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ENHANCING PRE-SERVICE TEACHERS' CREATIVE SCIENTIFIC COMPETENCE THROUGH AI-SUPPORTED RESEARCH-BASED LEARNING

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ABSTRACT

This study investigates the effectiveness of an Artificial Intelligence-Supported Research-Based Learning (AI-RBL) model in strengthening the creative scientific competence of pre-service primary school teachers and examines how they perceived the role of AI during inquiry activities. A mixed-methods design with a one-group pre-test and post-test structure was implemented over a 15-week semester, during which a large language model acted as a digital mediator in problem formulation, hypothesis development, methodological planning, literature exploration, and data interpretation. Creative scientific competence was operationalized as originality, flexibility, elaboration, and relevance. These dimensions reflect key inquiry practices that underpin scientific literacy. Specifically, they involve the ability to generate meaningful questions, apply scientific reasoning, use evidence appropriately, and construct coherent explanations. A repeated-measures multivariate analysis of variance showed a significant effect of time, with improvements across all dimensions, and univariate tests indicated the strongest gains in elaboration and flexibility. Qualitative reflections revealed that the model supported divergent idea generation, strengthened structural reasoning, and encouraged the critical evaluation of AI suggestions, thereby enhancing both cognitive and metacognitive aspects of inquiry-based learning. The findings highlight the educational significance of pedagogically constrained AI mediation in developing inquiry-oriented competencies that underpin scientific literacy, and they contribute to international discussions on responsible and pedagogically grounded integration of AI in science teacher education.

Keywords: research-based learning; creative scientific competence; pre-service teachers; artificial intelligence

INTRODUCTION

The development of scientific literacy has become a central priority in global education. It is consistently emphasized in major international assessment frameworks such as the Program for International Student Assessment (PISA) and the Trends in International Mathematics and Science Study (TIMSS). These frameworks view scientific literacy not as the passive accumulation of scientific facts but as the ability to formulate meaningful questions, draw evidence-based conclusions, and understand science as a dynamic process of human inquiry. This perspective places particular responsibility on primary education, where inquiry habits, critical thinking, and attitudes toward science are initially formed (Spronken-Smith & Walker, 2010). The preparedness of pre-service

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primary school teachers to design and facilitate inquiry-based learning is therefore central to the long-term development of both scientific literacy and creativity.

Strengthening scientific literacy and creativity in teacher education is directly aligned with Sustainable Development Goal 4 (Quality Education), which emphasizes improving learning quality and competence development. Recent interdisciplinary reviews examine AI in the context of SDG 4 and its role in supporting instructional quality when implemented with pedagogical and ethical safeguards (AlSagri & Sohail, 2024; Singh et al., 2024; Gohr et al., 2025). At the same time, sustainability-oriented analyses emphasize that evidence demonstrating measurable competence development remains limited and requires structured pedagogical intervention models rather than technological adoption alone (Regona et al., 2024; Anwar et al., 2025). In science education, bibliometric evidence shows growing interest in AI-supported inquiry practices (Karampelas, 2025). However, structured intervention studies examining how AI integration strengthens scientific literacy and creativity in teacher preparation remain limited. Addressing this gap requires pedagogical designs that specify how AI supports inquiry processes and how resulting competence gains can be evidenced, which motivates the present study.

Despite policy emphasis on inquiry-based pedagogy, many teacher preparation systems continue to struggle to cultivate research-oriented and creativity among future teachers. Studies consistently report that pre-service teachers often possess adequate declarative knowledge of science content but struggle to translate this knowledge into authentic investigative practice (Beghetto & Kaufman, 2014; Bereczki & Kárpáti, 2018). Research activities are frequently perceived as linear and procedural rather than iterative and creative processes that require originality, flexibility, and elaboration (Apaydın & Güven, 2022; Novak et al., 2024). These challenges are particularly visible in reform-oriented contexts such as Kazakhstan. Although inquiry-based curricula have been introduced, instructional readiness remains uneven (Kunnath & Botes, 2025; Muñoz-Salinas et al., 2025).

A preliminary survey of 158 in-service primary teachers in Kazakhstan corroborates these patterns: respondents reported low student competence in hypothesis formulation and experimental design and acknowledged limited confidence in guiding creative research processes. International findings similarly associate limited teacher experience in authentic research with reduced classroom implementation of inquiry-based strategies (Acar et al., 2023; Novak et al., 2024). Collectively, the literature reveals a persistent gap between curricular expectations for scientific literacy and teachers' actual preparedness to cultivate creative inquiry practices.

Research-Based Learning (RBL) provides a pedagogical framework for integrating scientific literacy and creativity in teacher preparation. In this context, pre-service teachers must not only conduct inquiry but also learn to design, justify, and facilitate it for future pupils. In this sense, RBL serves as both a learning approach and a model of professional practice. It engages learners in authentic research processes, including problem identification, question formulation, evidence collection, data analysis, and communication of findings. These processes correspond to core components of scientific literacy and to established dimensions of creative thinking, including originality, flexibility, elaboration, and relevance (Almeida et al., 2008; Runco, 2014). Syntheses of higher education research indicate that RBL strengthens analytical reasoning and knowledge construction; however, its effectiveness depends on structured scaffolding, particularly for novice researchers (Muñoz-Salinas et al., 2025). Without such support, pre-service teachers may experience cognitive overload during question formulation, methodological planning, and interpretation (Lang et al., 2024). This overload can constrain higher-order inquiry competence and creative engagement.

Within this framework, AI can be conceptualized not as a substitute for inquiry but as a structured scaffold embedded across phases of the RBL cycle. Generative AI and large language models (LLMs) have been shown to support idea generation, alternative hypothesis construction, argument structuring, and reflective revision when pedagogically framed and transparently integrated (Walter, 2024; Giannakos et al., 2025; Nelson et al., 2025). Procedurally, AI can help refine research questions, suggest methodological options, encourage consideration of different perspectives, and support clear connections between evidence and claims. In this way, it can strengthen inquiry competence and the creative dimensions of originality, flexibility, and elaboration (Jin et al., 2023; Gkintoni et al., 2025). From a sociocultural perspective, such use positions AI as a temporary mediation within the Zone of Proximal Development. It can enable engagement with complex inquiry tasks while maintaining learner agency. However, this requires explicit safeguards to prevent overreliance and protect academic integrity (Zawacki-Richter et al., 2019; Li & Wilson, 2025).

