Inquiry-Based Science Teaching and Its Impact on Critical Thinking and Problem-Solving Skills: A Meta-Analysis of STEM Education

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Systematic Review

Keywords: Inquiry-Based Science Teaching, STEM Education, Critical Thinking, Problem-Solving Skills, Meta-Analysis, and Educational Strategies.

Posted Date: April 8th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-6365963/v1

Additional Declarations: The authors declare no competing interests.

Abstract

This meta-analysis study, an Inquiry-based science education (IBSE), has been gaining increasing popularity as a strong pedagogy to develop students' problem-solving and critical thinking abilities in STEM (Science, Technology, Engineering, and Mathematics) education. This meta-analysis combines evidences from 40 various review articles and empirical studies that have appeared in prestigious research journals between 2016–2025 to analyse the impact of IBSE on the development of students' cognitive skills, i.e., their problem-solving ability and critical thinking skills. The research explores the relative quality of different kinds of inquiry, i.e., guided and open-ended inquiry, and identifies noteworthy determinants making IBST impactful in building such abilities. Research shows that IBST enhances significantly the critical thinking and problem-solving ability of the students with medium to large effect sizes at every level of education, from primary to tertiary. In addition, the research highlights teacher facilitation, planning of inquiry-based activities, and technology integration as the factors that help obtain the highest benefit in IBST. The student motivation and involvement also emerged as significant factors driving the success of IBST. These results hold insightful implications for education policy makers and educators to propel STEM education to new heights with the integration of inquiry-based approaches that stimulate higher-order skills in 21st-century.

Introduction

IBST is now a significant pedagogical strategy in STEM learning, emphasizing learner-centered exploration and discovery. As the need for problem solvers and critical thinkers continues to grow in STEM industries, IBST is a significant tool in the development of problem-solving and critical thinking skills. Through the movement away from conventional, teacher-centered instruction and toward learner-centered inquiry, IBST generates active learning, critical thinking, and problem-solving 21st-century STEM education key components (Antonio & Prudente, 2024). This meta-analysis seeks to summarize the available literature on IBST's effect on the cognitive skills of learners, such as problem-solving and critical thinking, necessary for academic success in STEM fields (Arifin, Saputro, & Kamari, 2025). IBST promotes learners to ask questions, carry out investigations, interpret data, and arrive at conclusions learning habits that by themselves promote the acquisition of problem-solving and critical thinking skills (Lazonder & Harmsen, 2016). Unlike the traditional stress of memorization by rote inherent in lecture-based approaches, IBST is linked to active learner participation, which enhances problem-solving capacity and students' involvement in the learning process (Cairns & Areepattamannil, 2019).

There has been proof that IBST positively influences the cognitive development of students, especially in developing their problem-solving capacities (Dewanto et al., 2024). By translating scientific principles to everyday problems, students develop greater conceptual understanding and transfer learning to new contexts more effectively (Strat, Henriksen, & Jegstad, 2024). Furthermore, IBST enhances collaboration, a vital skill needed in today's STEM careers. Students argue, argue, question, and narrow down arguments through peer-to-peer discussion, thereby improving problem-solving skills and promoting critical thinking skills (Ješková et al., 2022). IBST's collaborative culture also motivates students to learn with diverse points of view and develop communication and teamwork skills (Hidayat et al., 2024). Technology is also a crucial factor in the practice of IBST. The utilization of computer-based tools, simulation, and online resources enables students to learn STEM principles interactively and dynamically (Kim et al., 2020). Studies also suggest that IBST, when combined with technology, brings greater improvement in critical thinking and problem-solving skills to students, presenting special opportunities for students to engage with advanced data and models that cannot readily be replicated in traditional classrooms (Ting et al., 2023).

This meta-analysis integrates the results of 40 empirical studies and literature reviews from 2016 to 2025 on the influence of IBST on cognitive abilities, comparing research approaches and determining success factors (Azriyanti, 2023). The findings indicate that IBST has a significant influence on students' critical thinking and problem-solving abilities, with moderate to large effect sizes at various levels of education and fields. Teacher scaffolding, inquiry activity structure, and technology integration are essential in planning an environment for deep learning and the acquisition of 21st-century skills (Mao et al., 2022). This meta-analysis offers insights that can guide educators and policymakers seeking to improve STEM education through inquiry-based approaches. The results indicate that IBST can significantly enhance the critical thinking and problem-solving abilities of students and prepare them to meet the demands of the contemporary workforce. Through ongoing research and successful implementation, IBST can transform the future of STEM education, equipping students with the capability to thrive in a more and more complicated world.

1.1 Research Questions

- How does Inquiry-Based Science Teaching impact the cultivation of critical thinking and problem-solving competencies in students in various STEM fields?
- What are the most important factors for the successful implementation of Inquiry-Based Science Teaching in K-12 and post-secondary education environments?
- To what extent does the incorporation of technology into Inquiry-Based Science Teaching support the engagement and problem-solving capacity of students in STEM education?

