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Integrating QR Code Technology in Elementary Science Content: A Developmental Study on Critical Thinking Skills

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Abstract: Critical thinking skills among prospective elementary school teachers remain limited, requiring innovative approaches in learning. This study developed and evaluated QR Code–based teaching materials for the course Basic Concepts of Elementary School Science to enhance students' critical thinking. Using a quasi-experimental one-group pretest–posttest design with 59 PGSD students, critical thinking was assessed through four dimensions: clarification, assessment, inference, and strategy. Results showed a significant improvement, with an average N-Gain of 0.429 (moderate), indicating meaningful progress in students' critical thinking abilities. Score distributions shifted markedly toward higher categories, with the most consistent improvement in the strategy dimension. These findings demonstrate that QR Code–based materials not only make learning more flexible and interactive but also effectively foster higher-order thinking skills. The study concludes that integrating such materials into teacher education curricula is essential to strengthen 21st-century competencies and better prepare future elementary school teachers.

Keywords: Critical thinking skills; Instructional materials; Pre-service teachers; QR code-based learning; Science education

Introduction

The 21st-century demand for teacher education graduates who not only master content but are also skilled at critical thinking is becoming increasingly prominent, along with the implementation of the Independent Curriculum in Indonesia (Loeneto et al., 2022; Masjudin, 2024). The policy document places critical thinking skills as a core competency that must be cultivated from elementary school through contextual and project-based learning (Chusni et al., 2020; Erfan et al., 2025). However, diagnostic studies indicate that the critical thinking skills of prospective elementary school teachers remain moderate or even low, due to the dominance of lecture methods and the lack of teaching materials that stimulate deeper reflection (Thorndahl et al., 2020). Students' technological literacy is relatively high, yet the transition from passive media consumption to active cognitive interaction still faces pedagogical barriers. This imbalance creates urgency for developing learning media that can integrate concrete classroom experiences with digital resources (Doyan et al., 2023; Hazrullah et al., 2023; Mujib et al., 2021; Suartama et al., 2020). Therefore, innovative teaching materials that combine the strengths of physical classrooms and online content are a strategic choice. One simple yet promising technology that has gained global attention is Quick Response (QR) Code, a two-dimensional medium that instantly connects printed learning resources with the digital world.

The adoption of QR Codes in primary and secondary education has demonstrated significant improvements in motivation and cognitive outcomes (Datta et al., 2024; Haetami et al., 2025; Nurwahidah et al., 2024). For example, Istianah et al. (2025) reported post-test gains from 34 to 87 using QR-based science cards, while Bahari et al. (2024) achieved an N-Gain of 0.80 (high category) with a Pocket Solar System module.

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Similarly, Syafira et al. (2024) validated a biodiversity module as "very feasible" with a 90% positive student response. Collectively, these studies show that QR Codes can effectively integrate text, images, videos, and simulations in one scan. However, most findings are limited to elementary school students. Little is known about how QR Codes can specifically support prospective teachers, whose pedagogical readiness is crucial for cultivating a culture of critical thinking in classrooms.

Literature on teacher education emphasizes that pre-service teachers need active, reflective, and problem-based learning experiences. Song et al. (2024) found that project-based learning under the Independent Curriculum enhances elementary students' critical thinking, yet challenges remain in teacher readiness for authentic assessments. Khalid et al. (2021) further identified barriers such as limited resources and minimal training in analytical methods. This suggests the need for teaching materials that not only deliver content but also provide scaffolding for clarification, assessment, inference, and strategy. QR Code technology—with its flexibility and capacity—can embed experimental videos, infographics, and reflective quizzes to trigger prospective teachers' metacognitive processes.

Although QR Code studies are widespread, explicit investigations linking this medium to critical thinking among pre-service teachers in the Basic Concepts of Elementary Science course are scarce. Deamita et al. (2024) demonstrated gains in high school students' critical thinking through QR-assisted Problem-Based Learning, but its generalizability to teacher education remains uncertain. Moreover, prior studies emphasize general cognitive outcomes rather than N-Gain by critical thinking dimensions, and rarely address moderator variables such as gender that may influence adoption. These gaps call for comprehensive quasi-experimental R&D studies to produce validated and empirically tested teaching materials that directly target critical thinking in pre-service teacher education.

Theoretically, Vygotsky's social constructivism highlights the role of scaffolding in moving learners from actual development to the zone of proximal development. QR Codes can serve as mediated tools that provide timely contextual support while allowing learner autonomy. This aligns with Oviawe's (2020) findings that interactive engagement strategies yield normalized gains twice that of traditional learning. Integrated into worksheets, videos, and reflective quizzes, QR Codes can enhance both conceptual understanding and metacognitive engagement (Ahmed et al., 2019; Tan et al., 2021). From a connectivist perspective, QR Codes also function as gateways to digital networks, enabling efficient access to printed and online resources. Together, these frameworks suggest that QR-based teaching materials can improve performance and foster problem-solving habits aligned with real-world contexts.

Following the ADDIE R&D model, the needs analysis confirmed that PGSD students require flexible media accessible offline and online. Expert validation revealed that conventional science content often appears abstract and detached from students' context. The initial design embedded QR Codes in each sub-chapter, linked to demonstrations, simulations, and higher-order thinking questions. Revisions from material and media experts improved feasibility, and limited implementation showed ease of classroom use. Formative evaluation further aligned content with critical thinking indicators. Thus, this study is not a mere replication but an extension to the PGSD level, with explicit focus on critical thinking dimensions and gender as a moderating variable.

Based on this background, this study has three objectives: (1) to develop valid and practical QR Code-based teaching materials for the Basic Concepts of Elementary School Science course; (2) to test their effectiveness in improving the critical thinking skills of prospective teachers both overall and per dimension; and (3) to analyze gender differences in learning gains as an indicator of technology adoption tendencies. The results are expected to enrich the literature on integrating simple technologies into higher education and guide lecturers in designing instruction that emphasizes higher-order thinking. Findings on N-Gain and score distribution will also inform campus policymakers in aligning teacher education with the Independent Curriculum. Ultimately, this study contributes to global discourse on QR Code–assisted learning by providing empirical evidence from the Indonesian context with a focus on pre-service teachers.

