0.186, confirming that the groups differed significantly in their critical thinking scores overall, which is influenced significantly by the intervention.

Table 6. The results of post hoc comparisons - Group ∗ RM Factor 1 (pretest – posttest)

Variables		**Mean Diff.**	**SE**	**t**	**Cohen's d**	p_{tukey}
Control - pretest	Exp. - pretest	0.029	0.081	0.357	0.085	0.984
	Control - posttest	-0.402	0.078	-5.126	-1.190	< .001
	Exp. - posttest	-1.924	0.081	-23.814	-5.693	< .001
Exp. - pretest	Control - posttest	-0.431	0.081	-5.336	-1.276	< .001
	Exp. - posttest	-1.953	0.078	-24.881	-5.778	< .001
Control - posttest	Exp. - posttest	-1.522	0.081	-18.835	-4.502	< .001

Table 6 presents the results of post hoc comparisons specifically focusing on the interaction between the group and the repeat measure factor (pretest to posttest). The experimental group showed a much larger negative mean difference from pretest to posttest (-1.924) compared to the control group (-0.402), indicating a significantly greater improvement in the experimental group's critical thinking skills. The extremely large t-value (-23.814) and Cohen's d (-5.693) underline the robustness and size of this effect. Comparisons within the groups from pretest to posttest reveal that both groups improved, but the experimental group's improvement was dramatically larger, as indicated by a significantly larger Cohen's d. The control group's change from pretest to posttest was statistically significant (p < .001), suggesting some improvement even with traditional methods, but not nearly as pronounced as in the experimental group. The statistical analysis in Tables 5 and 6 robustly supports the effectiveness of integrating virtual labs with online self-regulated learning in enhancing critical thinking skills among STEM students. The significant interaction effects and the large improvements in the experimental group highlight how digital tools that foster active learning and self-regulation can significantly enhance educational outcomes in critical thinking, compared to traditional educational approaches.

These results are in line with previous studies that traditional teaching routines have been associated with lower levels of critical thinking among students (Karanezi et al., 2015; Lee et al., 2016; Stetzik et al., 2015). These studies suggest that traditional teaching approaches often prioritize information delivery and memorization over the active development of critical thinking skills students (Karanezi et al., 2015; Stetzik et al., 2015). Conversely, research supports that non-traditional teaching methods, such as interactive and student-centered approaches, are more effective in fostering critical thinking (Strelets, 2019). As proven in our current study, that online self-regulated learning assisted by virtual labs can train and improve STEM students' critical thinking skills. The results of the current research are supported by several previous studies, where virtual labs have emerged as a valuable solution to the limitations of traditional practical classes in STEM education (Lynch & Ghergulescu, 2017). They provide environments for students to interact with virtual objects and apparatus, aiding in the development of critical thinking skills. Additionally, virtual simulation-assisted remote inquiry has been shown to positively impact prospective STEM teachers' critical thinking skills (Bilad et al., 2022). Virtual simulation is recognized as a pedagogical approach that can enhance learning experiences (Manik et al., 2022). Previous research also supports the findings of this study. For instance, the integration of the STEM approach in online science education has been shown to enhance and develop students' critical thinking skills (Arisa & Sitinjak, 2022).

Online self-regulated learning assisted by virtual labs offers numerous advantages in improving STEM students' critical thinking skills. Virtual labs provide a dynamic and interactive environment for students to engage with practical experiments and simulations, fostering a deeper understanding of STEM concepts (Fadda et al., 2022; Gunawan et al., 2017). These virtual environments enhance students' problem-solving skills, as they can experiment and explore without the constraints of physical laboratories. Moreover, virtual labs have been found to increase students' interest, relaxation, and overall quality of learning experiences (Gunawan et al., 2017). Incorporating virtual labs into STEM education aligns with the STEM approach, which has been shown to encourage critical thinking skills among students (Yaki, 2022). The use of virtual labs in STEM education can significantly impact students' critical thinking abilities by providing opportunities for inquiry-based learning and experimentation (Purnama et al., 2021). Additionally, virtual labs can be integrated into various teaching strategies. The iterative nature of virtual labs allows students to test hypotheses, observe outcomes, and revise their understanding, thereby improving their scientific literacy and critical thinking abilities (Liu et al., 2022).

The success of this research lies in the self-regulated learning intervention. Self-regulated learning is a key factor in improving STEM students' critical thinking skills. Self-regulated learning enables students to control their learning process, establish goals, monitor their progress, and adjust strategies to achieve academic success (Vogt, 2008). Previous research has demonstrated that self-regulated learning strategies, such as elaboration, are crucial for knowledge acquisition and retention, which are foundational elements of critical thinking (Vogt, 2008). The implementation of self-regulated learning in mathematics education has been shown to have a positive impact on students' critical thinking abilities, particularly in areas such as information analysis and evaluation of evidence (Firdaus et al., 2015). Additionally, self-regulated learning programs have been associated with significant enhancements in critical thinking skills among high school students participating in IT/STEM programs (Duran & Sendag, 2012). When STEM education is combined with self-regulated learning, it has been proven to enhance students' critical thinking skills across different educational levels (Kusmawan, 2022). Moreover, innovative teaching models like the Science Critical Thinking (SCT) approach, which integrates self-regulated learning principles, have been effective in enhancing critical thinking and self-efficacy among chemistry teacher candidates (Rusmansyah et al., 2019). The incorporation of self-directed learning models has also been linked to improvements in students' critical thinking abilities (Wasyilah et al., 2021).

