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Implementing a Hybrid Ethnoscience Project-Based Learning (E-PjBL) Model Integrated with Virtual Assistive Technology to Enhance Critical Thinking Performance of Science Teacher Candidates

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Abstract

Training critical thinking skills in science teacher candidates (STC) faces challenges, particularly due to the ineffectiveness of traditional teaching models, resulting in suboptimal critical thinking performance. This study aims to implement a Hybrid Ethnoscience Project-Based Learning (E-PjBL) model integrated with virtual assistive technology as a solution to enhance critical thinking performance in STC. A mixed-method approach combining quantitative and qualitative methods was utilized. An experimental design involving 51 STC at the University of Mataram was conducted, dividing participants into experimental and control groups. The experimental group engaged in learning activities using the hybrid E-PjBL model, while the control group followed traditional teaching methods. Quantitative data were collected through critical thinking skill tests administered pre- and post-intervention, while qualitative data were obtained from observations of learning implementation. Results demonstrated that the hybrid E-PjBL model significantly enhanced critical thinking skills compared to traditional methods. The experimental group's posttest scores averaged 4.123, significantly higher than the control group's 2.667. Statistical analysis using ANOVA revealed substantial differences in critical thinking scores between the groups, with an F-value of 99.613 ($p < 0.001$) for between-subject effects. Furthermore, a significant interaction was observed between test repetition (pretest-posttest) and group (control vs. experimental), with an F-value of 104.205 ($p < 0.001$). Qualitative findings indicated the model's practicality, as evidenced by high student participation and engagement. These findings highlight that integrating ethnoscience, project-based learning, and virtual assistive technology offers an innovative and effective pedagogical approach to enhancing the quality of science teacher education. Further research is needed to explore the model's adaptability across diverse educational contexts.

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INTRODUCTION

The acquisition of critical thinking skills is essential for science teacher candidates (STC), particularly as a core objective in cultivating a talent pool of students under the Independent Learning-Independent Campus (*Merdeka Belajar Kampus Merdeka* - MBKM) program in Indonesia (Prayogi et al., 2022). In modern higher education systems, critical thinking is recognized as a competency that supports students' future professional abilities (Erikson & Erikson, 2019). Consequently, critical thinking is emphasized as a fundamental graduate attribute in the curricula of developed nations (Verawati et al., 2019). This implies that every teaching effort should be oriented toward improving students' critical thinking performance (Bezanilla et al., 2019). However, achieving this goal remains challenging, as fostering critical thinking skills is still a prevalent issue (Lee et al., 2021), largely due to the inadequacy of instructional models employed in teaching practices (Gilmanshina et al., 2021).

As a result, the critical thinking performance of students often falls short of expectations. For instance, a recent essay-based study on STC in Sweden revealed poor analytical skills (Trostek, 2020). Similarly, ineffective learning experiences that fail to emphasize critical thinking through effective pedagogy have led to low critical thinking performance among teacher candidates in China (Ma & Luo, 2021). Studies in Indonesia have reported equally concerning findings, where STC' critical thinking skills remain undeveloped in classroom settings (Fitriani et al., 2019). Moreover, the abstract nature of science content often compounds learning difficulties and impedes the development of students' critical thinking skills (El Kharki et al., 2021). This situation calls for serious and well-planned efforts to address the low critical thinking skills among STC (Fitriani et al., 2019).

The emphasis on critical thinking has been outlined in the Indonesian National Higher Education Standards (SN-Dikti), particularly regarding process standards aimed at fostering critical thinking. This is further supported by the MBKM program, which underscores project-based learning (PjBL). PjBL is considered more engaging than traditional teaching methods (Maros et al., 2021) and enhances student participation (Made et al., 2022). However, studies have shown that PjBL is not robust enough to foster critical thinking when applied as a standalone model (Sumarni & Kadarwati, 2020). A potential solution is to combine PjBL with digital technology, particularly advanced assistive technologies (Hujjatusnaini et al., 2022). To the best of our knowledge, such a hybridization of PjBL with advanced assistive technology—while maintaining the characteristics of learning processes as outlined in SN-Dikti—has yet to be realized. Consequently, the issue of underdeveloped critical thinking skills among STC remains a priority problem that needs resolution.