This research has potential implications for elementary classrooms, as PGSD graduates may apply similar approaches in practice. Strengthening critical thinking from the pre-service stage is expected to influence teaching patterns, enhance students' scientific literacy, and align with the profile of Pancasila Students. Operational recommendations can also guide institutions in lecturer professional development, particularly in digital literacy and authentic assessment. The results and discussion that follow confirm the validity, reliability, and tangible impact of QR Code–based teaching materials on improving prospective teachers' critical thinking skills.

Method

This study employed a quasi-experimental one-group pretest-posttest design to examine the

effectiveness of QR Code-based teaching materials in the Basic Concepts of Elementary School Science course. The subjects were 59 pre-service teachers enrolled in the Elementary School Teacher Education (PGSD) Study Program, who took the course in the even semester.

The intervention was conducted over eight lecture sessions during one semester, where students engaged in structured learning activities using the validated QR Code-based teaching materials. Before the intervention, participants completed a pretest to measure their initial critical thinking abilities. After completing the series of learning activities, a posttest was administered to assess the improvement in their critical thinking skills.

The test instrument consisted of essay questions based on Ennis's (1996) framework of critical thinking, covering four dimensions: clarification, argument assessment, inference, and problem-solving strategies. The data obtained were analyzed using the normalized gain (N-Gain) to evaluate the effectiveness of the teaching materials in improving pre-service teachers' critical thinking skills. The N-Gain was calculated by comparing individual pretest and posttest scores, and then averaging them to provide an overall picture of improvement. In addition, descriptive analysis was used to illustrate the distribution of scores after the intervention, providing a clearer understanding of the extent to which the developed teaching materials supported the strengthening of critical thinking in the context of science learning.

Figure 1. Research activity flow

Result and Discussion

This section presents the research findings obtained from the analysis of pretest and posttest data conducted on the participants. The study measured the effectiveness of QR Code-based teaching materials in improving students' critical thinking skills in the Basic Concepts of Elementary Science course. Critical thinking was assessed across four dimensions: clarification, assessment, inference, and strategy (Bahtiar et al., 2023; Erfan et al., 2024; Teng et al., 2023). The results are presented through average scores, score distributions, and normalized gain (N-Gain) values, and further categorized based on improvement levels and gender differences. Data visualization is provided in the form of bar charts, box plots, histograms, and pie charts to give a clear and comprehensive overview of the outcomes. The respondents in this study are presented in the following figure.

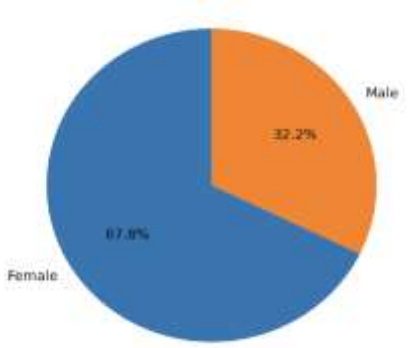

Figure 2. Student gender distribution

Based on the gender distribution diagram above, the majority of respondents were female (67.8%) (40 female students), while 32.2% were male (19 male students). This composition reflects the tendency of female dominance in the Elementary School Teacher Education (PGSD) study program. The greater number of female respondents provides a general overview of the characteristics of participants who will implement the teaching materials in the field. This is also an important consideration in analyzing the perception and effectiveness of the developed QR Code-based teaching materials. With this diversity of backgrounds and gender proportions, the results of this study are expected to provide a comprehensive picture of the readiness and response of prospective teachers to science learning innovations at the elementary school level. The following is presented in Figure 3 regarding the Distribution of Total Scores.

Figure 3 shows a significant shift in the distribution of students' total scores between the pre-test and post-test results after the use of innovative QR Code-based learning materials. In the pre-test, the distribution of scores was concentrated in the 10–11 range, with an average (marked by the red dotted line) of 10.7. Meanwhile, the post-test distribution shifted to the right, indicating a significant jump in scores with a new average (blue dotted line) of 15.1. Most students scored

between 14–16, with a large group even reaching the maximum score. This shift reflects not only improved individual performance but also an overall improvement in the quality of student learning outcomes. This phenomenon reflects that the majority of participants were able to absorb and apply the critical thinking content provided in the interactive learning materials. Furthermore, the new, denser distribution of high scores indicates the consistency and effectiveness of the intervention.

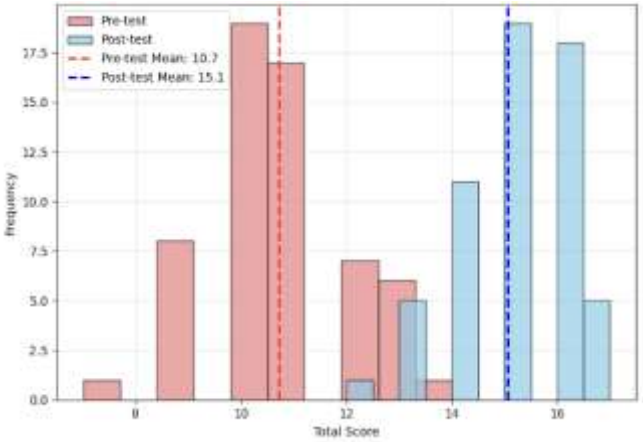

Figure 3. Distribution of total scores

These results support Bandura's social cognitive learning theory, which emphasizes that observation, internal reinforcement, and interaction with learning media influence academic achievement. QR Codes enable quick access to multimedia content, broaden the scope of learning stimuli, and enhance student interactivity with the material. This aligns with previous research by Moghimi et al. (2024) and Kandiri et al. (2025), which demonstrated that QR Code-based learning media can improve concept retention and encourage active student engagement in content exploration. In the context of critical thinking, exposure to open-ended questions and additional learning resources through QR Codes stimulates metacognitive processes, encouraging students to analyze, evaluate, and draw conclusions more rigorously (Ali et al., 2025; Nirwana et al., 2025). Because critical thinking requires repeated practice and in-depth reflection, media integration that supports flexible learning is highly relevant in the modern learning era (Cyndirela et al., 2025; Doyan et al., 2022; Kusumadani et al., 2025). With an average improvement of 4.4 points, it can be concluded that this learning material has optimally fulfilled its pedagogical and technological functions.