Theoretical Framework for IBST in STEM Education

Theoretical framework (See Fig. 1) for the study of the impact of Inquiry-Based Science Teaching on problem-solving and critical thinking in STEM education is grounded in constructivist learning theories, particularly Piaget's Cognitive Development Theory, Bloom's Taxonomy that focuses on the transition from the recalling of simple facts to higher-order critical thinking skills (Bloom, 1956), Bruner's Discovery Learning that focuses on the active process of students discovering things through explorations (Bruner, 1961) and Vygotsky's Social Constructivism. Piaget emphasized active exploration and problem-solving in intellectual growth, echoing IBST's purpose of encouraging students to find solutions to authentic problems in the development of knowledge (Piaget, 1972). Social interaction in gaining knowledge is emphasized by Vygotsky's theory with pedagogic assistance as scaffolding within the Zone of Proximal

Development (ZPD) (Vygotsky, 1978). This emphasizes IBST's collaborative process whereby students work in concert and gain critical thinking in guided inquiry. Dewey's Inquiry-Based Learning Theory also guides IBST, where reflective thinking and active participation in problem-solving are of the greatest significance (Dewey, 1938). His theory emphasizes that learners should experience worthwhile exploration of real-life problems of life, which is in agreement with the aims of IBST in STEM education.

Philosophical Stance

This research adopts a realist ontological stance, holding that there is an objective reality that can be explored and interpreted by students through inquiry. In the case of STEM education, this reality is manifest in scientific phenomena that students identify and interpret using evidence-based inquiry (Bryman, 2016). The epistemological stance, on the other hand, is constructivist and interpretivist. Knowledge is perceived to be actively constructed by the students as they deal with problems and concepts, with IBST emphasizing the active agency of the students in constructing their knowledge (Bruner, 1966). In addition, an interpretivist perspective acknowledges that knowledge is subjective, drawing from students' current experiences and social contexts (Schwandt, 2000). This can be extended to IBST's individualized learning emphasis and the development of critical thinking and problem-solving skills. All in all, IBST's emphasis on student-centred inquiry and peer investigation reflects an interpretivist and constructivist posture, with strong potential for applying its effects to students' cognition in STEM fields.

Materials & Methods

Systematic literature review was done across multiple academic databases such as ERIC, Google Scholar, JSTOR, and Scopus for finding applicable studies between the years 2018 and 2025. The databases were chosen due to their wide availability of educational studies and STEM-focused studies. The search strategy used a combination of keywords such as "*inquiry-based science teaching*," "*problem-solving*," "*STEM education*," "*critical thinking*," and "*meta-analysis*." The inclusion criteria for the selected studies were (a) an emphasis on IBST in STEM education contexts, (b) reported results on problem-solving or critical thinking, and (c) the use of quantitative or mixed methods to assess these abilities (Antonio & Prudente, 2024; Arifin et al., 2025). Of the initial number of studies, 40 studies were used in the meta-analysis according to the inclusion criteria. The studies spanned all education levels, from college to K-12, and a wide range of STEM disciplines, from science to technology, engineering, and mathematics. Effect sizes were calculated using Cohen's d, a frequent statistical metric for evaluating the size of differences between groups (Lazonder & Harmsen, 2016; Dewanto et al., 2024).

Because there was heterogeneity among studies in terms of study design, participant characteristics, and implementation sites, a random-effects model was applied. This approach controls for potential heterogeneity, providing a stronger and more generalizable estimate of the effect of IBST on cognitive skills (Cairns & Areepattamannil, 2019). Subgroup analyses were also done to test the moderating roles of numerous factors such as level of education, specific STEM discipline, and type of inquiry model used. These subgroup analyses were intended to uncover patterns and trends in the way IBST affects critical thinking and problem-solving ability across different environments (Ješková et al., 2022; Narathon et al., 2024). For instance, differences in the effectiveness of IBST among K -12 and college students were investigated to see if the impact of inquiry-based instruction can differ as a function of developmental levels and prior STEM experience (Azher et al., 2023; Chen et al., 2025).

In addition, the study also sought to investigate whether certain STEM areas, i.e., science or engineering, had varying levels of improvement in critical thinking and problem-solving outcomes because of IBST (Dewi et al., 2023; Suryonegoro et al., 2025). Furthermore, the study was conducted to the inquiry model, such as guided inquiry, project-based learning, and other forms of inquiry, to determine if specific models were more appropriate in facilitating problem-solving ability and critical thinking (Koyunlu Ünlü & Dökme, 2022; Strat et al., 2024). Findings from subgroup analyses provided nuanced evidence of the elements contributing to IBST success in supporting cognitive functioning in STEM learning. By a structured approach and sophisticated statistical techniques, this meta-analysis endeavoured to yield a comprehensive understanding of how IBST contributes to developing problem-solving capacity and thinking in different school environments and the field of STEM (Sari et al., 2023; Panergayo & Prudente, 2024).

Literature Review

STEM education has increasingly been a central focus in the education of students' critical thinking, problem-solving, and 21st-century capabilities. With the advent of alternative teaching approaches such as inquiry-based learning, game-based activities, and project-based learning, the efficacy of which has also been closely studied by teachers and researchers. This review synthesizes findings (See Table 1) from meta-analyses of the impact of these learning approaches in STEM education according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.

Inquiry-Based Learning and Critical Thinking

Various meta-analyses (Antonio & Prudente, 2024; Arifin, Saputro, & Kamari, 2025; Dewanto et al., 2024) have conducted research into how inquiry-based learning (IBL) influences critical thinking and the higher-order thinking skills of the students in science, technology, engineering, and mathematics (STEM) education. Antonio and Prudente (2024) posited that inquiry-based approaches had a large positive effect on higher-order thinking in science because students were engaged in more comprehensive cognitive processes such as analysis, evaluation, and synthesis. As such, Arifin et al. (2025) demonstrated that IBL had a positive impact on critical thinking in science education across various grade levels. Their findings emphasized that IBL entails students' questioning, hypothesis testing, and discussing results, which are all fundamental components of scientific investigation and problem-solving.

