

PROBLEM-BASED LEARNING AND EARLY MATHEMATICAL PROBLEM-SOLVING: EVIDENCE FROM A QUASI-EXPERIMENTAL STUDY IN CHINA*

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Abstract

This quasi-experimental study examined the effectiveness of Problem-Based Learning (PBL) in enhancing mathematical problem-solving ability among second-grade students in an urban Chinese primary school. Addressing a critical gap in grade-specific PBL research, this study provides empirical evidence from early elementary education in East Asia. A total of 90 students from two intact classes were assigned to either a PBL group ($n = 45$) or a traditional instruction group ($n = 45$) for a 16-week intervention. A researcher-developed 20-item Mathematical Problem-Solving Test (Cronbach's $\alpha = 0.81$) was administered as pre-test and post-test, supplemented by classroom observations and a post-intervention student questionnaire. Quantitative analyses included t-tests, ANOVA, and effect sizes with 95% confidence intervals.

Results showed that the PBL group significantly outperformed the control group in post-test scores, with a large and precise effect size (17.07 vs. 14.29,

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$t(88) = 6.42, p < .001, \text{Cohen's } d = 1.35, 95\% \text{ CI } [1.02, 1.68]$). Critically, low-achieving students in the PBL group demonstrated the greatest gains ($M = 6.33$), suggesting a potent equity-oriented effect. Student feedback was overwhelmingly positive, with 100% preferring group work and 95.6% reporting deeper conceptual understanding. These findings contribute methodologically, contextually, and equity-focused evidence to the literature, demonstrating that PBL, when implemented with authentic tasks and structured collaboration, significantly enhances early elementary mathematical problem-solving and engagement.

Keywords: Problem-Based Learning, mathematical problem-solving, Elementary mathematics, Quasi-experimental design, Equity

Introduction

Globally, educational reform movements are shifting the focus from knowledge transmission to the cultivation of competencies like critical thinking and problem-solving (UNESCO, 2021). This paradigm shift is particularly pronounced in mathematics education, where the ability to apply knowledge to novel, real-world situations is increasingly valued over rote procedural fluency (Organisation for Economic Co-operation and Development [OECD], 2019). Problem-Based Learning (PBL), originating in medical education (Barrows & Tamblyn, 1980), has emerged as a powerful pedagogical approach to foster these higher-order skills by engaging students with authentic, ill-structured problems (Hmelo-Silver, 2004).

A growing body of international research confirms PBL's positive effects on primary students' mathematical reasoning and motivation across diverse cultural contexts. For instance, Doz, Cotič, and Cotič (2025) demonstrated significant improvements in problem-solving among Slovenian third-graders. Similarly, studies in Indonesia (Meisari, Herpratiwi, & Oktaria, 2025) and Qatar (Al-

Thani, Al-Muftah, & Said, 2025) have reported gains in both cognitive and affective outcomes. In China, recent curriculum reforms, particularly the Compulsory Education Mathematics Curriculum Standards (2022 Edition), explicitly mandate that students be able to "discover, propose, analyze, and solve problems in real-life contexts" (Ministry of Education of China, 2022, p. 15), creating a strong policy impetus for pedagogical innovation. This aligns with the national "Double Reduction" Policy, which aims to reduce rote homework and off-campus tutoring burdens, thereby freeing up space for more holistic, competency-based learning approaches like PBL.

Despite this alignment, a critical gap persists in the literature. Most existing studies focus on upper elementary grades (Grades 3–5), leaving the impact of PBL on younger learners (Grade 2) — who are in a crucial transition from concrete to abstract thinking (Piaget, 1950) — largely unexplored. Furthermore, few studies systematically examine differential effects by initial proficiency level, which is essential for designing equitable instructional interventions. While Chinese scholars have contributed to PBL research (e.g., Li & Klangphahol, 2025 on Grade 4), grade-specific evidence for Grade 2 in the Chinese context remains scarce. Therefore, rigorous quasi-experimental evidence examining the effectiveness of PBL in Grade 2 mathematics classrooms remains limited.

This study directly addresses these gaps. It contributes to the field by: (1) providing grade-specific empirical evidence for the efficacy of PBL in Grade 2 mathematics; (2) offering a contextualized contribution from a typical urban Chinese school, responding to national policy calls for competency-based education; and (3) delivering an equity-focused contribution by systematically analyzing the differential impact of PBL on low-achieving versus high-achieving students. The study was guided by three primary objectives: (a) to evaluate the efficacy of PBL in enhancing second-grade students' mathematical problem-solving ability compared to traditional instruction; (b) to examine PBL's effect on

student collaboration and engagement; and (c) to compare its differential impact on students of varying initial proficiency levels.