The inadequacy of critical thinking skills among students is often attributed to training mechanisms that fail to employ appropriate instructional models. This underscores the need for developing innovative pedagogical models to train and enhance critical thinking skills in STC. Researchers in 2023 developed a Hybrid Ethnoscience-Project-Based Learning (E-PjBL) model integrated with virtual assistive technology (Wahyudi et al., 2023). This pedagogical model has been validated through a Focus Group Discussion (FGD) mechanism and deemed content- and construct-valid for improving students' critical thinking performance. Simulation results have also shown the potential of this model to enhance the critical thinking performance of teacher candidates in science education (Wahyudi et al., 2023). Building on these findings, this study seeks to implement the E-PjBL model integrated with virtual assistive technology and evaluate its practicality and effectiveness in improving the critical thinking performance of STC.

Problem-Solving Approach

Addressing the low critical thinking performance of STC requires the intervention of innovative pedagogical infrastructure, which integrates three key aspects. The first aspect involves ensuring that the learning process aligns with the standards set by the Indonesian National Higher Education Standards (SN-Dikti). This standard emphasizes holistic learning processes that foster comprehensive thinking patterns while integrating local wisdom. Ethnoscience-based learning, which incorporates cultural knowledge into the educational context, serves as a practical means to achieve these objectives. Such an approach not only enhances cognitive engagement but also encourages students to contextualize their learning within their cultural framework, fostering deeper understanding and critical analysis (Sudarmin et al., 2019).

The second aspect focuses on modernizing learning processes to create opportunities for students to manipulate and refine their cognitive skills through exploration. Project-Based Learning (PjBL) is recognized as an effective method for engaging students in active learning, promoting critical inquiry, and fostering problem-solving abilities. This approach aligns well with the Independent Learning-Independent Campus (MBKM) program, which emphasizes student-centered, experiential learning models. By engaging students in complex projects that require exploration and creativity, PjBL provides a structured environment for developing higher-order thinking skills (Almazroui, 2022). However, its efficacy can be further enhanced by incorporating advanced digital tools, which leads to the third aspect of the approach.

The third aspect involves integrating virtual assistive technology to establish a digital pedagogical infrastructure. Virtual assistive technologies can create a dynamic and motivating learning environment by providing interactive and visually engaging content. These tools are particularly effective for visualizing abstract scientific concepts and presenting ethnoscience contexts in ways that are accessible and relatable for students. This integration not only aids in the comprehension of complex materials but also fosters critical thinking through enhanced student interaction and participation (Papadakis, 2021; Poultsakis et al., 2021). Additionally, the use of such technology aligns with global trends in digital education, which emphasize the importance of leveraging technological advancements to enhance pedagogical outcomes (Bilad et al., 2022).

The combination of these three aspects forms the foundation of the Hybrid Ethnoscience-Project-Based Learning (E-PjBL) model. This innovative model blends ethnoscience with PjBL, enhanced through the use of virtual assistive technology. By doing so, it offers a comprehensive framework that addresses the limitations of traditional pedagogical approaches in fostering critical thinking. The hybrid model provides students with experiential learning opportunities that are culturally relevant, cognitively stimulating, and digitally enhanced, making it a practical and effective solution for improving critical thinking performance.

Research Objective

The objective of this study is to implement and evaluate the Hybrid Ethnoscience-Project-Based Learning (E-PjBL) model integrated with virtual assistive technology in improving the critical thinking performance of science teacher candidates (STC).

State of the Art and Novelty of the Study

Empirical studies have demonstrated that ethnoscience, Project-Based Learning (PjBL), and virtual assistive technology have been examined within separate domains. However, their combination as an innovative pedagogical infrastructure to train critical thinking skills in STC remains unexplored. Ethnoscience, as a developing concept, integrates local cultural values with scientific principles (Sudarmin et al., 2019). It serves as a knowledge system encompassing explanations about nature with practical applications and predictive purposes in learning processes (Wang, 2013). Previous studies have shown that integrating ethnoscience into learning enhances the scientific literacy of teacher candidates (Dewi et al., 2021) and influences their logical and critical thinking approaches in science learning (Risdianto et al., 2020; Verawati et al., 2022).