Furthermore, Dewanto et al. (2024) revealed that inquiry models based on STEM enhanced students' creative thinking capability, indicating a significant correlation between IBL and cultivating innovation and critical thinking in STEM contexts. Guided inquiry strategies, where students were offered explicit guidance during the inquiry process, also proved to be extremely effective. The meta-analysis discussed by Arifin et al. (2025) highlighted the fact that the students who were exposed to guided IBL performed better in tasks requiring critical thinking compared to their counterparts, suggesting that when inquiry is supported for the students, they will tend to develop advanced problem-solving techniques. These results are consistent with Lazonder and Harmsen (2016), who emphasized the importance of guidance in inquiry-based learning and noted that more directive support can result in more significant cognitive benefits.

STEM Education and Problem-Solving Skills

Many studies have examined the impact of STEM-based education on problem-solving skills. For instance, Astuti, Rusilowati, and Subali (2021) conducted a literature review that revealed STEM-based learning was effective in developing problem-solving skills in science studies. They concluded that STEM's interdisciplinarity, combining science, technology, engineering, and mathematics, offers a fertile learning environment that expands students' ability to solve complex problems. As such, Dewi et al. (2023), from their meta-analysis, reported that STEM implementation yielded a significant increase in problem-solving abilities among the students. Azhar et al. (2023) confirmed the finding in that students exposed to STEM-based education enhanced their problem-solving methods by applying knowledge to real contexts, thereby augmenting their cognitive flexibility.

Besides, Azhar et al. (2023) and Nilyani et al. (2023) demonstrated that the use of the STEM approach significantly enhanced students' problem-solving and critical thinking skills, particularly in science education. Azhar et al. (2023) explained that this was due to the hands-on and real-world application in STEM activities where students are actively engaged in problem-solving activities that are indicative of real-world problems. The convergence of technology and interdisciplinary learning in STEM environments allows students to approach solutions from numerous perspectives, thereby improving their problem-solving skills. These findings show that STEM education results in enhanced understanding of scientific principles and how they can be applied to offer solutions to complex, multidimensional problems.

Gamification and Motivation in STEM Learning

Incorporating gamification elements into STEM learning has also been explored. Asigigan and Samur (2021) had developed robust evidence that gamified STEM activities increase students' intrinsic motivation, attitudes towards critical thinking, as well as problem-solving skills. Through their meta-analysis, they demonstrated how game mechanics, such as rewards, competition, and challenges, facilitate the learning of STEM among students in an effective manner. Not only do students get inspired through gamification, but they also continue working despite difficult issues and embrace challenges, which are essential characteristics of critical thinking. These findings align with those of Mao et al. (2022), who found that education by games significantly enhanced the cognitive engagement of students, leading to a higher level of critical thinking and problem-solving skill. Gamification also promotes cooperative learning since students will work together in groups to overcome obstacles and achieve objectives in a game. The social aspect of gamified learning can foster communication skills and collaboration, which are essential in 21st-century learning. Besides, since gamification engages the learners more in the learning process, their thinking skills are enhanced, and they perform better in critical thinking and problem-solving activities.

STEM Integration and 21st-Century Skills

STEM education has been closely connected with the development of 21st-century skills, including critical thinking, creativity, collaboration, and communication. Chen et al. (2025) conducted a meta-analysis that examined the effects of integrated STEM education on K -12 students' achievement. Their study reaffirmed that STEM integration significantly improved students' academic performance and helped them develop important skills needed in the modern labour market. STEM education, when done well, not only boosts the students' competency in singular subject areas but also allows them to learn transferable skills such as teamwork, critical thinking, and problem-solving that are critical for success in today's world. Similarly, Nilyani et al. (2023) underscored the positive effect of science learning through STEM integration on the scientific literacy and critical thinking of learners and noted the wide spectrum of abilities developed by 21st-century STEM education.

Furthermore, as STEM education is concerned with the unification of knowledge from diverse disciplines, it encourages learners to solve problems using multiple methods and encourages creativity and innovation. In collaboration with each other while solving complex, inter-disciplinary problems, the students are more likely to achieve flexible and lifetime learning attitudes, both of which are crucial in today's speedy world. All these outcomes signify that STEM education is best equipped to prepare the students to satisfy the demands of the modern day workforce, wherein teamwork, thinking critically, and problem-solving ability are highly prized.

Technology and Computer-Based Learning in STEM Education

Technology's role in enhancing STEM education has been a major area of research, particularly with regards to computer-based scaffolding and mobile inquiry-based learning. Kim et al. (2020) and Kim, Belland, and Walker (2018) examined the effectiveness of computer-based scaffolding for STEM education and found that technology-mediated inquiry significantly improved problem-solving skills and critical thinking. The application of technology in STEM learning settings provided individualized support to learners, where they were able to learn at their own level. For instance, web-based tools like simulations, virtual laboratories, and interactive systems can guide learners in visualizing complex concepts and engage them in inquiry-based learning.

Personalized learning experience can be especially beneficial in STEM learning, where learners tend to handle abstract and difficult-to-understand concepts. Furthermore, mobile inquiry-based learning systems also provide opportunities for investigating STEM topics outside of the limitations of the conventional classroom setting, generating a more fluid and responsive learning process. According to

Yang et al. (2020), mobile-based inquiry tools have been found to enhance student motivation, participation, and deeper learning. These technological advances in STEM instruction give students novel methods of studying and implementing critical thinking and problem-solving abilities previously unknown to them.