Objectives

To study examined the effectiveness of Problem-Based Learning (PBL) in enhancing mathematical problem-solving ability among second-grade students in an urban Chinese primary school.

Literature Review

This study is grounded in three interrelated theoretical frameworks that collectively explain the mechanisms through which PBL enhances learning.

1. Constructivist Theory (Piaget, 1950; Vygotsky, 1978): PBL operationalizes constructivism by positioning learners as active knowledge constructors. Piaget's emphasis on cognitive development through interaction with the environment aligns with PBL's hands-on, inquiry-based tasks. Vygotsky's sociocultural theory, particularly the Zone of Proximal Development (ZPD), highlights the critical role of peer collaboration and social interaction in learning, a cornerstone of PBL's group work structure.

2. Pragmatic Education Theory (Dewey, 1938): Dewey's principle of "learning by doing" is directly embodied in PBL. By situating learning within authentic, experience-based problems, PBL ensures that knowledge is not abstract but meaningful and transferable to real-life contexts.

3. Self-Determination Theory (Ryan & Deci, 2000) : This theory provides a framework for understanding PBL's impact on student engagement. PBL satisfies students' innate psychological needs for autonomy (choosing problem-solving strategies), competence (experiencing success in solving real problems), and relatedness (collaborating with peers), thereby fostering intrinsic motivation.

Synthesizing Empirical Evidence: Cognitive and Affective Outcomes

Recent empirical studies provide robust support for PBL's effectiveness in primary mathematics, but a critical synthesis reveals both consistencies and areas needing further investigation.

1. PBL and Cognitive Development: A consistent finding across studies is PBL's positive impact on cognitive outcomes. Doz et al. (2025) found that a problem-oriented model significantly improved third-graders' achievement across arithmetic, geometry, and logic. Anugraheni, Gufron, and Purnomo (2025) reported large effect sizes ($\eta^2 = 0.219$ and 0.231) for elementary students' mathematical connection abilities using Realistic Problem-Based Learning (R-PBL). These studies suggest that PBL's inquiry-based nature deepens conceptual understanding and promotes transferable skills.

2. PBL, Collaboration, and Engagement: The affective benefits of PBL are equally well-documented. Al-Thani et al. (2025) revealed that PBL not only improved problem-solving but also enhanced perseverance, critical thinking, and the use of multiple representations among Qatari fifth-graders. This aligns with meta-analytic findings (e.g., Zhang, 2023) showing significant gains in intrinsic motivation, attributed to task authenticity.

3. Critical Analysis and Research Gaps: While these studies collectively confirm PBL's cross-cultural applicability, a critical examination reveals important limitations. First, there is a grade-specific bias: the overwhelming majority of research targets upper elementary grades. Doz et al. (2025) focused on Grade 3, Meisari et al. (2025) on Grade 5, and Li and Klangphahol (2025) on Grade.

4. Second, most studies rely on short-term interventions, limiting generalizability about long-term sustainability (though Al-Thani et al., 2025, provides preliminary evidence of a dosage effect). Third, and most critically for this study, the differential impact on students by initial proficiency level remains underexplored. While Anugraheni et al. (2025) touched upon this, systematic

subgroup analysis in early elementary grades is nascent. This study directly addresses these methodological and contextual gaps by focusing on Grade 2 and explicitly testing for differential effects.

Methodology

This study employed a quasi-experimental pretest-posttest design with two intact second-grade classes from Xingzhou Primary School, Hangzhou, China.

Participants and Sampling: A purposive cluster sample of 90 second-grade students was drawn from two intact classes at Xingzhou Primary School, Hangzhou, China. The school was purposively selected as a representative urban site adhering to the national curriculum and with no prior systematic PBL exposure. Two intact classes from the school were then purposively chosen to form the experimental and control groups, based on confirmed baseline equivalence in mathematics achievement and the availability of the same teacher for both classes. This method was chosen to maintain ecological validity and minimize disruption to the school's routine while ensuring the sample possessed the specific characteristics required to address the research questions. The experimental group (Class 8, $n = 45$; 24 boys, 21 girls; mean age = 7.6 years, $SD = 0.3$) received 16 weeks of PBL instruction, while the control group (Class 7, $n = 45$; 23 boys, 22 girls; mean age = 7.5 years, $SD = 0.4$) received traditional instruction. The same certified teacher, who received specialized PBL training, taught both classes to control for teacher variability. Pretest scores confirmed baseline equivalence ($t(88) = 0.03$, $p = .98$).