Practical teaching using an ethnoscience context can promote thinking skills, particularly when combined with a core learning model that emphasizes exploration (Verawati et al., 2022). Through exploration, students' cognitive skills can develop as potential indicators of critical thinking improvement (Wahyudi et al., 2018, 2019a, 2019b). One exploratory learning method capable of helping students develop and manipulate cognitive skills is Project-Based Learning (PjBL) (Almazroui, 2022). PjBL aligns with the methods emphasized in the Independent Learning-Independent Campus (MBKM) program and positively impacts motivation, collaborative performance, and real-world competency development (Hussein, 2021; Molina-Torres, 2022; Ngereja et al., 2020). The investigative processes in PjBL, particularly when supported by technology, enhance students' creativity in thinking, improve academic achievement (Alamri, 2021), increase engagement (Umar & Ko, 2022), and make learning more appealing (Granado-Alcón et al., 2020).

The integration of modern technology in science education has become increasingly relevant, with virtual systems being a major focus (Stoyanov et al., 2022). This trend reflects current advancements in educational methodologies (Yu & Jee, 2021). The use of virtual technology in science teaching positively influences conceptual understanding, preferences for scientific theories, and the development of thinking skills (Islahudin et al., 2022). By visualizing abstract scientific concepts, virtual technology enhances students' detailed thinking processes, contributing to their analytical and critical thinking abilities (Bilad et al., 2022). Student acceptance of virtual technology applications is notably high (Hassan et al., 2013), with demonstrated positive impacts on knowledge acquisition, skills, and attitudes (Diwakar et al., 2015). Furthermore, virtual technology effectively addresses accessibility challenges in learning (El Kharki et al., 2020) and provides spaces where students can manipulate experimental parameters to meet their needs (de la Torre et al., 2015).

This study introduces virtual assistive technology as a supportive element for the combination of ethnoscience and PjBL (E-PjBL). The developed E-PjBL framework integrates virtual technology into a hybrid model, adaptable to various learning modes, aiming to improve the critical thinking performance of STC. The novelty of this research lies in its integration of ethnoscience, PjBL, and virtual assistive technology into a cohesive pedagogical approach.

The study positions ethnoscience as a method to enhance scientific literacy and influence students' logical and critical thinking skills. PjBL plays a vital role in developing and manipulating cognitive skills while positively impacting motivation, performance, and competency development. Virtual assistive technology significantly contributes by enhancing concept mastery and critical thinking through the visualization of abstract scientific concepts. Together, these components form the foundation of an innovative learning approach that unites the strengths of each method.

The primary novelty of this research lies in the hybrid integration of ethnoscience, PjBL, and virtual assistive technology, termed the Ethnoscience-Project-Based Learning (E-PjBL) model with Virtual Assistive Technology Integration. This approach represents an innovative and flexible pedagogical framework applicable to diverse learning modes for improving the critical thinking skills of STC. The integration aligns with the national higher education standards (SN-Dikti) and supports the core model emphasized in the MBKM program. Consequently, this research not only introduces a sustainable and relevant pedagogical innovation but also contributes significantly to advancing the quality of science teacher education in the digital era.

METHODS

Research Design

This study employed a mixed-method approach, integrating quantitative and qualitative methods to achieve the research objectives (Creswell & Creswell, 2018). The aim was to implement the hybrid E-PjBL model integrated with virtual assistive technology and evaluate its practicality and effectiveness in improving the critical thinking performance of STC. Specifically, the quantitative approach utilized an experimental design with a pretest-posttest control group framework. The experimental group received instruction using the hybrid E-PjBL model integrated with virtual assistive technology, while the control group followed traditional expository teaching methods. Over a two-month period, the intervention was conducted during a basic science course covering topics related to motion and force.

The qualitative approach was applied to evaluate the practicality of the learning model through direct observation of its implementation. This method allowed researchers to collect in-depth data regarding the application of the hybrid E-PjBL model in a real classroom setting.

The combination of these two approaches (quantitative and qualitative) provided a comprehensive understanding of the learning model's impact on enhancing critical thinking skills in STC, while also evaluating its practical applicability in actual learning contexts.

Participants

The study involved 51 STC from the University of Mataram as participants. They were divided into two groups: an experimental group comprising 26 students and a control group with 25 students. The gender distribution was relatively balanced between males and females, and participants' ages ranged from 18 to 19 years. Participants were selected based on their involvement in the MBKM program and their willingness to participate in the study. Ethical approval was obtained from the relevant institutional review board, and all participants were fully informed about the study's objectives and their rights as participants. They were also given the freedom to withdraw from the study at any time without facing any consequences.

