Review Article

Enhancing critical thinking in university mathematics courses through project-based learning: A mapping review

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ARTICLE INFO	ABSTRACT
	Active learning methodologies have gained prominence in university mathematics education, with project-based learning (PjBL) standing out for its ability to foster critical thinking. This study conducted a mapping review to visualize from literature those specific PjBL strategies are most effective in fostering critical thinking in university mathematics courses. A total of 170 peer-reviewed articles were selected from Scopus and ERIC, based on inclusion criteria that considered studies published in English and Spanish. The review followed three stages: (1) Keyword co-occurrence analysis using VOSviewer to visualize research trends, (2) Description of strategies of PjBL strategies implemented in the selected studies, and (3) Identification of evaluation of effectiveness through validated assessment instruments and exploratory factor analysis. The results revealed a triangular relationship among critical thinking, mathematics, and PjBL, where key strategies (such as problem-solving in groups, guided reflection, constructive feedback, and self-assessment) enhance active learning and facilitate knowledge transfer to real-world context. The integration of these strategies with continuous assessment and validated tools was found to strengthen critical thinking development. Additionally, the study highlighted the importance of designing contextualized projects aligned with students´ interests to improve motivation and knowledge retention. However, challenges such as teacher training, curricular adjustments, and institutional resistance to innovative methodologies persist. The study concludes that the effective implementation of PjBL requires structured planning, curricular integration, and ongoing formative assessment to maximize its impact on mathematics education and adequately prepare students to tackle complex real-world problems in their professional careers. **Keywords:** critical thinking, mathematics education, mapping review, higher education, project-based learning

INTRODUCTION

Identifying effective and meaningful teaching and learning strategies for all stakeholders involved in education has been a longstanding challenge in educational innovation (Ansina, 2021; Barragán Moreno et al., 2024; Guerra, 2020; Guo et al., 2020). Today, university mathematics teachers continue to face challenges that highlight the limitations of traditional education and raise questions about its effectiveness. Therefore, it is essential to implement alternative methodologies in university courses, particularly active learning approaches, which provide a promising perspective. Project-based learning (PjBL), particularly in higher education, exemplifies such an alternative.

PjBL is an active methodology that gained prominence in recent decades mathematics education. Teachers have implemented it in their courses and often regard it as successful due to its benefits for students, including improved academic performance, increased motivation, and enhanced critical thinking (Bezanilla-Albisua et al., 2018; Villanueva Morales et al., 2022).

This study aims to theoretically address the following question: Which specific PjBL strategies are most effective in fostering critical thinking in university mathematics courses? Therefore, the objective here is to visualize from the literature those specific PjBL strategies are most effective in fostering critical thinking in university mathematics courses. To this end, the article was structured as follows. First, the article outlines the theoretical and practical definition of PjBL in both general and higher education mathematics courses, highlighting its impact on education quality and student development. Such conceptual definition of PjBL includes a review of the historical development of active methodologies. Then, through a mapping review, the effectiveness of the methodologies to foster critical thinking in students is analyzed. At the end of the review, the main results are presented, along with a discussion about them, and possible further developments of the research conducted. This study contributes to a deeper understanding of PjBL and informs future proposals in this field. Namely, it establishes the fundamental principles of PjBL and the advantages it offers in developing competences and skills both for future professionals and for teachers.

Dewey, Ausubel, and Vygotsky–philosophers, sociologists, and educators–proposed pedagogical alternatives to the traditional education model of the early 20th century, which was broadly linked to behaviorism. These three authors established the principles of what later became known as the "active school," which is an active metacognitive approach to concepts and processes. This approach emphasizes, "learning by doing" (Allueva, 2002). This approach suggests that learning is more effective when based on students' interest, encourages analysis and problem-solving, and enhances skills applicable to real-life situations. If prepared to learn, individuals can adapt to changing and challenging situations (Osses & Jaramillo, 2008). In this model, teaching and learning processes center on the student as an active participant. Teachers become facilitators of student's learning, guiding them in their individual processes of knowledge to develop autonomy (Carceller, 2019; Espinoza-Freire, 2022; Jojo & Madikizela-Madiya, 2022).