However, the current body of research presents a fragmented picture. Empirical studies frequently investigate isolated AI tools rather than structured pedagogical models embedded within inquiry cycles. As a result, reported outcomes often remain general and fail to differentiate specific dimensions of creative scientific competence such as originality, flexibility, elaboration, and relevance (Zulyusri et al., 2023; Ratniyom et al., 2025). While some research addresses digital or algorithmic literacy and technological readiness in teacher education (Ng et al., 2023; Dilek et al., 2025; Guan et al., 2025), fewer studies examine how AI integration directly supports inquiry processes central to scientific literacy and creativity.

Moreover, limited attention has been given to how pre-service teachers perceive AI when it is systematically integrated into authentic research activities that require balancing technological scaffolding with intellectual autonomy (Ntsobi & Costa, 2024). Taken together, the literature indicates that research on intelligent technologies in teacher education remains methodologically fragmented. It rarely embeds these systems within structured RBL models and seldom evaluates multivariate effects on clearly defined components of creative scientific competence linked to scientific literacy. This synthesis underscores the need for pedagogically grounded intervention designs that integrate AI within inquiry processes and evaluate their multivariate effects on clearly defined dimensions of creative scientific competence.

In response to this gap, the novelty of the present study explicitly lies in the design and empirical evaluation of a structured AI-RBL model for pre-service teacher education. The study advances prior research by combining multivariate quantitative analysis of creative scientific competence with qualitative examination of pre-service teachers' perceptions of AI as a digital mediator. Creative scientific competence is operationalized through originality, flexibility, elaboration, and relevance, dimensions closely aligned with the core scientific practices that underpin scientific literacy in primary education.

Accordingly, this study aims to examine the effectiveness of the AI-RBL model in enhancing pre-service primary teachers' creative scientific competence and to explore their perceptions of AI as a mediator in inquiry-based research activities. The study addresses two research questions: (1) What is the multivariate effect of the AI-RBL model on pre-service teachers' creative scientific competence across the four dimensions between pre-test and post-test measurements? (2) How do pre-service teachers perceive the role of AI as a digital mediator in supporting the design and execution of scientific inquiry projects during the AI-RBL intervention?

METHODS

This study was conducted as a mixed-methods quasi-experimental investigation using a convergent parallel design. Quantitative and qualitative data were collected simultaneously and integrated during the interpretation stage through triangulation and narrative weaving of statistical results with emerging qualitative themes (Costa, 2024). A quasi-experimental pre-test–post-test design without a separate control group was used to examine changes in creative scientific competence following the AI-RBL intervention. The absence of a control class was due to institutional course constraints, as the intervention was embedded in a required course delivered to intact student groups. This approach is common in classroom-based educational research and supports ecological validity by reflecting authentic instructional conditions (Wondim et al., 2024). Although a control group was not included, the consistent instructional context and fixed semester timeline helped minimize potential threats to internal validity such as maturation or external influences. All procedures complied with institutional ethical standards, personal identifiers were removed, and ethical approval was granted by the University Scientific Ethics Committee (Conclusion No. 23/24).

The participant group comprised 280 pre-service primary school teachers enrolled in second- and third-year pedagogical programs at two higher education institutions in Kazakhstan. Their mean age was 19.4 years (SD = 1.2), and all demonstrated sufficient English proficiency to interact with AI-generated prompts, as English was the language of instruction. The intervention was implemented within a compulsory 15-week course titled "Project-Based Research Activity," which focuses on inquiry related to natural and environmental phenomena in primary education. Participants were selected through convenience sampling based on course enrollment, allowing intact classes to participate without disrupting institutional structures. In addition, 158 in-service primary teachers (mean age = 42.1 years, SD = 5.8; average teaching experience = 15 years) completed a contextual survey. This comparative group did not participate in the intervention or complete pre- and post-testing, but they provided baseline information on common challenges in facilitating inquiry-based science instruction in regional practice.

The AI-supported Research-Based Learning (AI-RBL) model structured the intervention as a sequence of inquiry stages in which artificial intelligence functioned as temporary cognitive and metacognitive scaffolding rather than as a solution generator (Figure 1). At each stage, AI served as a reflective partner, offering prompts, clarifying questions, and structural suggestions, while students retained responsibility for final decisions. The intervention spanned the full research cycle and supplemented instructor guidance rather than replacing it. This design aimed to strengthen idea generation, methodological reasoning, and logical structuring while preserving learner autonomy.

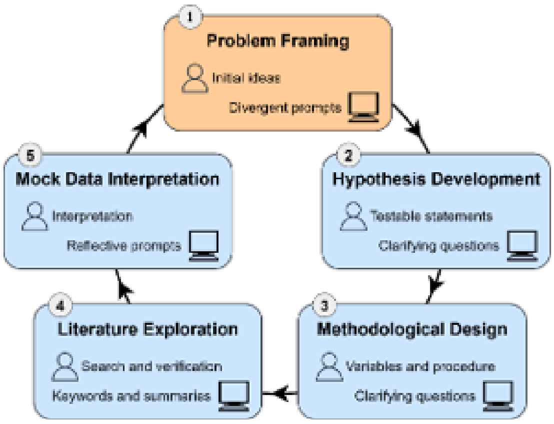

Figure 1. Operational Structure of the AI-RBL Model

The intervention progressed through five consecutive inquiry stages designed to mirror the authentic research process. During problem framing, students used AI to explore thematic areas and generate research questions appropriate for primary education, consistent with dialogic models of AI-supported inquiry (Bearman & Ajjawi, 2023). In the hypothesis formulation phase, AI assisted in transforming questions into measurable predictions, reflecting structured reasoning scaffolds (Kasneci et al., 2023). During methodological design, AI provided suggestions for identifying variables, controls, and procedural steps, aligning with research on AI-supported experimentation skills (Ratniyom et al., 2025). In the literature review stage, AI suggested keywords, summarized foundational concepts, and aligned concepts with scientific principles (Garzón et al., 2025). Finally, in mock data interpretation, AI-guided examination of hypothetical results and conclusion drawing is consistent with classroom-based evidence of AI-supported explanatory reasoning (Bitzenbauer, 2023). Across these stages, AI provided structured support for inquiry processes while students retained full responsibility for final decisions. The AI system used was Gemini 2.5 Pro, selected for its capacity to process extended instructions and maintain coherent interaction. Instructors provided predefined prompt templates to ensure that AI adopted a Socratic, supportive role rather than generating complete solutions.