Implicitly, this distribution reinforces the argument that technology integration in teaching materials is not merely a supplement, but a real tool for transforming learning. The Independent Curriculum, which demands differentiated learning and the strengthening of the Pancasila Student Profile, becomes more easily achieved through this approach. The nearly uniform improvement in scores across all students demonstrates that QR Code media is not only effective for high-ability students but also helps groups with lower initial abilities catch up. This encourages equality in learning outcomes, a crucial indicator of transformative education. Moving forward, curriculum developers and lecturers can utilize these results to design more systematic interventions, such as project-based enrichment or digital portfolio-based assessments integrated with QR codes. With such designs, the potential for improving critical thinking occurs not only in the classroom but also extends to students' professional practice as future teachers. Therefore, this graph does not simply represent numbers but also forms an argumentative basis for developing a more adaptive and meaningful future learning direction. The Box Plot Score Comparison Figure is also presented below.

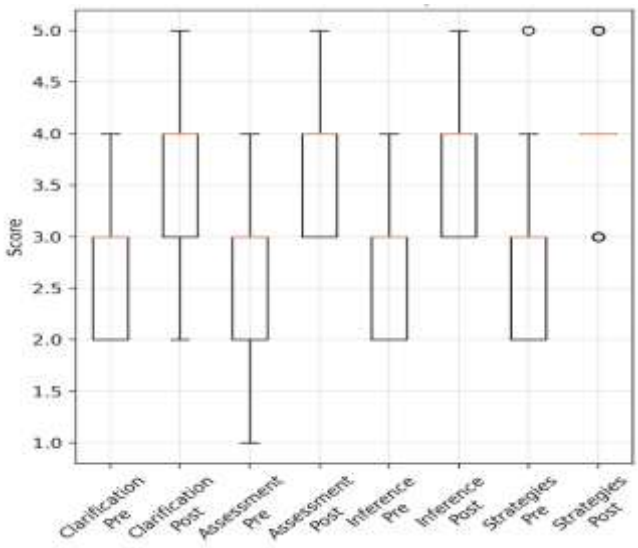

Figure 4. Box plot score comparison

Figure 4 shows the distribution of pre-test and post-test scores for each dimension of critical thinking, namely Clarification, Assessment, Inference, and Strategies. In all four dimensions, the median post-test score is higher than the pre-test score, indicating a consistent improvement in performance. The interquartile range (IQR) also shifts upward, particularly in the Strategies and Assessment dimensions, suggesting that most participants achieved higher and more consistent results after the intervention. Outliers in the post-test, especially in Strategies and Inference, indicate that some participants reached maximum scores, while the pre-test distribution was more varied and concentrated in the lower range. These findings confirm that QR Code-based teaching materials

not only improved individual achievement but also reduced disparities between students.

This pattern of improvement supports the constructivist view that learning is most effective when students actively engage with contextual and interactive resources. The integration of QR Codes into basic science teaching materials provides quick access to videos, simulations, and infographics that reinforce concepts and stimulate reflection. This aligns with the Independent Curriculum's emphasis on higher-order thinking and differentiated learning, allowing students to progress at their own pace—providing reinforcement for those who struggle and enrichment for those who advance more quickly (Sari et al., 2024; Yusuf et al., 2025). The increase in median scores and narrowing of the IQR therefore serve as empirical evidence that QR Code-assisted learning materials embody these theoretical principles and can be considered for broader application in teacher education courses.

Figure 4 also provides important insights for lecturers and higher education policymakers in designing data-driven assessments and enrichment programs. For example, the emergence of high-scoring outliers on the post-test can be used to identify potential students who deserve additional challenges in the form of project assignments or teaching assistance. Meanwhile, the increase in median scores across all dimensions indicates that the majority of students not only understand the concepts but are also able to apply critical thinking skills in real-world settings. This is crucial for developing the profile of prospective elementary school teacher graduates who are ready to face the complexities of basic education. Future research can further explore the relationship between learning styles, QR Code utilization, and scores on each dimension to produce a more adaptive and personalized learning approach. Thus, the graphBox Plot Score Comparison is not simply a statistical visualization, but a reflection of the success of a planned, contextualized learning intervention that supports strengthening 21st-century competencies. Figure 5 also presents the Inter-Dimensional Correlation.

Figure 5 shows the correlations between critical thinking dimensions in both the pre-test and post-test. In general, the correlation values shown are in the low to moderate range, indicating that the relationships between the dimensions are still quite weak but still show a certain interconnectedness. In the pre-test, the strongest relationship was seen between Pre-Inference and Pre_Strategies a correlation value of 0.26, indicating that students who initially had fairly good inference skills also tended to have supporting thinking strategies. Meanwhile, in the post-test, the highest correlation was found between Post_Clarification and Post_Assessment of 0.11, which indicates that after learning, the relationship between components tends to become more balanced, although not significant. Negative correlations, such as between Post_Clarification and Post_Strategies (-0.15), indicate a potential trade-off, or a tendency for emphasis on one dimension to reduce achievement in another. However, because the values are still low, this cannot yet be concluded as a strong causal relationship. Overall, this matrix indicates that the critical thinking dimensions operate relatively independently but still complement each other.