PjBL was first developed at McMaster University School of Medicine (ON, Canada) in 1965. Initially, this methodology focused on learning through contextualized medical problems (Savery, 2006). Approaching knowledge through projects requires research, reflection, and collaboration to solve problems that are usually related to the so-called real life or associated with the future field of work of the students. PjBL, as an active methodology, places the students (the protagonists of their own learning) at the center of the process and turns the teacher into a facilitator and a guide. Therefore, it can be seen as a strategy for autonomous (individual or in a group) teaching and learning (Villanueva Morales et al., 2022). The goal of the teamwork in PjBL was to develop a range of skills, including responsibility, conflict resolution, interdisciplinary knowledge integration, and both hard and soft skills (Guo et al., 2020). Additionally, it encourages assessment practices that incorporate elements of self-evaluation, co-evaluation, and teacher assessment (Anasagasti et al., 2023; Binti et al., 2019; Luy-Montejo, 2019; Villanueva Morales et al. 2022; Zambrano et al., 2022).

Since the 1970s, active learning methodologies have been implemented widely adopted in teaching and learning worldwide. Examples include constructivism, social constructivism, problem-based learning (PBL), situated learning, PjBL, experiential learning, communities of practice (Reis et al., 2023; Savery, 2006), cooperative learning, and gamification strategies–all of which maintain the core principles of student-centered learning and the teacher as a guide. The differences lie in how and where each of them is developed and in the tools they require. Understanding these differences is essential for properly defining these methodologies, as overlooking them can result in ineffective implementation or failure to achieve desired outcomes.

 PjBL is implemented (how) by developing contextualized projects aligned with students' interests, where they collaborate in teams, contributing their knowledge, skills, attitudes, and aptitudes. PjBL takes place in the learning environment (where), whether a classroom or another setting, at a specified time, utilizing cognitive (conceptual and procedural), technological, and instrumental resources (artifacts) available to students. In recent times, governments, official entities, and organizations have taken PjBL into the classroom (OEI, 2020; UNICEF, 2020), even into the grades with the youngest students. Elements of PjBL have already been

integrated into institutional curricula, mainstreaming its application, and inspiring methodologies such as STEM, STEAM and STEAM+ (Blumenfeld et al., 1991; Bogdan & García-Carmona, 2021; Carnicero, 2023; Castro, 2019; García-Carmona, 2020; Savery, 2006; Velázquez et al., 2021).

Espinoza-Freire (2022), Guo et al. (2020), Guerra (2020), and Castro (2019) have analyzed experiences–in secondary education courses close to graduation and in academic mathematic environments–which show that PjBL is a tool that teachers and institutions are using to effectively address students' apathy and disinterest in mathematics–beyond the deficiencies with which secondary students graduate and face their undergraduate studies (Ansina, 2021; Velázquez et al., 2021; Zambrano et al., 2022). Addressing issues such as apathy requires considering relevant sociopolitical factors, including dropout and repetition rates that impact educational institutions (Ansina, 2021; García-González & Martínez-Padrón, 2020; Guerra, 2020; Muntaner et al., 2020).

In university mathematics, PjBL has primarily been applied in subjects such as statistics (Vargas et al., 2021), linear algebra (Domínguez-García et al., 2016; Izquierdo et al., 2016; Nuñez & Romero, 2018; Taberna & García Planas, 2016; Taberna et al., 2016), and engineering programs (Duarte Barón et al., 2024; García et al., 2020; Reis et al., 2023), due to the fact that PjBL (and other active methodologies) have the potential to enhance the skills of future professionals (Alca & Vidal, 2023; Barragán Moreno et al., 2024; Cobo & Valdivia, 2017; Paredes & Fraga, 2022; Torres et al., 2022). The initial review identifies the following factors that are key in the design and implementation of PjBL classroom activities:

1. Defining knowledge and skills: objectives, specifying the knowledge and skills students should develop within their academic training, and aligning them with the institutional syllabus and curriculum. It is important to emphasize that PjBL is a central tool, and not adjacent to the curriculum (Barragán Moreno et al., 2024; Paredes & Fraga, 2022; Torres et al., 2022).

2. Designing a guiding question: This central question initiates the project and can be proposed either by the teaching team or by students under teacher guidance. For the answer to be achievable and clear, the question must propose a challenge in an area of work or knowledge close to the students (OEI, 2020; UNICEF, 2020; Zambrano et al., 2022).