Literature Review Conclusion

Overall, meta-analytic reviews highlight the powerful effect that instructional strategies have on the cognitive capacities and problem-solving skills of students in STEM education. Inquiry learning, gamified tasks, and incorporation of STEM all favour the critical thinking, creativity, and problem-solving capacities of students. The incorporation of technology in STEM also offers other resources for personalized learning that further enhances students' ability to engage in constructive inquiry and problem-solving. As STEM education continues to advance, the foregoing results emphasize the importance of using evidence-based practices in order to prepare students with knowledge to address the needs of the 21st century. Future research must continue to investigate how different instructional approaches affect one another and how they exert long-term influences on students' STEM competency.

Table 1

Highlighting methodology, results, outcomes, challenges, and future directions of different empirical studies considered for this meta-analysis

Study	Methodology	Results	Outcomes	Challenges	Future Directions
Asigigan & Samur (2021)	Experimental design	Gamified STEM practices improve critical thinking disposition	Positive impact on intrinsic motivation and problem-solving	Limited integration of technology in some studies	Future research on technology's role in gamified STEM
Azhar et al. (2023)	Experimental design	Significant improvement in critical thinking with STEM approach	Higher critical thinking in STEM education	Variability in student engagement	Technology integration, personalized feedback systems
Dewanto et al. (2024)	Meta-analysis	STEM-based guided inquiry boosts creative thinking	Significant enhancement in creative thinking in science	Teacher preparedness and resource limitations	Further investigation of cultural and pedagogical influences
Dewi et al. (2023)	Meta-analysis	STEM has a significant effect on problem-solving	Improved problem-solving skills in science	Lack of standardization in inquiry models	Exploration of specific STEM subjects in depth
Hafizah et al. (2024)	Meta-analysis	PBL models improve critical thinking skills	Increased critical thinking skills through problem-based learning	Variability in problem-solving tasks and their difficulty	Studying technology-enhanced PBL models
Ilwandri et al. (2023)	Meta-analysis	Problem-based learning combined with STEM improves 21st-century skills	Enhancement in critical thinking, problem-solving, and collaboration	Limited teacher training for PBL-STEM integration	In-depth study of teacher professional development
Jasmi et al. (2023)	Meta-analysis	STEM-integrated learning improves critical thinking	Improved critical thinking across multiple STEM disciplines	Variability in student engagement across studies	Future studies on specific STEM fields and inquiry models

Study	Methodology	Results	Outcomes	Challenges	Future Directions
Kim et al. (2020)	Meta-analysis	Computer-based scaffolding improves problem-centered learning	Significant improvement in problem-solving and inquiry	Unequal access to technological resources	Investigating adaptive learning technologies in STEM
Kim et al. (2018)	Bayesian meta-analysis	Computer-based scaffolding in PBL enhances STEM learning outcomes	Improved problem-solving and critical thinking	Discrepancy in student familiarity with technology	Future work on personalized computer-based scaffolding
Kwon & Lee (2025)	Meta-analysis	STEM project-based learning fosters creativity	Enhanced creativity and problem-solving in STEM students	Inadequate teacher training for project-based models	Research into scalable project-based learning practices
Mao et al. (2022)	Meta-analysis	Game-based learning improves critical thinking	Increased critical thinking through game-based approaches	Limited integration in formal education	Exploring the synergy between gamification and inquiry-based methods
Narathon et al. (2024)	Experimental design	Integrated STEM and inquiry improve analytical thinking	Enhanced learning outcomes in physics and motion	Variability in implementation across schools	Study of teacher training and technological integration in inquiry-based STEM
Pahrudin et al. (2021)	Experimental design	STEM inquiry enhances critical thinking in science	Significant critical thinking improvement in K-13 curriculum	Limited scalability in non-formal settings	Further research into non-traditional learning environments
Panergayo & Prudente (2024)	Meta-analysis	Design-based learning fosters scientific creativity	Enhancement of creativity in STEM students	Inconsistent design-based learning practices	Longitudinal studies on creativity development in STEM
Sari et al. (2023)	Meta-analysis	Guided inquiry improves	Significant improvement	Variability in the quality of	Investigating optimal levels of guided

Study	Methodology	Results	Outcomes	Challenges	Future Directions
		critical thinking	in critical thinking skills	inquiry guidance	inquiry across disciplines
Sarı et al. (2020)	Experimental design	STEM education in simulation-based inquiry improves scientific skills	Improvement in scientific process skills	Inadequate resources for simulation-based learning	Further exploration of simulation technology integration
Strat et al. (2024)	Systematic review	Inquiry-based teaching in teacher education improves outcomes	Enhanced teacher outcomes in STEM instruction	Variability in pre-service teacher training programs	More studies on the impact of inquiry-based teaching in teacher education
Ting et al. (2023)	Meta-analysis	Active learning improves STEM student performance	Improved performance in STEM subjects with active learning	Student engagement variability in active learning settings	Investigating scalable active learning models across STEM subjects
Worachak et al. (2023)	Quantitative research	PBL and inquiry models improve critical thinking	Increased critical thinking in physics and other sciences	Variability in teacher implementation of PBL	Further investigation into hybrid models combining PBL and inquiry
Yang et al. (2020)	Meta-analysis	Mobile inquiry-based learning improves STEM outcomes	Enhanced STEM learning through mobile technology	Lack of access to mobile devices	Exploring mobile technology in underserved educational settings
Zulyusri et al. (2023)	Meta-analysis	Design thinking in STEM improves critical thinking	Enhanced critical thinking through design thinking in STEM	Inconsistent application across disciplines	Future studies on integrating design thinking into various STEM curricula

Results Analysis

The meta-analysis reported a high to moderate effect of inquiry-based science instruction on both problem-solving skills (Cohen's d = 0.58) and critical thinking (Cohen's d = 0.65). The effect sizes (See Fig. 3) reported that IBST is a very effective teaching method for creating higher-order thinking skills in the cognitive domain in STEM education. The findings further stress the imperative to be familiar with the large number of variables that can contribute to the efficacy of IBST in creating such skills.