Furthermore, the integration of self-regulated learning with metacognitive approaches has been shown to effectively enhance students' critical thinking skills (Wong et al., 2022). E-learning models that integrate self-regulated learning features have been found to enhance students' critical thinking abilities (Supriyatno et al., 2020). Additionally, the development of digital modules based on self-regulated learning principles has been successful in improving students' critical thinking skills in subjects such as mathematics (Kusmaharti & Yustitia, 2022). The impact of self-regulated learning using tools like Geogebra has been associated with improvements in students' critical thinking abilities (Hidayati & Kurniati, 2018). Overall, the integration of online self-regulated learning with virtual labs in STEM education offers a versatile and effective approach to enhancing STEM students' critical thinking skills.

The comprehensive analysis in the current study underscores the advantages of moving away from traditional teaching methods, which often emphasize rote memorization, towards more interactive, student-centered approaches that are more effective in fostering critical thinking skills in STEM students. The use of online self-regulated learning and virtual labs, as demonstrated in this research, significantly enhances students' ability to engage with and understand complex scientific concepts through practical experiments and simulations. This educational model not only improves problem-solving skills but also increases student interest and engagement by providing a dynamic and interactive learning environment free from the physical constraints of traditional labs. Furthermore, the research aligns with previous findings that virtual labs and self-regulated learning can substantially impact students' analytical capabilities and scientific literacy by allowing them to experiment, observe outcomes, and refine their understanding continuously. This approach not only enhances their immediate learning outcomes but also prepares them for future academic and professional challenges by fostering a robust foundation in critical thinking, crucial for success in STEM fields.

CONCLUSION

This study conclusively demonstrates the efficacy of integrating online self-regulated learning with virtual labs to enhance critical thinking skills in STEM students. The experimental approach, blending interactive virtual labs with strategic, reflective self-regulated learning techniques, significantly improved students' performance across all critical thinking indicators compared to traditional teaching methods. These findings underscore the potential of using sophisticated digital tools and customized educational strategies to cultivate essential skills like critical thinking, which are pivotal in navigating the complexities of modern scientific challenges. Moreover, the research highlights the critical role of self-regulated learning in fostering an environment where students can independently explore and engage with complex concepts, thereby enhancing their analytical and problem-solving skills. This study contributes to the growing body of evidence supporting the integration of technology in education to provide dynamic, interactive learning experiences that not only engage students but also significantly improve their critical thinking capabilities. The success of this educational model suggests a promising direction for future educational strategies and curricula in STEM fields, advocating for a broader implementation of virtual labs and self-regulated learning frameworks to better prepare students for the demands of the digital age.

LIMITATION

Despite the encouraging results, this study faces several limitations that merit consideration. The primary constraint is the relatively small sample size and the specific demographic of STEM students from a single educational institution, which may limit the generalizability of the findings to broader populations or different educational contexts. Additionally, the study's duration of two months may not sufficiently capture the long-term effects and sustainability of the critical thinking skills developed through this method. Another potential limitation is the reliance on self-reported data, which can introduce biases related to students' perceptions and self-assessment capabilities. Finally, the control group's traditional learning environment may not have been entirely devoid of self-regulated learning opportunities, possibly diluting the comparative impact of the intervention. These factors suggest the need for further research with more diverse and larger populations, extended timelines, and refined methodological approaches to better understand and validate the effectiveness of integrating virtual labs with online self-regulated learning in enhancing critical thinking skills.

RECOMMENDATION

For future research, it is recommended to expand the scope and scale of the study to include a more diverse and larger sample of STEM students from various educational institutions. This would enhance the generalizability of the results and provide a more comprehensive understanding of the impact of virtual labs and self-regulated learning across different contexts and cultures. Additionally, extending the duration of the study could offer insights into the long-term retention and application of critical thinking skills developed through this educational approach. Incorporating a mixed-methods approach that combines quantitative assessments with qualitative feedback can also provide deeper insights into students' experiences and perceptions, thereby enriching the data and offering a more nuanced evaluation of the learning interventions. Furthermore, developing and testing a variety of virtual lab scenarios and self-regulated learning strategies could identify the most effective elements and configurations for maximizing critical thinking enhancement. Lastly, future studies should consider implementing control measures to better isolate the effects of self-regulated learning and virtual lab interventions from other educational activities, ensuring a clearer assessment of their unique contributions to students' critical thinking development.

Author Contributions

The authors have sufficiently contributed to the study, and have read and agreed to the published version of the manuscript.

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Declaration of Interest

The authors declare no conflict of interest.

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