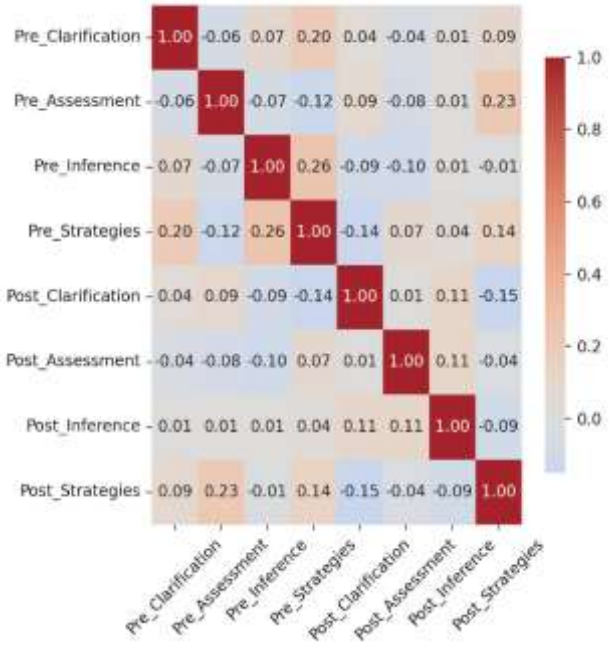

Figure 5. Inter-dimension correlation

This situation reinforces the theory that critical thinking is a set of specific skills that can be developed separately or in an integrated manner. According to Ennis (1993), critical thinking dimensions such as clarification, assessment, inference, and strategy, although interrelated, have unique cognitive processes and require different instructional approaches (Arisoy et al., 2021; Mardhatillah et al., 2025). Therefore, a QR Code-based learning approach that presents modular content per dimension can help develop skills proportionally. The low correlation between post-learning dimensions also means that students are given space to develop according to their strengths and interests, by the principle of differentiated learning in the Independent Curriculum. Previous research by Kravchenko et al. (2023) showed that technology-based learning models allow students to choose the learning path that best suits their thinking style. Therefore, in this context, a low correlation does not indicate ineffectiveness, but rather evidence of flexibility and personalization of learning. This is crucial in preparing

prospective teachers capable of critical and reflective thinking in diverse elementary school teaching contexts.

These results indicate that future development of teaching materials should consider designing activities that more explicitly integrate critical thinking dimensions. For example, in a project-based activity, students could be asked to clarify a problem, assess information, draw inferences, and develop a solution strategy within a single line of thought. This would strengthen the interconnections between the dimensions and create a more integrated learning experience. Improved post-learning correlations could also serve as an indicator of successful content integration, which could be monitored in subsequent learning evaluations. These correlations could also form the basis for developing an analytical dashboard for lecturers to map each student's critical thinking strengths and weaknesses. In the future, exploring correlations with other variables such as motivation, digital literacy, or self-regulated learning could also enrich our understanding of the dynamics of critical thinking skill development holistically. Therefore, this correlation heatmap provides not only an overview of the relationships between scores but also a direction for developing more adaptive and personalized data-driven learning designs. Individual improvement scores are also presented below.

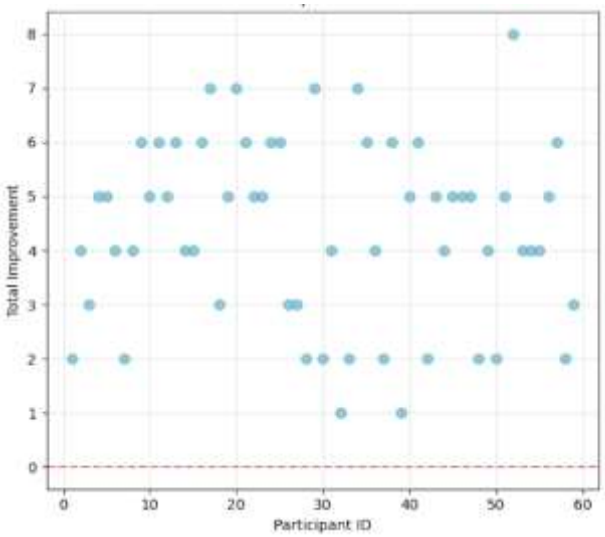

Figure 6. Individual improvement

This figure illustrates the increase in each participant's total critical thinking score after participating in learning with innovative QR Code-based learning materials. Most participants showed a score increase in the range of 3 to 6 points, indicating a uniform positive effect of the learning intervention. Some participants experienced significant increases of up to 7 or 8 points, indicating that this intervention was very effective for some individuals. However, there were still some participants who only experienced minimal improvements, even just one or two points. No participants scored zero or decreased (the red line of zero remained uncrossed), indicating that there were no negative effects from the learning materials used. This strengthens the claim that these learning materials are safe and beneficial in the context of improving critical thinking skills. In other words, the variation in scores indicates that learning outcomes are influenced by internal student factors such as motivation, interests, and individual learning strategies.

These findings are consistent with a differential approach to learning, which suggests that the same intervention can produce different learning outcomes depending on the individual characteristics of the learner. In this context, students with active and independent learning styles are likely to be better able to utilize the interactive features of QR Codes. They may be more interested in exploring additional links, videos, or digital learning resources provided. On the other hand, learners who are more passive or accustomed to conventional approaches are less likely to utilize the learning materials' potential. Therefore, while generally effective, these results highlight the need for additional mentoring or scaffolding strategies to ensure all learners receive optimal benefits. Technology-based learning such as this needs to be designed with flexibility to reach various types of learners. Further research could delve deeper into the factors influencing the level of individual improvement in the use of innovative learning materials. Figure 7 is also presented below mean scores by dimension.