The recruitment procedure was voluntary, with eligible students who expressed interest in participating receiving detailed explanations about the research process. Confidentiality of participants' identities was strictly maintained, and all data collected were used solely for research purposes. These measures were taken to ensure that participants felt comfortable and secure throughout the study, adhering to ethical standards for research involving human subjects.

Research Procedure

The study began with the preparation of the hybrid E-PjBL learning system integrated with virtual assistive technology. This system included instructional content and supporting materials for the topics of motion and force, as illustrated in Figure 1.

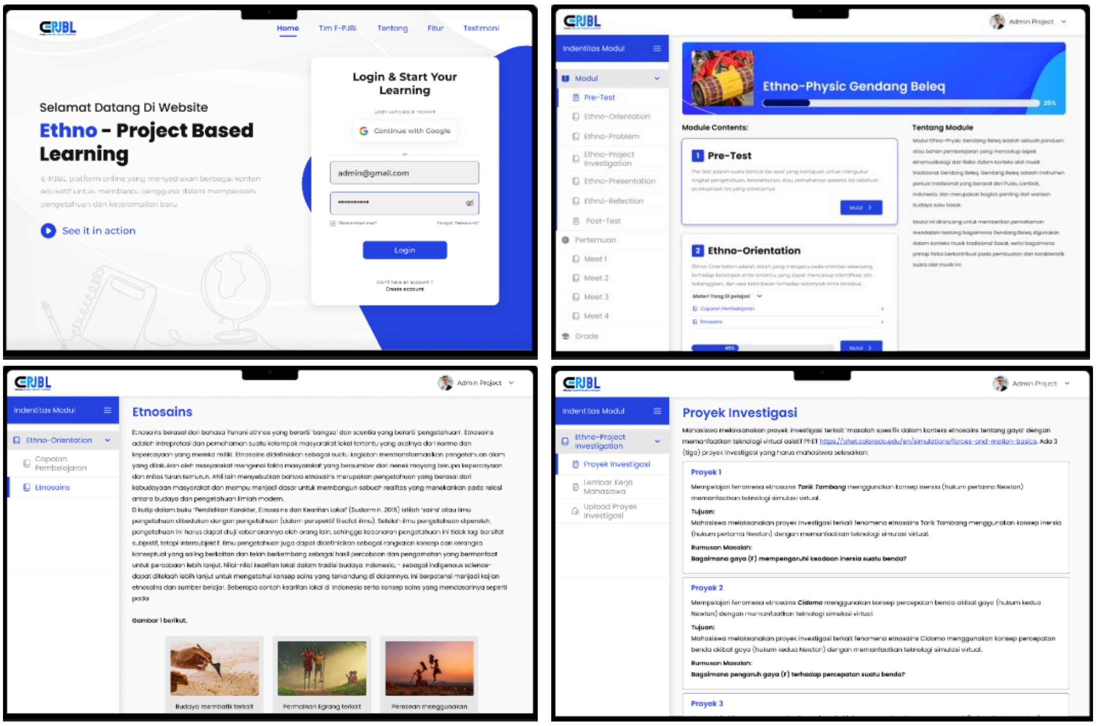

Figure 1. Hybrid E-PjBL learning system integrated with virtual assistive technology

Once the learning system was ready, training sessions were conducted for the course instructors to ensure they understood and could effectively implement the designed learning model. The intervention phase commenced with a pretest to assess the baseline critical thinking skills of students in both the experimental and control groups.

Following the pretest, the experimental group underwent a two-month learning intervention using the hybrid E-PjBL model integrated with virtual assistive technology, while the control group followed traditional instructional methods. During the intervention period, learning implementation observations were conducted to collect qualitative data on the application of the model. At the end of the intervention, a posttest was administered to evaluate the improvement in students' critical thinking skills in both groups. Quantitative data from the pretest and posttest were analyzed to assess the model's effectiveness, while qualitative data from observations were analyzed to evaluate its practicality.

Instruments and Data Analysis

For quantitative data collection, an essay-based critical thinking skill test was used. This test, administered before and after the learning intervention (pretest and posttest), aimed to measure changes in students' critical thinking abilities. The test assessed key indicators such as analysis, inference, evaluation, and decision-making skills. Data from the tests were analyzed using descriptive quantitative methods and statistical ANOVA. The ANOVA analysis aimed to identify significant differences between the experimental and control groups and evaluate the interaction effects between the learning model and critical thinking skills.