To ensure structured and responsible implementation, specific operational parameters governed AI use throughout the semester. Students interacted with AI individually during idea generation and hypothesis formulation to promote personal creativity, and in small groups of three to four during methodological design and literature exploration to simulate collaborative inquiry. Across the 15-week semester, students engaged in approximately 10–12 structured AI-supported sessions lasting 20–35 minutes each. A protocol for responsible AI use was implemented to safeguard academic integrity (Sakhipov et al., 2025). Students were required to critically review AI outputs, justify acceptance or rejection of suggestions, and avoid verbatim copying. Instructors periodically reviewed AI interaction logs to ensure responsible and appropriate use.

Data were collected using three instruments aligned with the quantitative and qualitative components of the study. The primary quantitative instrument was the Creative Scientific Competence Test (C-SCT), adapted from elements of the Torrance Test of Creative Thinking (Alabbasi et al., 2022; Tsai & Hsu, 2024). The test required students to generate original research ideas in response to a primary-level science scenario and assessed four dimensions: originality, flexibility, elaboration, and relevance. Students in the intervention group completed the test before and after the intervention, resulting in 560 total submissions. Three experts independently evaluated responses using a 5-point analytic rubric (Bicer et al., 2024). Internal consistency of the aggregated rubric scores was estimated using Cronbach's alpha, yielding $\alpha = 0.89$ (Zakariya, 2022), and content validity was supported through consultation with educational psychology specialists. Four inquiry process indicators were also scored from pre-test responses to describe baseline readiness, but were not included in inferential analyses.

The second instrument was a ten-item Likert-scale survey administered to the in-service teacher group to document perceived challenges in inquiry-based science teaching (Neubauer-Hametner et al., 2025). Although this group did not participate in the intervention, the survey provided context for regional instructional needs. The third instrument consisted of reflection journals written by a randomly selected subsample of 50 intervention participants. Students were selected through simple random sampling without replacement. The journals captured perceptions of AI as supportive or limiting and provided qualitative insight into its perceived role in creativity and research organization (Holdo, 2023).

Quantitative and qualitative data were analyzed using complementary statistical and thematic procedures. Quantitative data were analyzed using a repeated-measures MANOVA to assess the joint effect of the intervention on originality, flexibility, elaboration, and relevance. Analyses were conducted in SPSS version 29.0 with a significance level of $p < .05$. Assumptions of multivariate normality and covariance homogeneity were assessed following established procedures (Orcan, 2020). When distributional violations were detected, the Wilcoxon Signed Rank Test was used as a supplementary robustness check. Effect sizes were reported using partial eta squared. Qualitative journal data were analyzed thematically through iterative coding (Kushnir, 2025; Roberts et al., 2019). Integration of quantitative and qualitative findings occurred during interpretation to provide a comprehensive understanding of how AI-RBL influenced creative scientific competence. For manuscript preparation only, Grammarly was used to improve language clarity. It was not used during intervention implementation, data collection, scoring, or analysis.

RESULTS AND DISCUSSION

The results are organized around the study's two research questions. Quantitative analyses address the first by comparing pre-test and post-test performance across four dimensions of creative scientific competence, originality, flexibility, elaboration, and relevance. The second research question is examined through qualitative analysis of students' reflective journals, which describe how pre-service teachers experienced AI as a digital mediator during inquiry activities. Taken together, the quantitative and qualitative findings offer a coherent account of both the learning outcomes associated with the AI-RBL model and how AI support shaped students' inquiry practices.

Table 1 presents descriptive statistics for the four creativity dimensions assessed before and after the intervention. Across all indicators, students' performance improved, with the most pronounced gains in elaboration and flexibility. Distributions remained within acceptable normality thresholds, supporting the use of subsequent parametric analyses. These patterns suggest that students entered the course with moderately developed creative thinking abilities but experienced measurable cognitive and methodological growth during their participation in the AI-RBL process (Ekayana et al., 2025; Luthfia, 2024). The consistent improvements across dimensions suggest that the intervention fostered a holistic, rather than isolated, development of creative scientific competence.

Table 1. Descriptive Statistics for Pre-Test and Post-Test Scores

Variable	Time	Mean (M)	SD	Skewness	Kurtosis
Originality	Pre	3.24	0.51	-0.08	-0.21
	Post	3.49	0.53	-0.11	-0.17
Flexibility	Pre	3.18	0.48	-0.04	-0.31
	Post	3.45	0.50	-0.10	-0.22
Elaboration	Pre	3.11	0.52	0.05	-0.28
	Post	3.42	0.54	-0.14	-0.20
Relevance	Pre	3.33	0.49	-0.07	-0.25
	Post	3.58	0.50	-0.13	-0.19

These dimensions reflect both creative performance and core components of scientific literacy, including the ability to generate novel questions, consider alternative explanations, articulate methodological detail with clarity, and justify the relevance of proposed ideas within a scientific context. A repeated measures MANOVA revealed a significant effect of time (Table 2), indicating reliable changes in the combined creativity variables from pre-test to post-test. Because the within-subject factor included only two levels, all multivariate criteria yielded identical Approx. F and p values.

Table 2. Multivariate Results of Repeated Measures MANOVA

Statistic	Value	p
Wilks' Lambda	0.7045	< .001
Pillai's Trace	0.2955	< .001
Hotelling's Trace	0.4194	< .001
Roy's Greatest Root	0.4194	< .001

The use of a repeated-measures MANOVA was appropriate because the four dimensions of creative scientific competence constitute theoretically related, statistically interdependent indicators of a unified construct. A preliminary inspection of intercorrelations confirmed nontrivial positive associations among originality, flexibility, elaboration, and relevance, supporting a multivariate analysis rather than separate independent tests. By analyzing the shared variance and covariance structure among these indicators, the MANOVA assessed whether the intervention produced a coordinated shift across the creative thinking profile as a whole. The significant multivariate effect directly addresses Research Question 1 by demonstrating that the AI-RBL intervention influenced the integrated structure of creative thinking indicators rather than producing isolated improvements. Accordingly, the observed development should be interpreted as a coherent enhancement of creative scientific competence. The magnitude of the multivariate effect is moderate in educational research contexts and is comparable to effect sizes reported in studies on cognitive scaffolding and metacognitively supported inquiry (Asda et al., 2025). This pattern suggests that the AI-RBL intervention was associated with a meaningful improvement in the integrated configuration of creative thinking indicators.