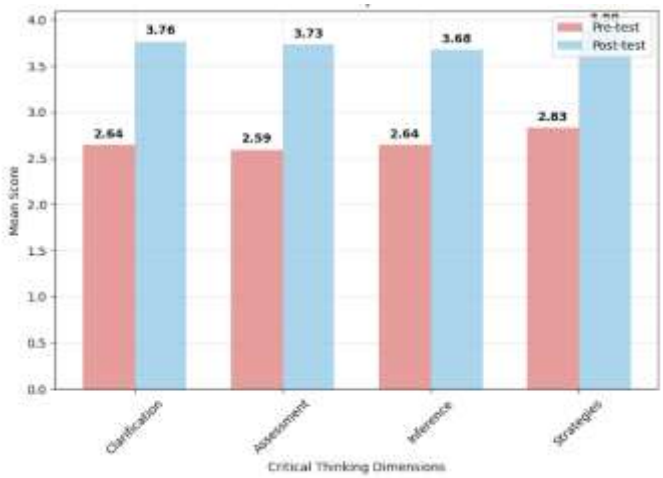

Figure 7. Mean scores by dimension

Figure 7 shows a consistent and significant increase in average scores in all dimensions of students' critical thinking after the learning intervention using innovative teaching materials assisted by QR Codes. Clarification experienced an increase from a score of 2.64 to 3.76,

Assessment from 2.59 to 3.73, Inference from 2.64 to 3.68, and the score increased from 2.83 to 3.89. This indicates that students not only gained a better understanding of concepts but also developed higher-order thinking skills such as analyzing, evaluating, and designing learning strategies. The consistent increase in scores across all dimensions also indicates that the teaching materials successfully addressed critical thinking aspects comprehensively.

These findings reinforce constructivist theory, where knowledge is actively constructed through direct engagement with learning experiences. QR Code-based learning materials provide access to interactive content that allows students to access additional information, answer reflective questions, and explore the material more deeply and independently. Furthermore, this approach aligns with cognitive learning theory, which emphasizes the importance of mental engagement and information processing in enhancing reasoning and critical thinking. This research aligns with previous findings by Kim et al. (2020) and Rossi et al. (2021), which stated that the use of technology in learning materials can increase students' active participation and the quality of their thinking in the context of science learning.

Practically, the results of this study demonstrate that the integration of technology through QR codes in basic science teaching materials not only increases motivation and learning independence but also encourages the development of critical thinking competencies as required by the Independent Curriculum. Prospective elementary school teachers who possess critical thinking skills will be better prepared to face the challenges of 21st-century education and will be able to develop creative and reflective learning models in elementary grades. Therefore, the development of technology-based teaching materials such as this deserves to be continued and expanded to other courses that require higher-order thinking skills (Doyan et al., 2020). This study provides evidence that targeted learning design can have a significant positive impact on the quality of learning outcomes for future prospective educators. Figure 8 presents a comparison of the distribution of pretest and posttest scores.

Figure 8 shows a clear shift in the distribution of total scores between the pre-test and post-test after students engaged in learning with innovative QR Code-based learning materials. In the pre-test, the median was around 10, while in the post-test, it rose dramatically to around 15, indicating a substantial increase in collective performance. The pre-test interquartile range (IQR) appears wider and extends to a low score of 7, indicating considerable initial variability among participants. In contrast, the post-test IQR is more concentrated in the high scores of 14–16, resulting in a more homogeneous and overall improved distribution of scores. The disappearance of extreme scores at the bottom from 7 in the pre-test to 12 in the post-test indicates that the intervention successfully improved the performance of previously low-achieving students. Meanwhile, the emergence of positive outliers around 17 reflects individuals who were pushed beyond average achievement due to exposure to interactive content. The median shift, IQR narrowing, and negative outlier pruning together provide strong visual evidence of the effectiveness of QRCode-based teaching materials in improving and stabilizing critical thinking capabilities.

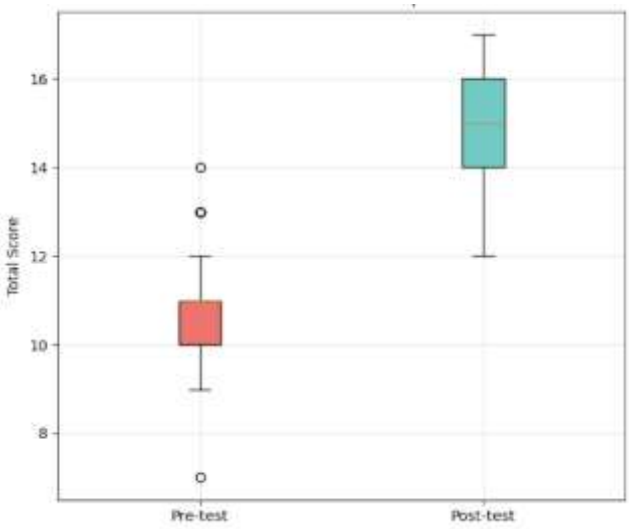

Figure 8. Score distribution comparison

This finding is in line with the principle of zone of proximal development (Vygotsky) emphasizes the importance of digital scaffolding, in this case, video links, simulations, and reflective quizzes triggered by QR Codes, to help students transcend their initial capabilities. When students are allowed to explore content independently but in a guided manner, they can construct knowledge at a higher level than is achieved through traditional lectures. Previous research by Nobutoshi (2023) and Hartati et al. (2025) emphasized that reflective interactions with diverse learning resources enrich cognitive frameworks and accelerate the internalization of reasoning skills. As a practical consequence, lecturers need to ensure that each element of the QR Code is designed not only to be informative but also to challenge and stimulate metacognition—for example, through higher-order, problem-based questions. Why is this important? Increasing the median is not enough; the new homogeneity created must be accompanied by opportunities for excellent students to continue to thrive. Conversely, students who were previously below average have now successfully surpassed the minimum skill "baseline," narrowing the

performance gap. Thus, this graph provides an empirical basis for universities to prioritize investments in learning technologies proven to increase academic achievement across the board.

This higher distribution has significant pedagogical implications for prospective elementary school teachers. Students who now score in the 12–17 range will enter the real classroom with more conceptual readiness and critical thinking skills, enabling them to design science learning experiences that foster curiosity and scientific reasoning in students. Stable results also make it easier for faculty to implement authentic, project-based assessments without having to focus too much on basic remediation. Future studies could explore non-cognitive factors—such as self-regulation, digital efficacy, and intrinsic motivation—that may bridge the relationship between QRCode technology and post-intervention score increases. Furthermore, integrating learning analytics into the QRCode system would enable real-time monitoring of student progress, allowing adaptive feedback to be provided before performance declines. This data-driven approach will ensure the sustainability of score increases and support target achievement. Pancasila Student Profilewhich emphasizes critical thinking, creativity, and digital literacy competencies. Therefore, this score distribution visualization serves not only as an indicator of short-term success but also as a foundation for ongoing learning innovation in the Elementary School Teacher Education environment. The following presents improvements by gender for each critical thinking skill indicator.