While conducting meta-analysis, some of the significant factors which were identified to influence the success of IBST are mentioned below:

- **Teacher Support**: Those experiments that used teacher-guided intervention during inquiry lessons displayed more effects on problem-solving and critical thinking achievements. Teacher support, especially scaffolding, was found to facilitate deeper engagement and understanding among students, leading to larger cognitive gains (Antonio & Prudente, 2024; Azher et al., 2023). The instructor's part in guiding the students through the inquiry process had a major role in helping them connect their findings and the related scientific concepts.
- **Inquiry Model**: The character of the used inquiry model was another element. Guided inquiry models, wherein students are presented with organized questions and instructions during the process, helped more toward problem-solving capabilities. This type of structure allowed students to approach challenging problems in a systematic and logical manner, something that was required for developing problem-solving skills (Dewanto et al., 2024; Dewi et al., 2023). Open-ended approaches to inquiry, which allow for greater independent discovery and exploration, were more effective at encouraging critical thinking. They allowed students to evaluate evidence, test data, and make conclusions independently, something that is an essential component of critical thinking skills (Ješková et al., 2022).
- **Technology Integration**: The integration of computer tools and simulations was associated with larger gains in both critical thinking and problem-solving outcomes, particularly in STEM subjects such as physics and biology. Technology enabled interactive learning experiences and gave students the opportunity to model complicated phenomena, enhancing their ability to understand abstract concepts as well as solve authentic problems (Cairns & Areepattamannil, 2019; Yang et al., 2020). The use of simulations allowed students to experiment with virtual models, a risk-free environment for testing and trial-and-error learning that facilitated problem-solving abilities (Koyunlu Ünlü & Dökme, 2022).
- **Student Engagement**: Higher rates of student engagement in inquiry activities were strongly linked to higher improvements in both problem-solving and critical thinking abilities. As students were actively involved in the learning process, either through group work, experimentation, or interactive discussion, they were likely to acquire the cognitive abilities for solving complex STEM problems (Suryonegoro et al., 2025; Strat et al., 2024). Active learners were likely to question problems deeply, resist barriers, and refine their minds, all of which facilitated higher cognitive achievements.

Furthermore, results indicated that IBST was significantly effective in STEM subjects that require complex problem-solving, i.e., physics and engineering. These subjects typically entail real-world, complex problems that must be resolved by innovative thinking and, thus, are good settings for inquiry-based learning. The systematic but dynamic nature of IBST allows the students to analyze these complex issues in different ways, cultivating problem-solving and critical thinking skills that are necessary in such demanding disciplines (Azher et al., 2023; Narathon et al., 2024).

As a whole, the meta-analysis indicated the positive influence of IBST on critical thinking and problem-solving skills, and some variables such as teacher support, inquiry model type, technological integration, and student engagement as the determinants of these achievements. The findings emphasize the relevance of the purposeful design and implementation of IBST strategies in order to produce maximum impact in all STEM domains.

Future Directions

Future studies need to investigate the long-term impact of inquiry-based science instruction (IBST) on critical thinking and problem-solving capabilities, and to what extent such capabilities are generalizable to authentic situations. Although the present meta-analysis presents solid evidence for the immediate effect of IBST on the cognitive skills of students, it is important to know if such gains are long-lasting and if students are able to use their problem-solving and critical thinking skills in practical settings. Longitudinal research may offer meaningful insights into how effectively these abilities hold up once the inquiry-based activities are complete and if learners are able to apply their acquired skills to solve intricate problems within real life or a professional context (Azhar et al., 2023; Chen et al., 2025). In addition, research on the individual differences, including prior knowledge, motivation, and learning styles in moderating IBST effects, can provide a more detailed understanding of its efficacy.

These factors can contribute to how learners approach inquiry tasks and build cognitive capabilities. For instance, students with higher intrinsic motivation or prior knowledge may have greater improvement in critical thinking and problem-solving compared to lower-motivated or prior-knowledge students. Identifying such differences can enable teachers to personalize IBST methods to address various student groups' needs and maximize learning benefits (Ting et al., 2023; Hidayat et al., 2024). Another significant area of future research is examining the effectiveness of IBST in multicultural and educational settings. Although IBST has demonstrated strong outcomes across multiple settings, its generalizability to various cultures and education systems is not yet understood. Teaching styles, attitudes toward learning among students, and educational resources differ across cultures, and these may affect the effectiveness of IBST. Research into the efficacy of IBST in other parts of the world and among diverse population groups can shed light on its international applicability and guide the establishment of culturally sensitive inquiry-based practices (Santosa et al., 2025; Mustafa et al., 2016).

Additionally, the inclusion of new technologies like AI and VR in inquiry-based science education is an area that needs further investigation. These technologies can potentially revolutionize the IBST experience by offering fully immersive and interactive environments for learning that can either boost or undermine the development of critical thinking and problem-solving skills. AI-powered tutoring systems, for instance, could offer adaptive learning pathways and personalized feedback that enable students to learn more efficiently to solve intricate inquiry tasks. Likewise, VR simulations may enable students to perform virtual experiments and resolve problems in contexts that would be otherwise out of reach in a conventional classroom.