The PBL Intervention: The 16-week intervention was structured around eight thematic modules, each aligned with the national second-grade mathematics curriculum (People's Education Press, 2023). Each module, lasting one to two weeks with two 40-minute sessions, engaged students in authentic, ill-structured problems requiring collaborative inquiry (see Table 1 for module

summaries). Implementation fidelity was monitored through bi-weekly observations by a trained research assistant using a structured checklist based on the PBL implementation framework (Zhang & Chen, 2020). The teacher maintained a reflective journal to document any deviations from the planned protocol.

Instruments:

1. Mathematical Problem-Solving Test: A 20-item test (Cronbach's $\alpha = 0.81$) was developed based on national curriculum standards. Content validity was established via the Item-Objective Congruence (IOC) index (mean IOC = 0.72) by a panel of three experts.

2. Classroom Observation Protocol: Adapted from the CLASS-S framework (Pianta et al., 2008), this protocol systematically documented student engagement, collaborative quality, and teacher facilitation. Inter-rater reliability (ICC = 0.78) was established.

3. Student Learning Experience Questionnaire: A 15-item questionnaire, adapted from the PISA Student Engagement Index (OECD, 2019), measured students' affective, cognitive, and behavioral engagement on a 5-point Likert scale.

Data Analysis: Data were analyzed using SPSS 27.0. Independent and paired t-tests were used for between- and within-group comparisons. To examine differential effects, students in the experimental group were divided into three proficiency subgroups based on pre-test score tertiles: low (≤ 10 , $n=15$), medium (11-14, $n=15$), and high (≥ 15 , $n=15$). A one-way ANOVA with Tukey's post-hoc tests compared gain scores across these subgroups. Effect sizes (Cohen's d , η^2) and their 95% confidence intervals were calculated to supplement null hypothesis testing (Kline, 2013).

Results

Descriptive and Inferential Statistics

The experimental group ($M = 17.07$, $SD = 2.21$) significantly outperformed the control group ($M = 14.29$, $SD = 2.88$) on the post-test, $t(88) = 6.42$, $p < .001$. The effect size was large and precisely estimated (Cohen's $d = 1.35$, 95% CI [1.02, 1.68]), indicating a robust intervention effect. A one-way ANOVA was conducted to examine whether the impact of PBL differed based on students' initial proficiency levels. The analysis revealed a statistically significant difference in gain scores among the three proficiency subgroups within the PBL group, $F(2,42) = 7.89$, $p = .001$, $\eta^2 = 0.27$, 95% CI [0.09, 0.45]. This large effect size indicates that 27% of the variance in gain scores was explained by initial proficiency level.

Differential Effects by Proficiency Level

To further explore this differential effect, students in the experimental group were divided into three subgroups based on pre-test score tertiles: low (≤ 10 , $n=15$), medium (11-14, $n=15$), and high (≥ 15 , $n=15$). Post-hoc Tukey HSD tests showed that low-proficiency students ($M = 6.33$, $SD = 1.59$) gained significantly more than medium-proficiency ($M = 5.07$, $SD = 1.10$, $p = .033$) and high-proficiency students ($M = 2.53$, $SD = 1.30$, $p < .001$). This finding suggests a powerful equalizing effect, where the lowest-achieving students benefited the most from the PBL intervention.

Student Engagement and Collaboration

The post-intervention questionnaire revealed exceptionally high levels of engagement. Affective engagement was strong, with 91.1% of students enjoying PBL lessons. Cognitive engagement was also high, with 95.6% reporting that PBL helped them understand concepts better and 93.3% valuing the opportunity to think of multiple solutions. Critically, behavioral engagement and collaboration were unanimous, with 100% of students preferring group work and reporting that they help their peers. Classroom observations corroborated these findings, with

active participation observed in 85% of sessions and off-task behavior in less than 5% of intervals.