For qualitative data collection, observation sheets were used to document the implementation of the learning model during the intervention. Observers completed these sheets to gather detailed insights into the application of the hybrid E-PjBL model. Qualitative data were analyzed descriptively by identifying patterns and themes from the observations. These findings were used to evaluate the strengths and weaknesses of the learning model, providing a comprehensive understanding of its practical application.

RESULTS AND DISCUSSION

The implementation of the hybrid E-PjBL model integrated with virtual assistive technology was carried out among science teacher candidates (STC) at the University of Mataram. The analysis of students' critical thinking performance is summarized in Tables 1, 2, and 3.

Table 1. Pre-test results on STC' critical thinking skills

Indicator	Group	N	Mean	SE	SD	Coeff. of var.
Interpretation	Control	25	2.087	0.097	0.484	0.232
	Experimental	26	2.276	0.070	0.358	0.157
Analysis	Control	25	2.760	0.160	0.802	0.291
	Experimental	26	2.286	0.091	0.466	0.204

Indicator	Group	N	Mean	SE	SD	Coeff. of var.
Evaluation	Control	25	2.206	0.094	0.469	0.213
	Experimental	26	2.290	0.095	0.486	0.212
Inference	Control	25	2.187	0.107	0.534	0.244
	Experimental	26	2.071	0.098	0.501	0.242
Explanation	Control	25	2.080	0.091	0.455	0.219
	Experimental	26	2.365	0.171	0.871	0.368
Self-regulation	Control	25	2.207	0.091	0.453	0.205
	Experimental	26	2.256	0.122	0.623	0.276

The analysis of pre-test critical thinking skills of Science Teacher Candidates (STC), as shown in Table 1, indicates that both the experimental and control groups had relatively similar baseline scores across most critical thinking indicators. For instance, on the Interpretation indicator, the control group had a mean score of 2.087 with a standard error (SE) of 0.097, whereas the experimental group had a slightly higher mean of 2.276 with an SE of 0.070. Other indicators, such as Analysis, Evaluation, and Inference, also exhibited minimal variation between the two groups. However, the Explanation indicator showed that the experimental group had a higher mean score (2.365) compared to the control group (2.080), with greater variability observed in the experimental group. Overall, the pre-test results suggest that before the implementation of the hybrid E-PjBL model integrated with virtual assistive technology, both groups demonstrated nearly balanced critical thinking skills, with a slight advantage in some indicators for the experimental group.

Table 2. Post-test results on STC' critical thinking skills

Indicator	Group	N	Mean	SE	SD	Coeff. of var.
Interpretation	Control	25	2.274	0.105	0.523	0.230
	Experimental	26	3.494	0.170	0.864	0.247
Analysis	Control	25	2.910	0.145	0.725	0.249
	Experimental	26	4.005	0.145	0.737	0.184
Evaluation	Control	25	2.867	0.131	0.653	0.228
	Experimental	26	4.013	0.147	0.751	0.187
Inference	Control	25	2.640	0.110	0.548	0.207
	Experimental	26	4.334	0.126	0.645	0.149
Explanation	Control	25	2.760	0.138	0.690	0.250
	Experimental	26	4.337	0.153	0.781	0.180
Self-regulation	Control	25	2.552	0.121	0.606	0.238
	Experimental	26	4.258	0.105	0.538	0.126

The post-test analysis, presented in Table 2, reveals a significant improvement in critical thinking skills for the experimental group following the application of the hybrid E-PjBL model integrated with virtual assistive technology. For example, on the Interpretation indicator, the experimental group's mean score increased to 3.494, whereas the control group's score showed only a slight rise to 2.274. Similar trends were observed across all other indicators, including Analysis, Evaluation, Inference, Explanation, and Self-regulation, where the experimental group consistently exhibited greater improvements than the control group. Notably, the Inference and Explanation indicators demonstrated the most substantial gains in the experimental group, with mean scores reaching 4.334 and 4.337, respectively, far exceeding the control group's scores of 2.640 and 2.760. These results indicate that the implemented learning model is not only effective but also has a significantly greater impact on enhancing STC's critical thinking skills compared to the traditional expository teaching methods employed in the control group.

The comparison of the mean pre-test and post-test scores for both groups (experimental and control) is presented in Table 3, while the descriptive plot of STC critical thinking scores for both groups is shown in Figure 2.