To examine the contribution of each creativity dimension, univariate repeated measures analyses were conducted (Table 3). All four variables (originality, flexibility, elaboration, and relevance) showed significant increases from pre-test to post-test. The largest effects were observed for elaboration (partial $\eta^2 = .110$) and flexibility (partial $\eta^2 = .105$), indicating that students benefited most from AI support when organizing methodological structures and generating diverse investigative pathways. Originality (partial $\eta^2 = .079$) and relevance (partial $\eta^2 = .087$) also improved significantly, although the effects were smaller.

Table 3. Univariate Tests for Each Dependent Variable

Variable	F	p	Partial η^2
Originality	23.838	< .001	.079
Flexibility	32.884	< .001	.105
Elaboration	34.409	< .001	.110
Relevance	26.445	< .001	.087

These findings further clarify Research Question 1 by showing coordinated improvement across all four dimensions, with the strongest effects observed in elaboration and flexibility. The AI-RBL model produced coherent development across originality, flexibility, elaboration, and relevance rather than isolated skill gains. The strongest effects in elaboration and flexibility indicate that AI mediation was particularly effective in supporting methodological structuring and the exploration of alternative inquiry pathways. At the same time, improvements in originality and relevance suggest that students maintained intellectual autonomy while generating scientifically meaningful ideas. Overall, the results show that the AI-RBL model addressed the research problem by strengthening both the creative and structural components of inquiry that underpin scientific literacy.

From a theoretical perspective, these results suggest that guided AI scaffolding primarily strengthened procedural organization and exploratory reasoning processes. The comparatively stronger gains in elaboration and flexibility point to the role of guided prompts in reducing cognitive overload during methodological planning, while the continued growth in originality and relevance indicates the preservation of intellectual autonomy. This pattern aligns with prior research showing that cognitive scaffolds are particularly effective for complex planning and structuring tasks (Behnamnia et al., 2020; Kwangmuang et al., 2021; Sari et al., 2021). These findings also align with the concept of the Zone of Proximal Development, as temporary AI scaffolding enabled students to perform inquiry tasks at a higher level without replacing their own reasoning. The moderate effect sizes further support the interpretation of AI as a scaffold that reduced procedural overload while preserving active cognitive engagement.

Qualitative findings from the 50 student journals provide further insight into why the intervention produced these improvements (Table 4). The three dominant themes, Divergent Idea Generation, Structural Scaffolding, and Ethical Authorship, capture students' perceptions of how AI supported or challenged their thinking. Divergent Idea Generation was the most frequently reported theme, with the majority of students noting that AI suggestions helped them explore multiple directions during problem identification and hypothesis development. Students also described this process as reducing initial uncertainty and encouraging risk-taking in idea generation, particularly at the early stages of inquiry. These observations help explain quantitative gains in originality and flexibility and align with prior studies showing that generative AI can enhance associative thinking by presenting alternative conceptual connections (Rafner et al., 2023).

Table 4. Themes From Qualitative Reflections (N = 50).

Qualitative Theme	Supported Cognitive Process	Frequency (%)	Summary of Observations
Divergent Idea Generation	Associative thinking	82%	AI prompts encouraged exploration of multiple directions and supported broader conceptual connections.
Structural Scaffolding	Metacognitive regulation	76%	Students reported shifting from struggling with organizing ideas to evaluating and refining methodological logic.
Ethical Authorship	Critical judgment	65%	Students used AI suggestions as material for critique rather than copying, noting that identifying errors strengthened their scientific reasoning.

The qualitative theme of Structural Scaffolding helps explain the strongest quantitative improvement observed in elaboration (pre-test M = 3.11; post-test M = 3.42; partial $\eta^2 = .110$). This dimension also contributed substantially to the significant multivariate MANOVA effect across the four creative thinking indicators (Wilks' $\Lambda = 0.7045$, $p < .001$), confirming that changes occurred not in isolation but within the integrated structure of creative scientific competence.

Students reported that AI mediation helped them understand hierarchical relationships among variables, refine procedural coherence, and identify weaknesses in their designs. Many described a shift from disorganized thinking to purposeful structuring, reflecting internalization of methodological reasoning. One student noted that "at the beginning I was afraid to use words like variable or hypothesis because I was not sure I understood them, but the AI explained them in simple language and I felt safer using them in my project." Another reflection emphasized that AI-generated outlines reduced cognitive overload: "when the AI showed where to place the background, question and method, the research report felt more like filling in a puzzle than facing something unknown." The larger effect size for elaboration compared to originality supports this interpretation and is consistent with evidence that explicit scaffolding is particularly effective for complex procedural tasks (Simanjuntak et al., 2021; Sardin et al., 2023).

Ethical authorship, the third theme, further contextualizes the multivariate result. Students emphasized responsibility for evaluating AI suggestions, rejecting implausible ideas, and verifying information independently (Chinoracky & Stalmasekova, 2025). This indicates that the significant MANOVA effect across originality, flexibility, elaboration, and relevance reflects structured cognitive support combined with preserved intellectual autonomy rather than passive reliance on AI. Together, divergent idea generation, structural scaffolding, and ethical authorship explain the coordinated pre–post increases across all four indicators shown in Figure 2. The pattern of consistent gains aligns with the statistically significant multivariate shift and reinforces the idea that the intervention strengthened the integrated profile of creative scientific competence rather than producing isolated improvements.