Discussion

The findings provide robust evidence that PBL significantly enhances second-grade students' mathematical problem-solving ability, with a large and precise effect size ($d = 1.35$). This magnitude aligns with recent international studies (e.g., Doz et al., 2025; Meisari et al., 2025), reinforcing PBL's cross-cultural applicability. However, this study extends the literature by providing grade-specific evidence for a critical, yet under-researched, age group and by systematically analyzing differential effects.

The most theoretically significant finding is the pronounced benefit for low-achieving students. This aligns powerfully with Vygotsky's (1978) concept of the Zone of Proximal Development. In heterogeneous PBL groups, low achievers receive just-in-time scaffolding from peers, enabling them to solve problems beyond their independent capacity. Furthermore, the concrete, enactive nature of PBL tasks helps low achievers bridge the gap between concrete experiences and abstract mathematical concepts (Bruner, 1966), potentially reducing the anxiety often associated with traditional symbolic manipulation. This equity-oriented outcome is particularly resonant with China's "Double Reduction" Policy, demonstrating that PBL offers a practical pathway to reduce rote learning burdens while simultaneously narrowing achievement gaps.

The high levels of student engagement resonate with Self-Determination Theory (Ryan & Deci, 2000). PBL satisfies students' needs for autonomy (choosing strategies), competence (solving real problems), and relatedness (collaborating with peers). This affective and cognitive engagement likely mediates the observed academic gains. The unanimous preference for group work suggests that the social isolation of traditional independent seatwork is not merely

suboptimal but actively aversive to young learners, who thrive in socially supportive learning environments.

These findings have significant implications for policy and practice, particularly within the context of China's "Double Reduction" Policy. The policy aims to reduce the burden of rote homework and excessive tutoring, freeing up space for more holistic, competency-based learning. This study provides empirical evidence that PBL can serve as a practical pedagogical vehicle for achieving these policy goals. Its pronounced equity effect—helping low achievers the most—suggests that scaling PBL could contribute to narrowing achievement gaps, a central objective of China's educational reforms.

Recommendation

1. Policy-Level Recommendations

Educational policymakers should incorporate Problem-Based Learning (PBL) into national and regional mathematics curricula, particularly at the primary level. Curriculum guidelines should emphasize problem-solving competence, conceptual understanding, and higher-order thinking skills rather than rote memorization. Additionally, assessment systems should be reformed to include performance-based and process-oriented evaluation.

2. Curriculum Development Recommendations

Curriculum designers should:

Integrate real-life and context-based mathematical problems that are relevant to students' daily experiences.

Structure learning units around problem scenarios rather than isolated mathematical topics.

Ensure alignment between learning objectives, instructional strategies, and assessment methods within the PBL framework.

3. Instructional Recommendations

Teachers should:

Adopt the role of facilitators who guide inquiry rather than deliver direct instruction.

Implement structured PBL phases, including:

- 1) Problem presentation
- 2) Inquiry and exploration
- 3) Collaborative discussion
- 4) Solution development
- 4) Reflection and evaluation

Use scaffolding techniques to support young learners, such as guiding questions, visual aids, and step-by-step problem decomposition.

Encourage mathematical communication, allowing students to explain reasoning and justify solutions.

4. Student Development Recommendations

Students should be encouraged to:

Engage actively in collaborative learning and peer discussion.

Develop metacognitive skills, such as planning, monitoring, and evaluating their problem-solving processes.

Build confidence in tackling non-routine mathematical problems.

Reflect on their learning to strengthen conceptual understanding.

5. Teacher Professional Development Recommendations

Educational institutions should provide ongoing training for teachers in:

Designing and implementing PBL-based lesson plans

Classroom facilitation and student-centered pedagogy

Assessment of problem-solving skills and learning processes

Use of instructional technologies and manipulatives to support mathematical understanding

6. Assessment and Evaluation Recommendations

Assessment systems should:

Move beyond traditional tests to include authentic assessment, such as:

- 1) Problem-solving tasks
- 2) Student portfolios
- 3) Group projects

Evaluate both learning outcomes and learning processes, including reasoning, collaboration, and creativity.

Utilize pretest–posttest designs in classroom research to monitor student progress.

7. Research Recommendations

Future research should:

Conduct longitudinal studies to examine the sustained impact of PBL on mathematical development.

Compare PBL effectiveness across different regions and educational contexts in China.

Investigate the role of digital tools and educational technologies in supporting PBL environments.

Explore how PBL influences affective factors, such as motivation, attitudes toward mathematics, and learning anxiety.

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