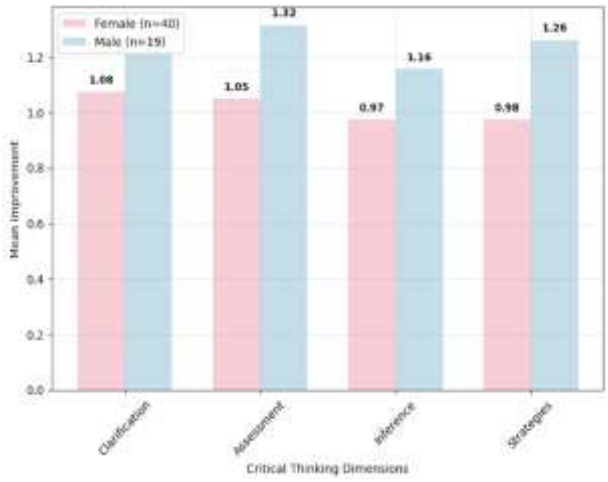

Figure 9. Improvement by gender

Figure 9 shows that the average increase in critical thinking scores after the learning intervention tended to be higher in male students than in female students across all dimensions. The most striking increase was seen in the critical thinking dimension. Assessment, where men achieved a score of 1.32 compared to women's 1.05. Likewise, in the dimension Strategies, males experienced an increase of 1.26, while females only experienced an increase of 0.98. Overall, although the number of female respondents was significantly greater (n=40) than male (n=19), males showed a greater learning response to innovative QR Code-based teaching materials.

This phenomenon can be explained through a differentiation approach to learning styles and intrinsic motivation. Research conducted by Gurian et al. (2005) shows that males tend to be more interested in visual, interactive, and technology-based activities. This aligns with the characteristics of the learning materials used in this study, which emphasize independent exploration through QR Code links. Conversely, females tend to have a more structured learning style and require direct guidance in constructing understanding, so this type of intervention may not fully accommodate their needs.

However, it's important to note that both gender groups still showed improved scores, demonstrating the overall effectiveness of the materials. These findings provide valuable input for developing more inclusive materials, taking into account the diversity of learning styles based on gender. Future adjustments to instructional design can be directed toward aligning interactive approaches with individual needs, so that all students, both male and female, can optimally benefit from improving critical thinking skills. The following also presents N-Gain by gender.

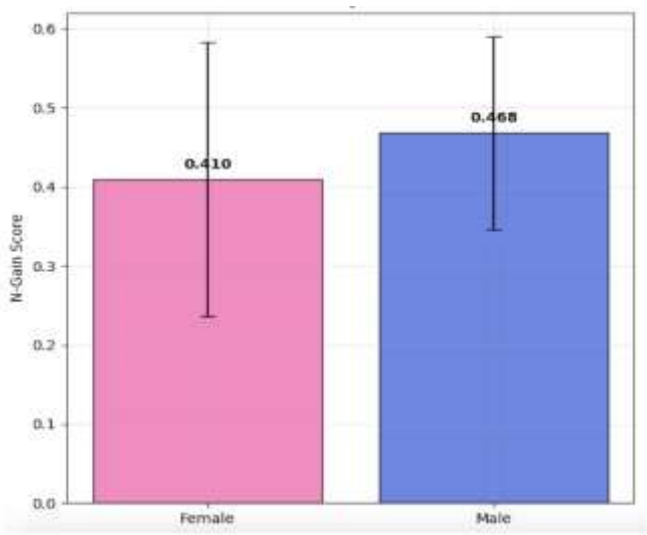

Figure 10. N-Gain by gender

The bar graph above shows a comparison of N-Gain scores by gender, with male students recording an average score of 0.468 and female students 0.410. This difference indicates that, in general, males experienced slightly higher improvements than females after participating in the learning intervention. However, it should be noted that this difference in scores is moderate

and does not necessarily reflect the superiority of one gender over another in terms of critical thinking skills. In the context of technology-based learning, such as the use of QR Code-assisted teaching materials, there may be different comfort factors, previous experiences, or learning styles between male and female students that influence this level of improvement. Research by Aruleba et al. (2023) shows that the perception and adoption of technology in learning can be influenced by gender factors, including self-confidence and technology use strategies.

Although male students demonstrated higher N-Gain scores, it is important to note that the distribution of scores is indicated by the relatively long error bars, indicating significant variation in scores across both gender groups. This suggests that within each group, there are individuals with varying levels of improvement. Therefore, learning strategies need to consider the diversity of individuals, even within a single gender group. Tomlinson et al. (2023) theory of learning differentiation emphasizes the importance of recognizing differences in student readiness, interests, and learning profiles to achieve optimal outcomes. Therefore, while aggregate data demonstrates certain trends, an individualized approach still needs to be prioritized to ensure all students receive meaningful and equitable learning experiences.

These results can also serve as a reflection for further evaluation of aspects of teaching material design that may be more resonant with certain characteristics. Are the developed teaching materials sufficiently inclusive and responsive to the needs of female students? Does the approach provide balanced exploration space for both genders? Answering these questions is crucial for optimizing the use of educational technology to truly support the development of critical thinking skills equitably. As Nehru et al. (2024) stated in their revised Bloom's taxonomy, the development of higher-order thinking skills such as analysis, evaluation, and creation must be actively facilitated through learning approaches that encourage interaction, reflection, and problem-solving. Therefore, differences in N-Gain scores between genders should not be the endpoint of analysis, but rather a foundation for developing more equitable and effective learning improvement strategies. Furthermore, the percentage increase based on dimension is also presented in Figure 11.