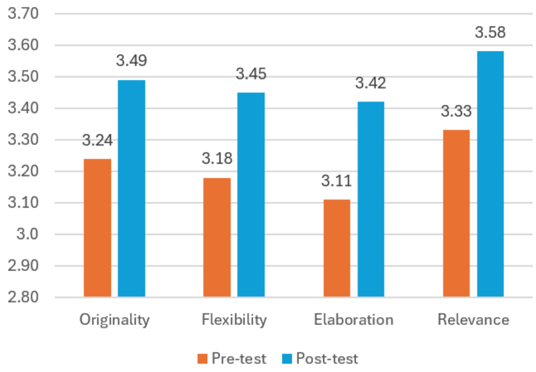

Figure 2. Pre-Test and Post-Test Scores Across Four Dimensions of Creative Scientific Competence

Accordingly, the qualitative findings directly confirm Research Question 2 by demonstrating how pre-service teachers experienced AI as a digital mediator that enhanced inquiry while maintaining learner agency. This interpretation gains further relevance when considered alongside baseline differences between pre-service and in-service teachers. Table 5 provides additional context. It summarizes baseline inquiry process indicator scores from the pre-test C-SCT and the percentages from the in-service teacher survey. Because these values come from different measures, they are interpreted descriptively, and no statistical comparisons are made.

Table 5. Baseline Inquiry Process Indicators from the Pre-Test C-SCT and Percentages of In-Service Teachers Reporting Difficulty

Inquiry Competency	Pre-Service Teachers (C-SCT pre-test indicator score, 1–5)	In-Service Teachers Reporting Difficulty (%)
Formulating hypotheses	3.11	65
Identifying variables & controls	3.14	58
Designing simple experiments	3.08	62
Interpreting results	3.21	54

In light of the baseline findings presented in Table 5, these results gain additional contextual relevance. These patterns align with systematic reviews that demonstrate that inquiry-based science education often reveals a gap between conceptual understanding and procedural enactment, especially in teacher education contexts (Urdanivia Alarcon et al., 2023; Strat et al., 2024). Meta-analytic evidence further confirms that inquiry-based learning positively influences higher-order thinking, yet its effectiveness depends strongly on structured scaffolding and sustained teacher mediation (Dah et al., 2024; Arifin et al., 2025).

In this context, the AI-RBL model can be interpreted as a structured response to documented procedural weaknesses in the implementation of inquiries. Iterative interaction with generative prompts led to clearer alignment among research questions, hypotheses, and variables, thereby strengthening methodological coherence. This interpretation aligns with broader syntheses indicating that generative systems enhance learning outcomes primarily when embedded within pedagogically constrained designs and guided by human oversight (Ouyang & Jiao, 2021; Zhang et al., 2024; Shi et al., 2026). Empirical studies further suggest that technology-supported formative feedback can increase creative fluency and engagement when instructional framing remains explicit (Naz & Robertson, 2024; Zhou & Peng, 2025).

The coordinated multivariate MANOVA effect suggests integrated development across originality, flexibility, elaboration, and relevance rather than isolated gains. This is consistent with theoretical models conceptualizing creative scientific competence as a multidimensional construct (Runco, 2014). Although generative tools have been shown to enhance individual creativity, they may also reduce the diversity of ideas when epistemic framing is inadequate (Doshi & Hauser, 2024). The Ethical Authorship theme observed here indicates that explicit responsibility protocols mitigated such risks, positioning the system as cognitive scaffolding rather than as an epistemic substitute.

At a broader level, the findings align with international evidence indicating that the educational effectiveness of intelligent technologies is determined primarily by pedagogical design and teacher competence rather than by technological availability alone (Zawacki-Richter et al., 2019; Wang et al., 2024). Large-scale syntheses show that such tools contribute to measurable learning gains when embedded within structured instructional frameworks and accompanied by active teacher mediation, whereas unstructured or purely tool-driven implementation produces inconsistent outcomes (Ouyang & Jiao, 2021; Zhang et al., 2024). In parallel, meta-analytic research on inquiry-based learning demonstrates that technology-enhanced inquiry yields statistically significant but context-sensitive effects, strongly moderated by scaffolding intensity and instructional guidance (Arifin et al., 2025). The moderate multivariate effects observed in the present study, therefore, correspond to patterns reported in the literature: generative support appears most beneficial when functioning as a cognitive scaffold that extends higher-order reasoning rather than as an autonomous knowledge source (Naz & Robertson, 2024; Zhou & Peng, 2025). At the same time, empirical research warns that such systems may enhance individual creative fluency while narrowing collective diversity when not explicitly framed epistemically (Doshi & Hauser, 2024). The emphasis on Ethical Authorship and critical evaluation in this intervention directly addresses this concern and aligns with emerging literacy frameworks that conceptualize generative systems as probabilistic tools requiring reflective and responsible use (Ng et al., 2023; Liu & Zhong, 2025; Park, 2025).

From a policy perspective, particularly in reform-oriented systems that prioritize inquiry-based pedagogy and scientific literacy, such as Kazakhstan, these findings address the documented gap between curricular reform agendas and teacher preparedness (Strat et al., 2024; Randez, 2025). International analyses further indicate that the sustainable integration of intelligent technologies depends on coordinated institutional support, professional development, and governance mechanisms rather than isolated classroom innovation (Vinuesa et al., 2020; Giannakos et al., 2025; Hooshyar et al., 2025). Accordingly, integration should be understood as a systemic pedagogical reform process grounded in structured inquiry design and sustained teacher capacity building.

In terms of novelty, this study contributes to the literature in four interrelated ways. First, it extends empirical research on generative-supported inquiry to the underrepresented Central Asian context (Garzón et al., 2025; Ko et al., 2025). Second, it examines the multivariate effects of structured AI scaffolding on distinct dimensions of creative scientific competence rather than isolated outcomes. Third, it integrates quantitative results with qualitative evidence to clarify the mechanisms through which AI mediation shapes inquiry processes. Finally, it proposes a structured AI-RBL model that can be adapted to other disciplines and educational levels, while also inviting further investigation into how variations in context and implementation may influence these effects.

Despite these contributions, several limitations should be noted. The intervention was conducted within a single course and institutional context, which may limit generalizability (Orcan, 2020). In addition, the absence of a control group limits causal inference, and improvements should therefore be interpreted as associated with the intervention rather than definitively caused by it. Creative scientific competence is also a multifaceted construct, shaped by contextual and individual factors that are not fully captured here. In addition, qualitative findings relied on self-reported reflections. Future research should therefore examine longitudinal effects, include comparative or control designs, and explore how different levels of generative guidance or alternative systems influence creativity, autonomy, and ethical judgment, building on recent work in technology-mediated learning design (Mang et al., 2023; Tsakeni et al., 2025). Overall, the findings demonstrate that the AI-RBL model can enhance creative scientific competence among pre-service teachers in a focused and educationally meaningful manner (Amofa et al., 2025). By functioning as a mediating scaffold rather than a replacement for human reasoning, the model contributes evidence to ongoing international discussions on responsible AI integration in science teacher education.