Table 3. Mean pre-test and post-test scores of experimental and control groups

Testing group	Group	Valid	Mean	SE	SD	Coeff. of var.
Pretes	Control	25	2.255	0.046	0.231	0.102
	Experimental	26	2.258	0.038	0.195	0.086
Posttest	Control	25	2.667	0.062	0.311	0.117
	Experimental	26	4.123	0.114	0.581	0.141

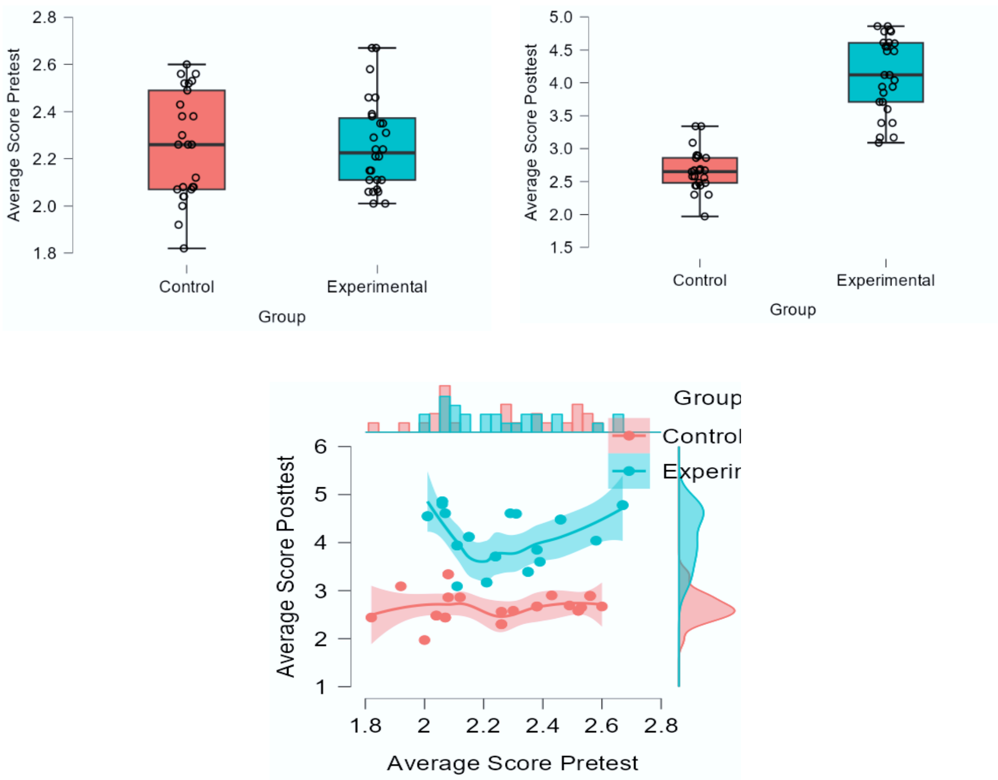

Figure 2. Descriptive plot of STC critical thinking scores

Table 3 summarizes the mean pre-test and post-test scores of both groups. In the pre-test, the control and experimental groups had nearly identical mean scores of 2.255 and 2.258, respectively, with low standard errors, indicating homogeneity among participants within each group before the intervention. However, in the post-test, a notable difference emerged, with the experimental group achieving a mean score of 4.123, nearly double that of the control group, which recorded a mean score of only 2.667. This significant improvement in the experimental group demonstrates that the implementation of the hybrid E-PjBL model integrated with virtual assistive technology is substantially more effective in enhancing critical thinking skills compared to the expository teaching methods used in the control group. The larger post-test score increase, along with the consistently low coefficient of variation, highlights the reliability of the outcomes among STC in the experimental group.

Figure 2 illustrates a comparison of the mean pre-test and post-test critical thinking scores between the control and experimental groups. The plot reveals that both groups exhibited nearly similar pre-test score distributions, with medians around 2.2–2.3, indicating initial homogeneity. However, the post-test results show a significant improvement in the experimental group, with the median score rising sharply to approximately 4.3, whereas the control group experienced only a slight increase, with a median score of around 2.7. The scatter plot further supports these findings, demonstrating a consistent increase in post-test scores for the experimental group regardless of their initial pre-test performance. This indicates that the hybrid E-PjBL model integrated with virtual assistive technology is significantly more effective in enhancing STC's critical thinking skills compared to the traditional expository teaching methods employed in the control group.