3. Connecting with the real world: Projects should be realistic, aligned with students' educational interest, and have a defined completion timeline corresponding to the academic period. The relevance of the project is given by its proximity to the students' context, to the experiences that they have or will potentially live in their near professional future (Cobo & Valdivia, 2017; OEI, 2020; Torres et al., 2022; UNICEF, 2020).

4. Student co-responsibility: Students play a central role in the learning process as active, accountable participants. Therefore, they must be active, proactive, and autonomous in defining who to work with and the roles they will play in the teamwork (Barragán Moreno et al., 2024; OEI, 2020; Torres et al., 2022; UNICEF, 2020).

5. Creating spaces for reflection: Encouraging diverse settings where students can assess their learning progress, process development, and competency acquisition. These can take place in various settings: within groups, as part of self-management follows-ups (where self-assessment and peer assessment naturally emerge) or during feedback sessions with other teams or the teacher (fostering both peer and teacher-led assessment). One of the core principles of active methodologies, as emphasized by Dewey, is reflection: "We do not learn from experience. We learn from reflection on experience" (Cobo & Valdivia, 2017; OEI, 2020; UNICEF, 2020).

6. Ongoing review and critical thinking development: Students and teachers should engage in regular feedback sessions assessing progress and refine critical thinking skills. Reviews should be conducted following time projection maps of progress that outline progress, incorporating schedules with defined responsibilities, actions, and rubrics. Additionally, reports from all stakeholders involved should be used to assess progress. Peer assessment, teacher evaluation, and even cross-disciplinary feedback enhances critical thinking, communication skills, respect, and conflict resolution (Alca & Vidal, 2023; Barragán Moreno et al., 2024; OEI, 2020; UNICEF, 2020; Zambrano et al., 2022).

7. Research as a core task: PjBL promotes engagement with diverse sources of knowledge, including textbooks, digital resources, expert opinions, and case studies from different contexts. The execution of a project serves as a research exercise, strengthening students' ability to investigate, track, evaluate, and synthesize information to develop a comprehensive understanding of the problem or subject (OEI, 2020; UNICEF, 2020; Zambrano et al., 2022).

8. Defining the final product: While projects may include theoretical components, their ultimate goal should be to develop a tangible outcome (whether a product or service), that addresses a problem, contributes to a solution, or meets specifics needs of a particular population (OEI, 2020; UNICEF, 2020).

PjBL enables universities to provide a holistic education, reducing stress associated with traditional evaluation methods and fostering meaningful learning (Alca & Vidal, 2023; Bezanilla-Albisua et al., 2018; Castro, 2019). It also creates opportunities for developing autonomy, fosters emotional intelligence in both teachers and students, and enhances critical thinking (Ansina, 2021; Bezanilla-Albisua et al., 2018). Technological advances further expand the possibilities of PjBL, particularly through the integration of artificial intelligence (AI). Critical thinking can be strengthened through classroom discussions on AI, its applications, inclusion criteria, outcomes, and contributions (Carnicero, 2023; Segovia-García, 2024; Semushin et al., 2017; Taberna & García Planas, 2016; Vargas et al., 2021).

The main challenges of PjBL, include developing student autonomy, training teachers, ensuring appropriate class sizes, implementing effective evaluation structures, allocating sufficient time for project development, incorporating feedback, and fostering commitment from both teachers and students to faithfully implement the methodology. It is important to acknowledge that improper implementation may lead to activism, where methodologies or strategies are imposed without proper diagnosis, process evaluation, or assessment of results. Likewise, concepts such as strategy, methodology and approach are often insufficiently defined or unclear in literature, sometimes overlapping the meaning. Additionally, Bogdan and García-Carmona (2021), García-Carmona (2020), and Carceller (2019) argue that PjBL is often implemented as a passing trend rather than a genuine transformation of teaching and learning. Institutions, they claim, have failed to fully commit to this shift, instead of placing the burden on teachers. As a result, teachers often feel overwhelmed by the methodology and develop resentment towards it. As Carceller (2019) highlights, although approaches like PjBL are now part of institutional discourses, traditional education structure remains camouflaged under the facade of fashion, since there are no true motivations or a real conviction to advance. Behind the frontage of good practices and innovation nothing has changed. Even though innovation has already been proposed in theoretical approaches, it is of no use if it does not reach practice (p. 2) (own translation, original in Spanish).