CONCLUSION

This study addressed two research objectives: (1) to examine the multivariate effect of the AI-supported Research-Based Learning (AI-RBL) model on pre-service teachers' creative scientific competence, and (2) to investigate their perceptions of AI as a digital mediator in inquiry-based research. Regarding the first objective, the results showed a statistically significant multivariate effect across originality, flexibility, elaboration, and relevance, confirming coordinated development of creative scientific competence, with the strongest effects observed in elaboration and flexibility. Regarding the second objective, qualitative findings indicated that participants perceived AI as a structured cognitive scaffold that supported idea generation, methodological organization, and critical evaluation, while preserving intellectual autonomy. These findings demonstrate that the AI-RBL model provides a pedagogically grounded approach to strengthening inquiry competencies that underpin scientific literacy and align with Sustainable Development Goal 4 through competence-oriented teacher preparation. Overall, the study provides empirical evidence for responsible, structured AI integration in science teacher education and lays the groundwork for further controlled, longitudinal research.

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REFERENCES

Acar, S., Lee, L. E., & Hodges, J. (2023). Assessing the robustness of the factor structure of TTCT-Figural: A meta-CFA replication-extension. *Creativity Research Journal*, *35*(4), 547–567.

Alabbasi, A. M. A., Paek, S. H., Kim, D., & Cramond, B. (2022). What do educators need to know about the Torrance Tests of Creative Thinking: A comprehensive review. *Frontiers in Psychology*, *13*, 1000385.

Almeida, L. S., Prieto, L. P., Ferrando, M., Oliveira, E., & Ferrándiz, C. (2008). Torrance test of creative thinking: The question of its construct validity. *Thinking Skills and Creativity*, *3*(1), 53–58.

AlSagri, H. S., & Sohail, S. S. (2024). Evaluating the role of artificial intelligence in sustainable development goals with an emphasis on "quality education." *Discover Sustainability*, *5*(1), 458.

Amofa, B., Kamudyariwa, X. B., Fernandes, F. A. P., Osobajo, O. A., Jeremiah, F., & Oke, A. (2025). Navigating the complexity of generative artificial intelligence in higher education: A systematic literature review. *Education Sciences*, *15*(7), 826.

Anwar, Y., Widodo, A., Kartika, D., Ariska, M., & Yusliani, N. (2025). Education for Sustainable Development Based on Technological Pedagogical Content Knowledge in Biology Education: Assessing Teachers' Readiness. *Jurnal Pendidikan IPA Indonesia*, *14*(3).

Apaydın, S., & Güven, S. (2022). Pre-service teachers' evaluations of creativity in higher education. *Educational Policy Analysis and Strategic Research*, *17*(1), 58–87.

Arifin, Z., Sukarmin, S., Saputro, S., & Kamari, A. (2025). The effect of inquiry-based learning on students' critical thinking skills in science education: A systematic review and meta-analysis. *Eurasia Journal of Mathematics, Science and Technology Education*, *21*(3), em2592.

Asda, E. F., Dasna, I. W., Parlan, P., & Suharti, S. (2025). The role of inquiry learning in enhancing creativity generating ideas from a self-efficacy perspective. *Eurasia Journal of Mathematics, Science and Technology Education*, *21*(5), em2628.

Bearman, M., & Ajjawi, R. (2023). Learning to work with the black box: Pedagogy for a world with artificial intelligence. *British Journal of Educational Technology*, *54*(5), 1160–1173.

Beghetto, R. A., & Kaufman, J. C. (2014). Classroom contexts for creativity. *High Ability Studies*, *25*(1), 53–69.

Behnamnia, N., Kamsin, A., Ismail, M. A. B., & Hayati, A. (2020). The effective components of creativity in digital game-based learning among young children: A case study. *Children and Youth Services Review*, *116*, 105227.

Bereczki, E. O., & Kárpáti, A. (2018). Teachers' beliefs about creativity and its nurture: A systematic review of the recent research literature. *Educational Research Review*, *23*, 25–56.

Bicer, A., Aldemir, T., Krall, G., Quiroz, F., Chamberlin, S., Nelson, J. L., Lee, Y., & Kwon, H. (2024). Exploring creativity in mathematics assessment: An analysis of standardized tests. *Thinking Skills and Creativity*, *54*, 101652.

Bitzenbauer, P. (2023). ChatGPT in physics education: A pilot study on easy-to-implement activities. *Contemporary Educational Technology*, *15*(3), ep430.

Chinoracky, R., & Stalmasekova, N. (2025). Ethical problems in the use of artificial intelligence by university educators. *Education Sciences*, *15*(10), 1322.

Costa, J. (2024). Mixed methods in educational large-scale studies: Integrating qualitative perspectives into secondary data analysis. *Education Sciences*, *14*(12), 1347.

Dah, N. M., Noor, M. S. A. M., Kamarudin, M. Z., & Azziz, S. S. S. A. (2024). The impacts of open inquiry on students' learning in science: A systematic literature review. *Educational Research Review*, *43*, 100601.

Dilek, M., Baran, E., & Aleman, E. (2025). AI literacy in teacher education: Empowering educators through critical co-discovery. *Journal of Teacher Education*, *76*(3), 294–311.

Doshi, A. R., & Hauser, O. P. (2024). Generative AI enhances individual creativity but reduces the collective diversity of novel content. *Science Advances*, *10*(28).

Ekayana, A. A. G., Parwati, N. N., Agustini, K., & Ratnaya, I. G. (2025). Project based learning framework with STEAM methodology assessed based on self-efficacy: Does it affect creative thinking skills and learning achievement in studying fundamental computers? *Journal of Technology and Science Education*, *15*(1), 107.

Garzón, J., Patiño, E., & Marulanda, C. (2025). Systematic review of artificial intelligence in education: Trends, benefits, and challenges. *Multimodal Technologies and Interaction*, *9*(8), 84.