Figure 11 confirms that all aspects of critical thinking of prospective elementary school teachers experienced a surge of more than a third from the initial condition after using innovative QR Code-based teaching materials. Assessment recorded the highest increase, namely 43.8%, followed by Clarification 42.3%, Inference39.1%, andStrategies37.7%. The largest proportion of increase in Assessment indicates that students are becoming more skilled at evaluating evidence and arguments objectively, a core skill for when they later guide elementary school students in analyzing science phenomena. The increase was almost commensurate with clarification, reflecting progress in identifying and formulating problems appropriately, while improvements in inference and strategies demonstrated improved skills in drawing logical conclusions and designing solutions. The differences in percentages between dimensions are thought to be related to the characteristics of the interactive content: assessment and clarification materials were presented in the form of reflection-inducing quizzes, while problem-solving strategies often required independent exploration that may not have been optimized by all participants. Nevertheless, the average increase of over 37% in each dimension demonstrates that this multimodal approach successfully stimulated the development of higher-order thinking across the board.

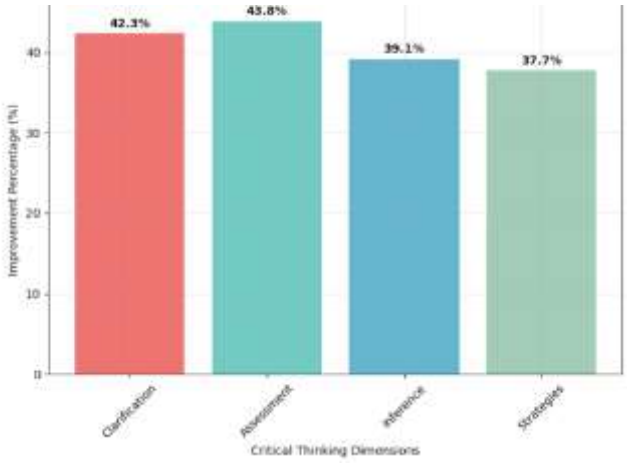

Figure 11. Percentage Improvement by Dimension

These findings are in line with constructivist theory and framework. Higher-Order Thinking Skillswhich emphasizes the importance of active, reflective, and contextual learning experiences to foster critical thinking. QRCode-based teaching materials facilitate independent learning through video links, virtual simulations, and digital worksheets that encourage students to formulate questions, compare concepts, and test hypotheses directly. Several recent studies, for example, the development of the IPAS QRCode card by Istianah et al. (2025), pocket-book A QR Code-based solar system by Bahari et al. (2024), and a digital e-module for science literacy by Herlina et al. (2024), also reported significant improvements in learning outcomes and higher-order thinking skills in elementary school students. These findings demonstrate that QR Code integration is not merely a technological gimmick, but rather a tool relevant to the characteristics of the digital

generation and the demands of the Independent Curriculum. In addition to enriching visual-interactive media, QR Code provides quick access to credible sources that strengthen evidence-based reasoning processes. This convergence of theory and empirical evidence strengthens the claims of the effectiveness of innovative teaching materials in current research.

These results also require lecturers and curriculum developers to continue designing materials that balance free exploration with structured scaffolding, so that all dimensions of critical thinking can be optimally encouraged. The lowest increase was in strategies. While still impressive, these findings signal the need for collaborative assignments or real-world case studies to help students become more skilled at planning problem-solving steps. Furthermore, regular formative evaluations are recommended so that lecturers can adapt the complexity of the content to students' cognitive profiles. These findings also provide empirical evidence for campus policymakers that investment in QRCode-based learning media is worth prioritizing to improve prospective teachers' readiness to face 21st-century challenges. Future research could explore the relationship between learning motivation, personal digital literacy, and the magnitude of improvement in each dimension, allowing for sharper instructional differentiation strategies. Developing similar teaching materials in other subjects, such as elementary school mathematics or social studies, would expand the positive impact of technology while validating these findings across disciplines. Thus, QRCode-based innovations have the potential to become a national reference model for strengthening a culture of critical thinking starting in pre-service teacher education. Figure 12 also presents the N-Gain distribution.

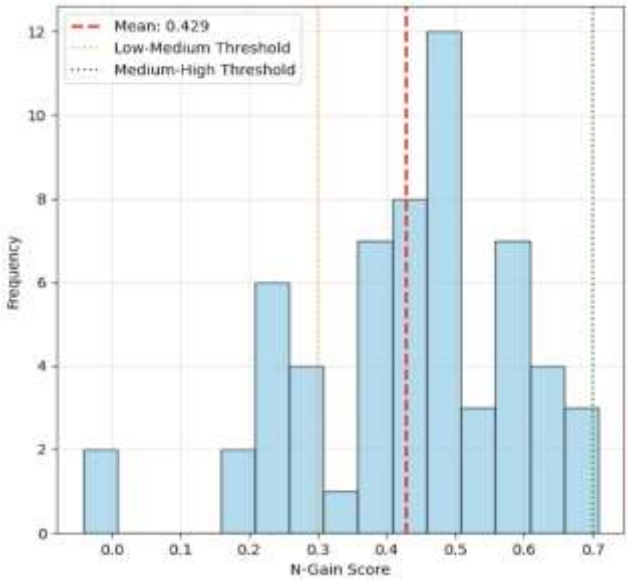

Figure 12. Overall n-gain

The distribution of student learning outcomes after using QR Code-based teaching materials shows an average N-Gain score of 0.429, which falls into the moderate category based on Hake's (1999) classification. This finding indicates that learning outcomes generally improved, although they have not yet reached a very high level. Most students achieved scores above the 0.3 threshold, with the highest concentration in the 0.45–0.5 range, reflecting consistency in learning success. A small number of students reached scores close to or above 0.7, suggesting the potential for stronger impacts on certain individuals. On the other hand, the presence of very low or even negative N-Gain scores among a few participants highlights the influence of personal factors such as motivation, readiness, or technical barriers. Overall, these results illustrate that the developed teaching materials are effective in enhancing critical thinking skills, while also showing variations that require further attention.