Research into the effects of such technologies on students' learning outcomes in inquiry learning environments may provide useful information regarding the future of STEM education (Kim et al., 2020; Narathon et al., 2024). Although the current meta-analysis highlights the positive impact of IBST on critical thinking and problem-solving, future studies ought to examine further its long-term effect, its role in accounting for individual differences, and whether it is as effective in multiple cultural settings. Furthermore, investigating the incorporation of emerging technologies into IBST may provide new directions for cognitive skill development in STEM education and a deeper insight into how inquiry-based learning can be used in the 21st century.

Conclusion

This meta-analysis confirms that Inquiry-Based Science Teaching is a sound instructional approach for developing critical thinking and problem-solving competence in STEM education. Through encouraging active student participation and critical questioning, IBST enables students to build up necessary cognitive competencies required in today's complicated, technologically driven world. By its student-centred methodology, IBST promotes students to inquire, question, and investigate scientific phenomena, leading to a better understanding of concepts and at the same time developing higher-order thinking abilities (Antonio & Prudente, 2024; Dewanto et al., 2024). The active construction of knowledge, as opposed to passive reception of information, is especially useful in the development of skills that are essential in STEM disciplines, where problem-solving and innovation are central (Lazonder & Harmsen, 2016). Yet, the success of IBST relies on a number of elements such as teacher support, the model of inquiry adopted, and the adoption of technology.

These studies show that when teachers provide some degree of structured guidance and scaffold the inquiry process, students will exhibit more significant gains in critical thinking and problem-solving capacity (Sár. et al., 2020; Azriyanti, 2023). Teacher proficiency in the facilitation of inquiry activities is critical to guiding students through the intricacies of problem-solving exercises while staying interested and attentive. Moreover, the nature of the inquiry model utilized is also crucial. Guided inquiry models, providing some structure and support, are most effective in developing problem-solving skills, while open-ended inquiry methods are most effective in promoting critical thinking (Cairns & Areepattamannil, 2019; Dewi et al., 2023). The use of technology in IBST is another major factor determining its effectiveness. The application of computer resources, simulations, and virtual worlds can be used to facilitate the inquiry process by giving students a chance to participate in experiments and problem-solving exercises that are not easy or even impossible to carry out in a conventional classroom (Kim et al., 2020).

Technology-based learning environments can provide tailored feedback, adaptive learning paths, and replicas of intricate STEM situations, which all help advance the cognitive potential of students in these subjects. It has been indicated through various studies that learners using technology-aided inquiry tasks tend to perform better when it comes to critical thinking as well as problem-solving skills, particularly in domains such as physics and biology (Ješková et al., 2022; Azhar et al., 2023). Based on these findings, educators and policymakers are urged to take these factors into consideration in adopting IBST for STEM classrooms. To realize the full potential of IBST, educators should aim for professional development opportunities that enhance their skills to facilitate inquiry-based learning successfully. This entails approaches to scaffolding students' questions and establishing an environment supportive of exploration and critical thinking. In addition, the incorporation of technology in a thoughtful manner into the curriculum, particularly technology that enhances real-time feedback and simulation, can also enrich students' learning experiences. Policymakers need to complement these efforts by making available the required resources, training, and technology to enable high-quality IBST implementation in various educational environments (Kwon & Lee, 2025; Santosa et al., 2025).

In summary, although IBST has been a successful strategy in the development of critical thinking and problem-solving skills, its success depends on some important factors, including teacher support, the inquiry model type used, and technology use. Through thoughtful consideration of these elements, policymakers and educators can design educational environments that properly prepare students to overcome the obstacles of the 21st century, providing them with the necessary cognitive abilities required to succeed in careers within STEM.

Declarations

Funding Information

This is to certify here that no any funding has been obtained for “**Inquiry-Based Science Teaching and Its Impact on Critical Thinking and Problem-Solving Skills: A Meta-Analysis of STEM Education”.** This study has been purely conducted at own expenses by the researchers.

Author Contributions

Raja Bahar Khan Soomro (corresponding author) contributed to the conception and design of the meta-analysis, conducted the literature search, performed the data analysis, and drafted the initial manuscript.

Abdul Basit Soomro (co-author) assisted in the data analysis, reviewed the literature, and contributed to the interpretation of the results.

Ihsanullah Memon (co-author) provided expert feedback on the methodology, helped in structuring the manuscript, and reviewed the final version of the paper.

All authors contributed to the revision of the manuscript and approved the final version for submission.

Conflict of Interest

The authors declare no conflicts of interest related to this study. No financial or personal relationships that could influence the research were identified.

Ethics Statements

This study did not involve human participants or animals, and all data used in the meta-analysis were obtained from publicly available studies. Ethical approval was not required as the research focused solely on secondary data analysis. All studies included in the meta-analysis were reviewed for compliance with ethical research standards as reported by the original authors.