Giannakos, M., Azevedo, R., Brusilovsky, P., Cukurova, M., Dimitriadis, Y., Hernandez-Leo, D., Järvelä, S., Mavrikis, M., & Rienties, B. (2025). The promise and challenges of generative AI in education. *Behaviour & Information Technology*, *44*(11), 2518–2544.

Gkintoni, E., Antonopoulou, H., Sortwell, A., & Halkiopoulos, C. (2025). Challenging cognitive load theory: The role of educational neuroscience and artificial intelligence in redefining learning efficacy. *Brain Sciences*, *15*(2), 203.

Gohr, C., Rodríguez, G., Belomestnykh, S., Berg-Moelleken, D., Chauhan, N., Engler, J.-O., Heydebreck, L. V., Hintz, M. J., Kretschmer, M., Krügermeier, C., Meinberg, J., Rau, A.-L., Schwenck, C., Aoulkadi, I., Poll, S., Frank, E., Creutzig, F., Lemke, O., Maushart, M., … von Wehrden, H. (2025). Artificial intelligence in sustainable development research. *Nature Sustainability*, *8*(8), 970–978.

Guan, L., Zhang, Y., & Gu, M. M. (2025). Pre-service teachers preparedness for AI-integrated education: An investigation from perceptions, capabilities, and teachers' identity changes. *Computers and Education: Artificial Intelligence*, *8*, 100341.

Holdo, M. (2023). Critical reflection: John Dewey's relational view of transformative learning. *Journal of Transformative Education*, *21*(1), 9–25.

Hooshyar, D., Šír, G., Yang, Y., Kikas, E., Hämäläinen, R., Kärkkäinen, T., Gašević, D., & Azevedo, R. (2025). Towards responsible AI for education: Hybrid human-AI to confront the elephant in the room. *Computers and Education: Artificial Intelligence*, *9*, 100524.

Jin, S.-H., Im, K., Yoo, M., Roll, I., & Seo, K. (2023). Supporting students' self-regulated learning in online learning using artificial intelligence applications. *International Journal of Educational Technology in Higher Education*, *20*(1), 37.

Karampelas, K. (2025). Artificial intelligence in inquiry-based science teaching: A bibliometric study. *European Journal of Science and Mathematics Education*, *14*(1), 104–116.

Kasneci, E., Sessler, K., Küchemann, S., Bannert, M., Dementieva, D., Fischer, F., Gasser, U., Groh, G., Günnemann, S., Hüllermeier, E., Krusche, S., Kutyniok, G., Michaeli, T., Nerdel, C., Pfeffer, J., Poquet, O., Sailer, M., Schmidt, A., Seidel, T., … Kasneci, G. (2023). ChatGPT for good? On opportunities and challenges of large language models for education. *Learning and Individual Differences*, *103*, 102274.

Ko, U., Hartley, K., & Hayak, M. (2025). Exploring AI in education: Pre-service teacher perspectives, usage, and considerations. *Journal of Information Technology Education: Research*, *24*, 21.

Kunnath, A. J., & Botes, W. (2025). Transforming science education with artificial intelligence: Enhancing inquiry-based learning and critical thinking in South African science classrooms. *Eurasia Journal of Mathematics, Science and Technology Education*, *21*(6), em2655.

Kushnir, I. (2025). Thematic analysis in the area of education: A practical guide. *Cogent Education*, *12*(1).

Kwangmuang, P., Jarutkamolpong, S., Sangboonraung, W., & Daungtod, S. (2021). The development of learning innovation to enhance higher order thinking skills for students in Thailand junior high schools. *Heliyon*, *7*(6), e07309.

Lang, D. L., Barry, C. M., Ibragimov, U., Rodriguez, J. L., & Walker, E. R. (2024). Lowering the stakes: Quasi-experimental, mixed-methods evaluation of a restructured grading approach in a graduate public health research methods course. *Pedagogy in Health Promotion*, *10*(4), 250–261.

Li, M., & Wilson, J. (2025). AI-integrated scaffolding to enhance agency and creativity in K-12 English language learners: A systematic review. *Information*, *16*(7), 519.

Liu, X., & Zhong, B. (2025). Integrating generative artificial intelligence into student learning: A systematic review from a TPACK perspective. *Educational Research Review*, *49*, 100741.

Luthfia, S. (2024). Enhancement of creative thinking skill using creative problem solving learning model. *International Journal of Education and Teaching Zone*, *3*(1), 107–118.

Mang, H. M. A., Chu, H.-E., Martin, S. N., & Kim, C.-J. (2023). Developing an evaluation rubric for planning and assessing SSI-based STEAM programs in science classrooms. *Research in Science Education*, *53*(6), 1119–1144.

Muñoz-Salinas, Y., Caro-Zúñiga, D., & Jeria, I. (2025). Creativity and pre-service teachers: A literature review of an underexplored field (2014–2024). *Education Sciences*, *15*(3), 395.

Naz, I., & Robertson, R. (2024). Exploring the feasibility and efficacy of ChatGPT3 for personalized feedback in teaching. *Electronic Journal of E-Learning*, *22*(2), 98–111.

Nelson, A. S., Santamaría, P. V., Javens, J. S., & Ricaurte, M. (2025). Students' perceptions of generative artificial intelligence (GenAI) use in academic writing in English as a foreign language. *Education Sciences*, *15*(5), 611.

Neubauer-Hametner, D., Wendt, H., & Kasper, D. (2025). Teacher perceptions of classroom composition and instructional strategies in primary school science education. *Frontiers in Education*, *10*, 1490875.

Ng, D. T. K., Leung, J. K. L., Su, J., Ng, R. C. W., & Chu, S. K. W. (2023). Teachers' AI digital competencies and twenty-first century skills in the post-pandemic world. *Educational Technology Research and Development*, *71*(1), 137–161.

Novak, E., Kuo, C.-L., Tassell, J. L., & Morris, G. (2024). Effects of a creativity-enhancement intervention on pre-service elementary teachers' creativity in computing education. *TechTrends*, *68*(6), 1095–1106.

Ntsobi, M. P., & Costa, K. (2024). Research as a pillar in STEAM education - Prospects to formalise research in science education. *Medicon Engineering Themes*, *7*(5), 3–12.