In the context of constructivist learning theory, the increase in N-Gain scores reflects how QR Code-based teaching materials place students at the center of learning activities. For example, when scanning a QR Code, students access short videos, simulations, or contextual explanations that allow them to connect prior knowledge with new information. This process illustrates Piaget's concept of assimilation and accommodation, as students adjust their mental structures while actively engaging with content in real time.

At the same time, QR Codes function as scaffolding in the Vygotskian sense. Each code provides step-by-step guidance or complementary resources that support students within their Zone of Proximal Development (ZPD). Learners who struggle can revisit QR Code materials at their own pace, while more advanced students can access enrichment links, thus experiencing differentiated support. In this way, the technology does not merely provide content but actively facilitates the social cognitive mechanisms described by Vygotsky. These characteristics explain why the N-Gain distribution tends to cluster in the medium-to-high range: the QR Code system simultaneously supports individual meaning-making and guided learning progression. Previous research by Sabdarifanti et al. (2025) also found that QR Code-based media increases students' activeness, curiosity, and absorption in science learning. In this study, these positive effects are reflected in the N-Gain distribution, which tends to be in the medium to high category. This provides empirical evidence that the use of simple yet contextual technology can produce meaningful pedagogical impacts. Therefore, the integration of QR Codes in teaching materials is worth considering as a good

practice in developing learning tools in higher education.

The findings from the N-Gain distribution are important for planning differentiated and remedial learning strategies. Students with low N-Gain can be identified for additional support, whether in the form of tutorials, further formative assessments, or adjustments to the learning approach. On the other hand, students with high N-Gain can be given enrichment assignments or involved in peer teaching activities to strengthen their mastery of the material and share it with their classmates. N-Gain analysis can also be used as a benchmark for the sustainability of teaching materials: whether content revisions, instructional reinforcement, or the addition of other interactive features are needed. In the context of program assessment, this figure is also useful as a reflection tool for lecturers in assessing whether competency-based learning objectives have been achieved evenly. Finally, this N-Gain distribution not only describes learning outcomes but also opens up room for continuous improvement, both in terms of teaching material design, instructional strategies, and student learning support systems. Figure 13 presents the distribution of N-Gain categories.

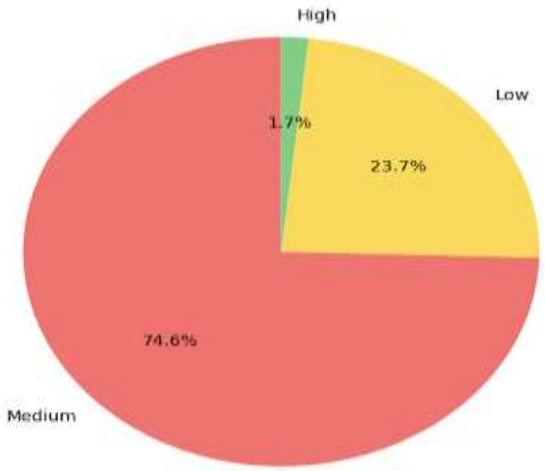

Figure 13. N-Gain interpretation summary

The pie chart in the figure above shows the overall distribution of N-Gain categories across the study participants. The results indicate that the majority of participants, 74.6%, were in the moderate improvement category (medium), while 23.7% were in the low category (low), and only 1.7% reached the high category (high). This shows that the implemented learning intervention is quite effective in encouraging increased critical thinking skills in most students, although there are still groups that require further attention. According to Hake's (1998) classification, N-Gain scores are categorized as low (<0.3), medium (0.3–0.7), and high (>0.7), and these results indicate that the QR Code-based approach can provide results in the following categories: moderate to wide. Although not many have reached the category high, category dominance medium is a positive achievement for the process of developing technology-based teaching materials in basic education.

These results also indicate that approximately one-quarter of students (23.7%) still experienced low progress, indicating the need for further evaluation of the learning approach for this group. There are several possible causes for this low achievement, such as different learning styles, lack of motivation to learn, or barriers to accessing and using technology-based learning materials. Constructivist theory suggests that learning should take into account the background, experience, and readiness of students to optimize learning outcomes. Therefore, learning differentiation strategies and additional guidance may be necessary to reach low-achieving groups. Previous research by Hamid et al. (2025) also showed that the use of technology in learning needs to be accompanied by mentoring so that all participants can maximize its use. Therefore, these results underscore the importance of reflecting on student diversity and the need for adaptive strategies.

Meanwhile, the achievement was 1.7% in the categoryhighcan be seen as the maximum potential for success from implementing innovative QR Code-based teaching materials. Although the proportion is small, this shows that teaching material design can have a significant impact on a small portion of students who may be more prepared, more motivated, or have higher digital literacy. According to the cognitive theory approach, students who already have a strong cognitive structure will more quickly understand new information and transfer it into higher-order thinking skills. Therefore, this data is important as a benchmark to identify the characteristics of high-achieving participants as a reference in developing learning support for other groups. Overall, this distribution demonstrates the relative success of the learning model used, but also signals the need for ongoing evaluation and improvement to ensure more equitable and inclusive learning outcomes.

Conclusion

Based on the research results and discussion, it can be concluded that the use of innovative QR Code-based teaching materials oriented toward critical thinking skills has a positive impact on improving students' critical thinking abilities. The findings confirm that this learning approach supports the development of critical thinking and demonstrates the potential of QR Code technology as an effective strategy for enhancing the

quality of learning in the Basic Concepts of Elementary Science course.

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Author Contributions
Conceptualization, I.I. and N.N; methodology, N.M.Y.S.; formal analysis, N.M.Y.S. and I.I.; investigation, I.I. and N.A.; resources, N.N. and N.A; data curation, I.I. N.A; writing—original draft preparation, I.I., N.M.Y.S., and N.N.; writing—review and editing, N.M.Y.S and I.I.; visualization, N.A. I.I.; funding acquisition, I.I. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
No conflict interest.

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