METHODS

To achieve the objective of visualizing the most effective PjBL strategies to promote critical thinking in university mathematics courses, the mapping review methodology was implemented. This methodology allows us to systematically describe the state of the art of a research topic, obtaining the basic information and methods of each study included in the sample, but not the results. The critical evaluation of the studies is optional since its scope is to identify gaps, scopes, and trends without reaching the discussion of results or critical evaluation (Chambergo et al., 2021; Grant & Booth, 2009).

Consequently, mapping enables teachers and institutions to make informed decisions regarding the implementation of PjBL in mathematics courses. These courses are affected by the low understanding of the calculation algorithms associated with the processes and concepts involved, the low motivation of students to learn autonomously, the persistent implementation of traditional methodologies (of teaching and learning, focused on the hierarchical role of the teacher), by the assignment of conventional and routine homework, and by the passive role assumed by students, who usually limit their commitment to sitting down in classrooms during lessons or to the sporadic presentation of evaluations or workshops. Likewise, the courses are impacted by high student dropout rates, which are usually attributed to school demotivation–caused by what students describe as insignificant learning–, although they are due to social, economic, or psychological factors (Barragán Moreno et al., 2024).

Parameterization and Protocol of the Mapping Review

The mapping review was parameterized in accordance with the international platform of registered systematic review and meta-analysis protocols. Its protocol was registered with the code INPLASY202470030 and doi: 10.37766/inplasy2024.7.0030 (Barragán Moreno & Aya Corredor, 2024).

Eligibility Criteria

The review included only documents focused on PjBL strategies aimed at enhancing the critical thinking of university students taking mathematics courses or their applications. The sample consisted of articles published in peer-reviewed academic journals. Articles published in English or Spanish were accepted.

Exclusion Criteria

All types of grey literature were excluded: Conference proceedings, book chapters, dissertations, or any other means of dissemination other than academic journals (blogs or websites).

Information Sources

To ensure the quality of the publications included in the sample, two databases were consulted: Scopus (interdisciplinary database) and ERIC (education disciplinary database).

Search Strategy

The following theoretical equation was designed to conduct the search. Terms related to PjBL, critical thinking, strategies, discipline, and educational level were included and applied with Boolean operators that would ensure the highest retrieval of documents:

("project-based learning" OR "PBL" OR "PjBL") AND ("critical thinking" OR "critical analysis" OR "analytical thinking") AND ("university mathematics courses" OR "college mathematics courses" OR "higher education mathematics")

Selection and Extraction of Information

The search conducted in Scopus and ERIC retrieved the articles clustered in the sample. A .ris file was created with all the metadata available from the articles. The file was managed with Zotero. Additionally, a data extraction table was created containing title, authors, abstract and keywords.

Processing the Information

The information available in the metadata and in the extraction table was processed in three stages:

(1) analysis of keyword co-occurrence and clusters to visualize the state of the art of PjBL research using VOSviewer (Al Husaeni et al., 2023),

(2) description and visualization of the PjBL strategies implemented in the sample articles aimed at fostering critical thinking in university mathematics courses, and

(3) valuation of the effectiveness of the strategies outlined in the sample articles and the assessment provided by the authors of this study.

Ethical Statement

This study did not involve human participants, animal subjects, or any sensitive personal data. Therefore, ethical approval and informed consent were not required. The research adhered to the principles of academic integrity, transparency, and responsible research conduct in all stages of data collection, analysis, and reporting. All information was obtained from publicly available, peer-reviewed academic sources indexed in Scopus and ERIC databases, and no identifiable or confidential data were used.

RESULTS AND DISCUSSION

Search and Selection of Documents

Figure 1 illustrates the methodology process and the composition of the sample (170 articles).