The statistical analysis results using ANOVA for differences in the mean critical thinking scores of STC are presented in Table 4, followed by a post hoc test analysis shown in Table 5.

Table 4. ANOVA test results

Cases	Sum of Sqrs.	df	Mean Sqr.	F	p	η^2
Within Subjects Effects						
RM Factor	33.040	1	33.040	255.908	< .001	0.452
RM Factor ✻ Group	13.454	1	13.454	104.205	< .001	0.184
Residuals	6.326	49	0.129			
Between Subjects Effects						
Group	13.575	1	13.575	99.613	< .001	0.186
Residuals	6.678	49	0.136			

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

The ANOVA test results presented in Table 4 indicate significant differences in the critical thinking scores of Science Teacher Candidates (STC) based on the repeated measures factor (pre-test to post-test) and group (control vs. experimental). The F-value for the within-subjects effect (Repeated Measures Factor) is 255.908, with a p-value < 0.001, demonstrating a significant overall difference between pre-test and post-test scores, accompanied by an effect size (η^2) of 0.452, indicating a strong effect. Additionally, the interaction between the repeated measures factor and group is also significant, with an F-value of 104.205 and a p-value < 0.001, and an effect size of 0.184, signifying substantial differences in score changes between the control and experimental groups.

The between-subjects analysis reveals a significant overall difference between the control and experimental groups, with an F-value of 99.613 and a p-value < 0.001, and an effect size of 0.186. These findings confirm that the hybrid E-PjBL model integrated with virtual assistive technology is significantly more effective in enhancing critical thinking skills compared to traditional expository teaching methods.

Table 5. The results of post hoc - Group ✻ RM Factor 1 (pretest – posttest)

Variables		Mean Diff.	SE	t	P_{holm}
Control - pretest	Experiment. - pretest	-0.003	0.102	-0.032	0.974
	Control - posttest	-0.412	0.102	-4.054	< .001
	Experiment. - posttest	-1.868	0.102	-18.310	< .001
Experiment. - pretest	Control - posttest	-0.409	0.102	-4.006	< .001
	Experiment. - posttest	-1.865	0.100	-18.714	< .001
Control - posttest	Experiment. - posttest	-1.456	0.102	-14.272	< .001

The post hoc test results presented in Table 5 support the ANOVA findings by showing significant differences in critical thinking scores across various conditions. No significant difference was found between the pre-test scores of the control and experimental groups (Mean Diff. = -0.003, p = 0.974), indicating that both groups started with similar critical thinking abilities. However, significant differences emerged in the post-test, where the experimental group showed a much greater improvement compared to the control group. The mean difference between the post-test scores of the control and experimental groups was -1.456, with a p-value < 0.001, demonstrating that the hybrid E-PjBL model integrated with virtual assistive technology significantly enhances STC's critical thinking skills. This strong and substantial impact of the intervention on the experimental group is further evidenced by significant differences in almost all post-test comparisons.

Based on observations conducted during the implementation of the hybrid E-PjBL model integrated with virtual assistive technology, the model has proven to be practical for use by STC in the MBKM program. Observations revealed that most STC actively engaged in the learning sessions, demonstrating strong capabilities in accessing and utilizing virtual assistive technology. The STC consistently showed high levels of participation in group discussions and completion of project-based tasks, indicating that this learning model successfully fosters collaboration and interaction among STC.

The findings of this study demonstrate that the hybrid Ethnoscience-Project-Based Learning (E-PjBL) model integrated with virtual assistive technology is significantly effective in enhancing the critical thinking skills of Science Teacher Candidates (STC). These results align with previous research emphasizing the importance of critical thinking as a core competency in higher education, particularly for prospective science teachers (Erikson &

Erikson, 2019; Prayogi et al., 2022). While traditional teaching models, such as standalone Project-Based Learning (PjBL), have been implemented to improve critical thinking, their effectiveness often diminishes without the support of additional interventions like advanced technology (Sumarni & Kadarwati, 2020). Within this context, the integration of E-PjBL with virtual assistive technology offers a holistic and modern approach, addressing existing challenges and yielding a greater impact on enhancing critical thinking performance among STC, as corroborated by prior studies (Bilad et al., 2022).