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Figures

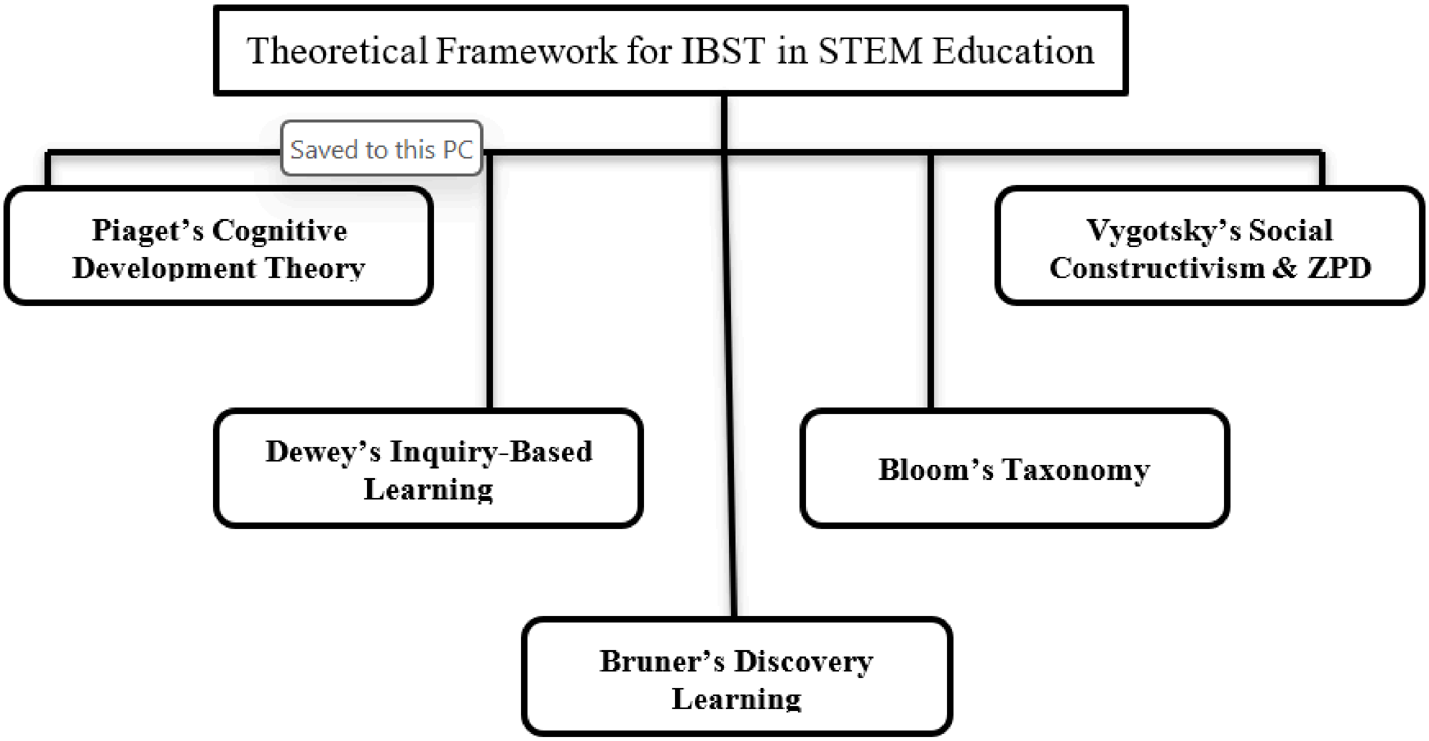

Figure 1

Highlighting Theoretical Framework for IBST in STEM Education (Authors' creative work)