Figure 1. Mapping review flowchart (Source: Authors' own elaboration)

Figure 2. Co-occurrence visualization network using VOSviewer (Created by the authors using VOSviewer software)

Keyword Co-Occurrence Analysis

For the co-occurrence analysis a threshold of two was considered, meaning that only keywords appearing in at least two of articles were considered. The visualization network in **Figure 2** shows 11 clusters (thematic groups) of keywords. The largest nodes represent the words that most frequently appear in the sample of articles. The special relationship between the two types of active learning is highlighted: PBL and PjBL. In both,

Table 1. Description and approach of clusters

Description	Color	Approach
Science teaching	Blue	Methods and approaches in science teaching
Active methodologies	Red	Promoting PBL and the development of critical thinking
Educational technology	Green	Using digital technologies to facilitate learning and teaching
Linguistic competences	Yellow	Specific strategies and techniques for language teaching, particularly English as a second language
Higher education	Purple	Aspects related to university education and the role of the teaching staff
Competence development	Orange	Cooperative learning and the development of communication skills
Pedagogical innovation	Turquoise	Innovations in instructional methodologies and the implementation of curricula
Educational assessment	Grey	Methods and tools for formative assessment and the use of rubrics
Interdisciplinary education	Light green	Interdisciplinary approaches in education, including the integration of social work
Engineering education	Olive green	Engineering education and specific methods associated with this discipline
Social aspects of education	Pink	The role of social media in education and the importance of sustainable development

the student is at the center of the teaching and learning processes and explores concrete problems or projects. Both also promote practical skills related to critical thinking, collaboration, and communication. **Figure 2** shows that PjBL, university mathematics (through STEM and engineering education), and critical thinking are closely interconnected, mutually reinforcing each other to enhance students' education, skills, and competencies.

The network in **Figure 2** and the clusters described in **Table 1** reveal a triangular relationship among three elements:

(1) critical thinking and mathematics subjects, linked through the development of analytical skills and the application of mathematical concepts in complex situations,

(2) critical thinking and PjBL, connected via complex problem-solving and the promotion of transferable skills, and

(3) mathematics subjects and PjBL, related through the practical application of mathematical concepts, motivation, and engagement.

Description and Visualization of Strategies

The strategies identified in the articles included:

(1) dividing students into groups with diverse skills levels and assigning tasks accordingly to foster collaboration and knowledge sharing,

(2) encouraging idea generating and self-directed learning through various resources (e.g., the Internet and educational applications) to enhance student autonomy,

(3) guiding students in problem identification and formulation to help them articulate in their own words, and connect them to prior knowledge and real-life situations,

(4) solving problems through group discussions and the application of different strategies, with justification selected steps to enhance critical thinking,

(5) engaging in guided reflection and evaluation when presenting results in various forms, incorporating feedback from other groups and reflecting on completed work to foster analytical and reflective thinking,

(6) providing constructive and specific feedback on students' work to support continuous improvement, and

(7) conducting reflective evaluations through introspective journals and self-assessments, allowing students to analyze their learning process and critical thinking development.

Figure 3 illustrates the frequency of PjBL strategies referenced in the sample articles.
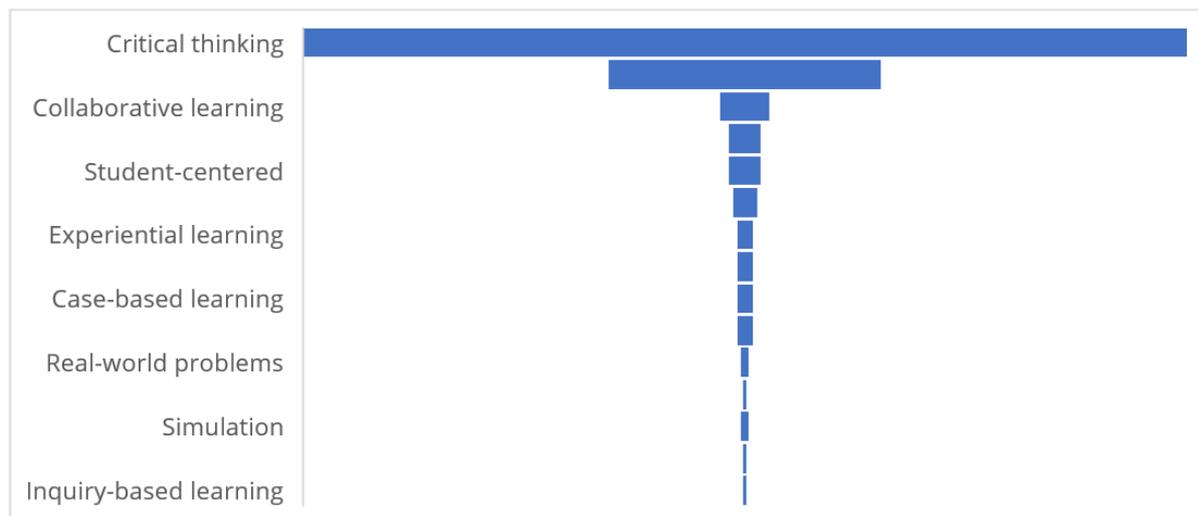
Figure 3. Frequency of strategies in relation to PjBL and critical thinking (Source: Authors' own elaboration)