The inclusion of virtual assistive technology in this learning model plays a crucial role not only in supporting the exploration of highly abstract scientific concepts but also in facilitating a deeper and more critical understanding through adequate visualization (El Kharki et al., 2020). Virtual technology enables students to manipulate experimental parameters and explore diverse learning scenarios, which in turn enhances their analytical capabilities and critical thinking skills (de la Torre et al., 2015). This finding supports the premise that the use of virtual technology in science teaching positively influences conceptual mastery, preferences for scientific theories, and critical thinking development among students.

Despite these promising outcomes, further research is needed to explore the full potential of this hybrid model on a larger scale and in diverse educational contexts. The successful implementation of the E-PjBL model integrated with virtual assistive technology underscores its potential adaptability in other countries facing similar educational challenges (Fitriani et al., 2019; Ma & Luo, 2021). However, it is essential to recognize that the practicality of this model requires ongoing evaluation to ensure continuous refinement, considering the dynamic nature of technological advancements and evolving educational demands (Wahyudi et al., 2023).

In this regard, the hybrid E-PjBL model not only contributes to the improvement of students' critical thinking skills but also fosters the creation of a more inclusive and adaptive learning environment in the digital era. By providing opportunities for students to engage with complex scientific concepts in an interactive and visual manner, this model effectively bridges the gap between theoretical knowledge and practical application, empowering students with the skills necessary to navigate and thrive in an increasingly complex scientific and technological landscape.

In conclusion, the integration of virtual assistive technology into the E-PjBL framework represents a transformative approach in education, particularly for STC. Its impact extends beyond skill enhancement, fostering a sustainable and innovative learning model that aligns with the demands of 21st-century education. However, as educational needs and technological landscapes continue to evolve, ongoing efforts must focus on assessing, refining, and scaling this model to maximize its effectiveness and ensure its relevance across diverse learning environments. Through such efforts, this model has the potential to significantly advance the quality of science teacher education globally.

CONCLUSION

This study successfully implemented the hybrid Ethnoscience-Project Based Learning (E-PjBL) model integrated with virtual assistive technology to enhance the critical thinking skills of Science Teacher Candidates (STC). The findings indicate that this learning model is not only effective but also practical in improving their critical thinking performance. Quantitative data from pre-tests and post-tests revealed significant improvements in critical thinking skills among students utilizing the hybrid E-PjBL model compared to the control group, which followed traditional teaching methods. Additionally, qualitative data from observations of the learning process highlighted that STC effectively accessed and utilized virtual assistive technology, demonstrating high levels of engagement and participation throughout the learning sessions.

The success of this hybrid model in improving critical thinking skills is attributed to the integration of ethnoscience, PjBL, and virtual assistive technology, which provides a holistic and modern learning experience. This model supports STC in exploring scientific concepts in a more visual and interactive manner, ultimately enhancing their analytical abilities and critical thinking skills. However, the study also underscores the importance of continuous evaluation to ensure that this model remains relevant and adaptable to technological advancements and evolving educational needs. Moving forward, further research with a larger scale and diverse educational contexts is necessary to fully explore the potential of this model and to optimize its contribution to improving the quality of science teacher education in the digital era.

LIMITATIONS

Despite its promising outcomes, this study has several limitations. First, the sample size was relatively small and limited to Science Teacher Candidates (STC) from a single university, which may restrict the generalizability of the findings to broader populations. Second, the study primarily focused on short-term improvements in critical thinking skills, leaving the long-term retention of these skills unexamined. Additionally, the study did not explore the impact of the hybrid E-PjBL model integrated with virtual assistive technology on other essential skills such as collaboration, creativity, and problem-solving. The limited diversity of the educational contexts assessed also suggests that further validation in various institutional and cultural settings is needed to fully establish the model's effectiveness and adaptability.

RECOMMENDATIONS

Based on the findings, it is recommended that the hybrid E-PjBL model integrated with virtual assistive technology be adopted more widely in science education programs, particularly within Indonesia's MBKM curriculum. Future studies should involve larger, more diverse samples and include longitudinal assessments to evaluate the sustained impact of the model on critical thinking and other 21st-century skills. Additionally, the model's implementation could be explored across different educational contexts to examine its adaptability and effectiveness in varying institutional and cultural settings. Continuous refinement of the model is essential to keep pace with technological advancements and evolving educational needs, ensuring that it remains a robust and practical pedagogical tool for enhancing science teacher education.

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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Conflict of interests

The authors declare no conflict of interest.

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