Orcan, F. (2020). Parametric or non-parametric: Skewness to test normality for mean comparison. *International Journal of Assessment Tools in Education*, *7*(2), 255–265.

Ouyang, F., & Jiao, P. (2021). Artificial intelligence in education: The three paradigms. *Computers and Education: Artificial Intelligence*, *2*, 100020.

Park, J. (2025). A systematic literature review of generative artificial intelligence (GenAI) literacy in schools. *Computers and Education: Artificial Intelligence*, *9*, 100487.

Rafner, J., Beaty, R. E., Kaufman, J. C., Lubart, T., & Sherson, J. (2023). Creativity in the age of generative AI. *Nature Human Behaviour*, *7*(11), 1836–1838.

Randez, R. A. (2025). The policy of teacher standards: A systems mapping framework for the implementation process of teacher preparation. *TESOL Quarterly*, *59*(3), 1410–1445.

Ratniyom, J., Panmas, W., Rattanakorn, P., & Tientongdee, S. (2025). Generative AI-assisted phenomenon-based learning: Exploring factors influencing competency in constructing scientific explanations. *European Journal of Educational Research*, *14*(4), 1087–1103.

Regona, M., Yigitcanlar, T., Hon, C., & Teo, M. (2024). Artificial intelligence and sustainable development goals: Systematic literature review of the construction industry. *Sustainable Cities and Society*, *108*, 105499.

Roberts, K., Dowell, A., & Nie, J.-B. (2019). Attempting rigour and replicability in thematic analysis of qualitative research data; a case study of codebook development. *BMC Medical Research Methodology*, *19*(1), 66.

Runco, M. A. (2014). *Creativity: Theories and themes: Research, development, and practice* (2nd ed.). Elsevier Academic Press.

Sakhipov, A., Omirzak, I., & Fedenko, A. (2025). Beyond face recognition: A multi-layered approach to academic integrity in online exams. *Electronic Journal of E-Learning*, *23*(1), 81–95.

Sardin, S., Dewi, S. P., Saleh, M., & Alrahhal, M. (2023). The guided note-taking learning model effectively improves students' mathematics learning creativity. *International Journal of Mathematics and Mathematics Education*, *1*(3), 236–249.

Sari, M. S., Sunarmi, S., & Mawaddah, K. (2021). The effect of scaffolding of information literacy on the botanical literacy of prospective biology teachers. *Jurnal Pendidikan IPA Indonesia*, *10*(2), 253-259.

Shi, Y., Yu, K., Dong, Y., & Chen, F. (2026). Large language models in education: A systematic review of empirical applications, benefits, and challenges. *Computers and Education: Artificial Intelligence*, *10*, 100529.

Simanjuntak, M. P., Hutahaean, J., Marpaung, N., & Ramadhani, D. (2021). Effectiveness of problem-based learning combined with computer simulation on students' problem-solving and creative thinking skills. *International Journal of Instruction*, *14*(3), 519–534.

Singh, A., Kanaujia, A., Singh, V. K., & Vinuesa, R. (2024). Artificial intelligence for sustainable development goals: Bibliometric patterns and concept evolution trajectories. *Sustainable Development*, *32*(1), 724–754.

Spronken-Smith, R., & Walker, R. (2010). Can inquiry-based learning strengthen the links between teaching and disciplinary research? *Studies in Higher Education*, *35*(6), 723–740.

Strat, T. T. S., Henriksen, E. K., & Jegstad, K. M. (2024). Inquiry-based science education in science teacher education: A systematic review. *Studies in Science Education*, *60*(2), 191–249.

Tsai, I.-C., & Hsu, F.-S. (2024). Effect of education based on creative problem-solving and asynchronous online discussions on student creativity in a product design course. *Thinking Skills and Creativity*, *54*, 101650.

Tsakeni, M., Nwafor, S. C., Mosia, M., & Egara, F. O. (2025). Mapping the scaffolding of metacognition and learning by AI tools in STEM classrooms: A bibliometric–systematic review approach (2005–2025). *Journal of Intelligence*, *13*(11), 148.

Urdanivia Alarcon, D. A., Talavera-Mendoza, F., Rucano Paucar, F. H., Cayani Caceres, K. S., & Machaca Viza, R. (2023). Science and inquiry-based teaching and learning: A systematic review. *Frontiers in Education*, *8*.

Vinuesa, R., Azizpour, H., Leite, I., Balaam, M., Dignum, V., Domisch, S., Felländer, A., Langhans, S. D., Tegmark, M., & Fuso Nerini, F. (2020). The role of artificial intelligence in achieving the sustainable development goals. *Nature Communications*, *11*(1), 233.

Walter, Y. (2024). Embracing the future of artificial intelligence in the classroom: The relevance of AI literacy, prompt engineering, and critical thinking in modern education. *International Journal of Educational Technology in Higher Education*, *21*(1), 15.

Wang, S., Wang, F., Zhu, Z., Wang, J., Tran, T., & Du, Z. (2024). Artificial intelligence in education: a systematic literature review. *Expert Systems with Applications*, *252*, 124167.

Wondim, B. M., Bishaw, K. S., & Zeleke, Y. T. (2024). Effectiveness of teachers' direct and indirect written corrective feedback provision strategies on enhancing students' writing achievement: Ethiopian university entrants in focus. *Heliyon*, *10*(2).

Zakariya, Y. F. (2022). Cronbach's alpha in mathematics education research: Its appropriateness, overuse, and alternatives in estimating scale reliability. *Frontiers in Psychology*, *13*, 1074430.

Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education – where are the educators? *International Journal of Educational Technology in Higher Education*, *16*(1), 39.

Zhang, X., Zhang, P., Shen, Y., Liu, M., Wang, Q., Gašević, D., & Fan, Y. (2024). A systematic literature review of empirical research on applying generative artificial intelligence in education. *Frontiers of Digital Education*, *1*(3), 223–245.

Zhou, M., & Peng, S. (2025). The usage of AI in teaching and students' creativity: The mediating role of learning engagement and the moderating role of AI literacy. *Behavioral Sciences*, *15*(5), 587.

Zulyusri, Z., Elfira, I., Lufri, L., & Santosa, T. A. (2023). Literature study: Utilization of the PjBL model in science education to improve creativity and critical thinking skills. *Jurnal Penelitian Pendidikan IPA*, *9*(1), 133–143.