Table 2. Suggested evaluation tools to assess the effectiveness of strategies (Zakaria et al., 2024)

Assessment method	Description
Application of assessment instruments	Applying validated questionnaires to measure teachers' perceptions of PjBL activities, assessing constructs such as group division, idea generation, and reflection
Exploratory factor analysis	Using exploratory factor analysis to determine instrument validity and reliability, ensuring that items adequately measure underlying constructs
Participant feedback	Obtaining direct feedback from teachers and students on the implementation of PjBL and its impact on learning, improving critical skills and motivation
Estimation of the scope of learning outcomes	Estimating the impact of PjBL on students' academic performance, motivation, and ability to apply knowledge in practical situations compared to traditional methods

Evaluating the Effectiveness of Strategies

The information in the articles included in the sample was used to construct **Table 2**, which summarizes the methodologies and the effectiveness of the strategies.

CONCLUSION

The methodology applied in this study enabled the visualization from literature those specific PjBL strategies are most effective in fostering critical thinking in university mathematics courses. These strategies are primarily based on integrating critical thinking, PjBL and mathematics subjects into the curriculum to create a rich learning environment that enhances students' mathematical skills and prepares them to effectively apply their acquired knowledge in various contexts. Additionally, they emphasize continuous and reflective assessment to monitor students' progress in conceptual understanding and practical application, allowing for the adjustment teaching and learning methods to their needs.

Assessment strategies and tools for PjBL activities should be designed to foster critical thinking, enhance collaboration, and develop problem-solving skills. This approach equips students to tackle complex challenges in their future professional careers by integrating various disciplines and methods that align with the demand for a broad-spectrum for diverse skills and competencies.

One of the most effective PjBL strategies for fostering critical thinking in university mathematics courses is the structured division of students into diverse groups, where tasks are assigned based on individual abilities. This approach not only promotes collaboration and knowledge exchange but also encourages students to articulate mathematical problems in their own words, relate them to prior knowledge, and apply them to real-life contexts. Moreover, guided reflection and peer evaluation play a crucial role in reinforcing analytical and critical thinking skills. Through discussions, feedback sessions, and self-assessments, students refine their reasoning process, identify misconceptions, and enhance their problem-solving abilities. These

strategies promote autonomy, encouraging students to take an active role in their learning process rather than passively absorbing information.

Another key strategy is integrating PjBL with real-world applications and interdisciplinary connections. By designing projects that are relevant to students´ future professional fields, teachers can enhance engagement and motivation, making learning mor meaningful. Effective PjBL implementation includes clearly defining learning objectives, formulating guiding questions that challenge students, and ensuring projects have a well-structured timeline. Furthermore, the inclusion of assessment tools such as validated questionnaires and exploratory factor analysis allows for the continuous evaluation of students´ progress, ensuring that PjBL activities effectively enhance their critical thinking skills. The reflective nature of PjBL, combined with emphasis on inquiry-based learning and collaborative problem-solving, makes it a powerful methodology for developing both mathematical competencies and essential cognitive skills.

Lastly, the findings of this study underscore the significance of PjBL as an effective methodology for fostering critical thinking in university mathematics courses. By mapping existing research, this review identified a strong interconnection between PjBL, mathematics education, and critical thinking, highlighting its role enhancing analytical reasoning, real-world problem-solving, and the development of transferable skills. Furthermore, the study emphasizes the necessity of structured assessment methods (such validated instruments, exploratory factor analysis, and participant feedback) to measure the impact of PjBL strategies effectively. Beyond its pedagogical benefits, PjBL also contributes to student motivation and institutional engagement, suggesting that its successful implementation requires alignment with curricular objectives and institutional support. However, for PjBL to realize its full potential, further research should explore best practices for overcoming barriers such as resistance to innovation, the need for teacher training, and the integration of technology in mathematics education. Future efforts should also focus on refining assessment techniques to ensure that critical thinking gains are accurately measured and sustained over time.

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