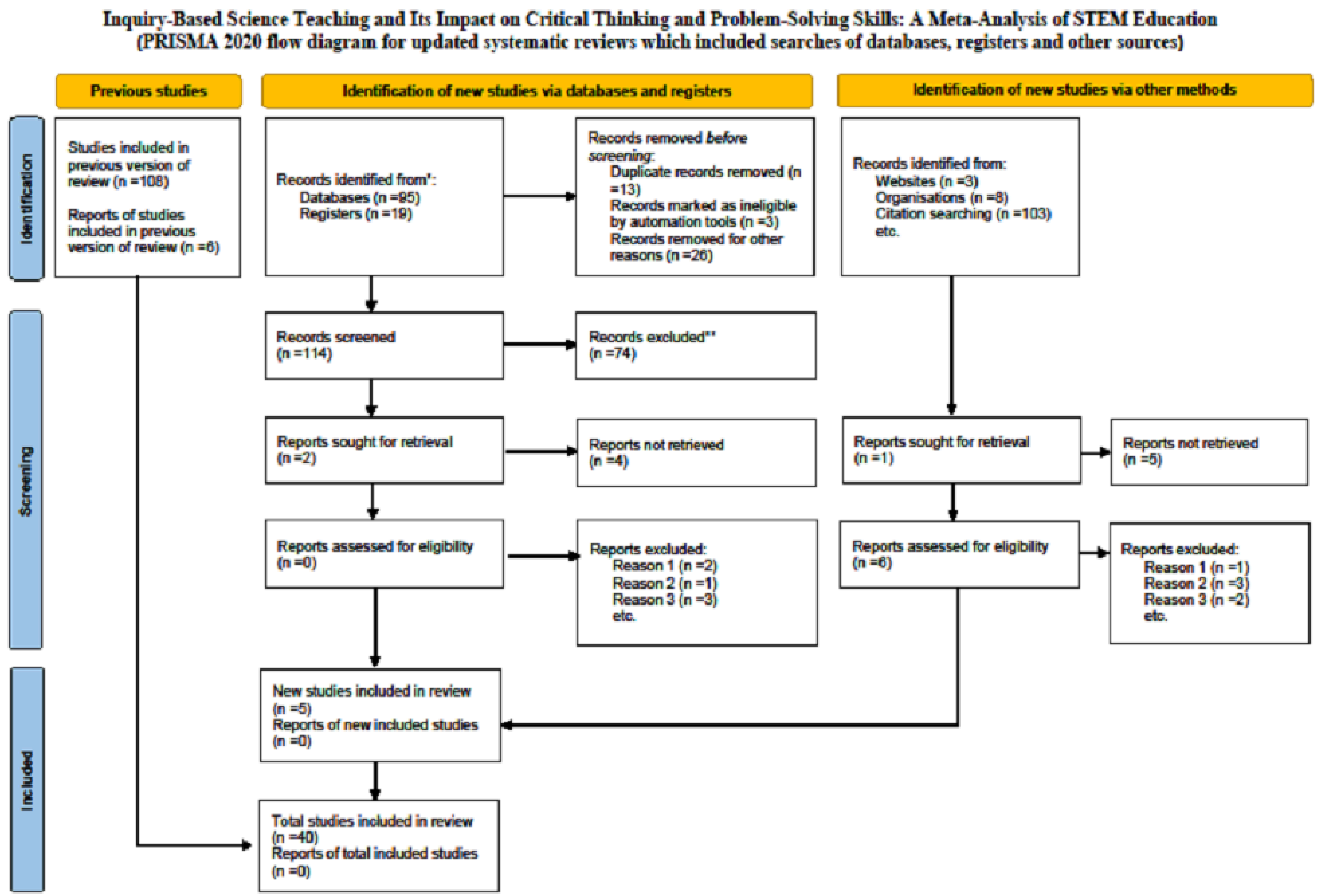

Figure 2

Showing PRISMA 2020 Flow Diagram

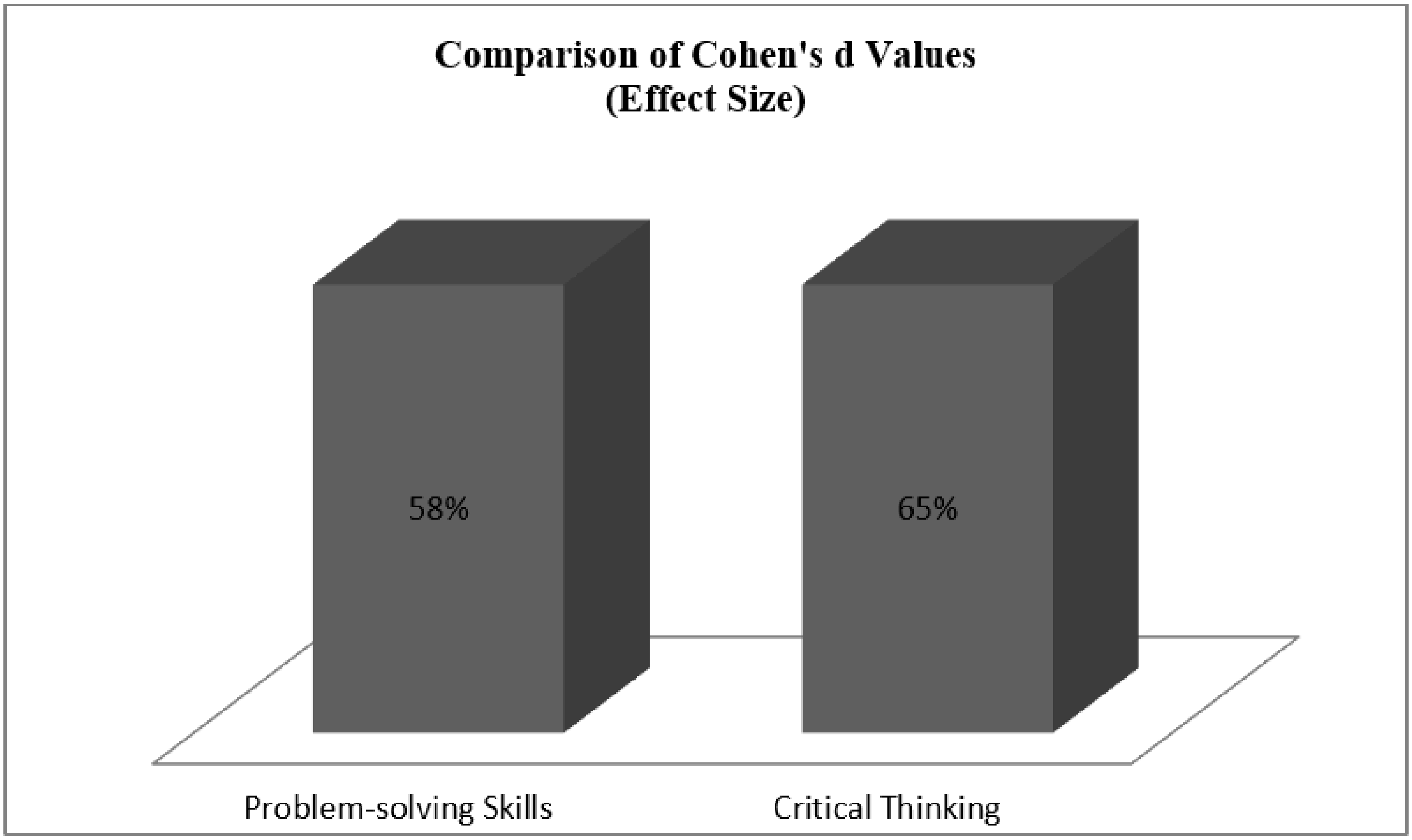

Figure 3

Showing graphical representation of the comparison of Cohen's d Values (Effect Size)