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Project-based STEM learning through vertical garden design: Enhancing elementary students' numeracy and mathematical problem-solving

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Abstract

Background: The persistently low numeracy performance of Indonesian elementary students, as indicated by the PISA 2022 results and the national Education Report Card, highlights the need for contextual mathematics instruction that connects mathematical concepts with authentic learning experiences.
Aims: This study investigated the effectiveness of project-based STEM learning through vertical garden design in enhancing fifth-grade students' numeracy and mathematical problem-solving compared with the Direct Instruction model.
Method: A quasi-experimental study employing a nonequivalent control group design was conducted with 46 fifth-grade students, comprising an experimental group (n = 23) and a control group (n = 23). Data were collected using validated and reliable numeracy and mathematical problem-solving tests and analyzed through descriptive statistics, normalized gain (N-Gain), paired-sample *t*-test, Wilcoxon signed-rank test, independent-sample *t*-test, and Cohen's effect size.
Results: Project-based STEM learning significantly improved students' numeracy ($p < 0.001$) and mathematical problem-solving ($p < 0.001$). The experimental group achieved significantly greater numeracy improvement (N-Gain = 0.68) than the control group (N-Gain = 0.52), with a large effect size ($d = 0.914$). In contrast, no significant between-group difference was found in mathematical problem-solving improvement ($p = 0.428$; $d = 0.236$), likely due to a ceiling effect.
Conclusion: Project-based STEM learning through vertical garden design effectively enhances elementary students' numeracy and mathematical problem-solving. Its strongest contribution lies in improving contextual numeracy, while its comparative advantage over Direct Instruction depends on the specific mathematical competency being developed.

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INTRODUCTION

Numeracy has become one of the most essential competencies required to enable individuals to function effectively in the twenty-first century. Modern society demands the ability to interpret, analyze, and apply quantitative information in various personal, academic, and professional contexts (Christou, 2023; Gerlich, 2025; López-Meneses et al., 2020). Everyday activities such as comparing prices, interpreting statistical information, estimating quantities, and making financial decisions all require adequate numeracy skills. Consequently, numeracy should not be viewed merely as the ability to perform arithmetic calculations but as a broader capacity to reason mathematically in authentic situations. Developing numeracy from the early years of schooling is therefore fundamental for establishing a strong foundation for lifelong learning. Elementary education plays a crucial role because students begin constructing conceptual understanding of numbers, operations, measurement, and quantitative relationships during this stage (Idrus et al., 2022; Manfreda Kolar &

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Hodnik, 2021; Yi et al., 2026). However, evidence indicates that many elementary students continue to experience considerable difficulties in applying mathematical knowledge beyond routine classroom exercises. These difficulties are reflected in their limited ability to connect mathematical concepts with meaningful real-life situations. As a result, improving numeracy has become an important priority for mathematics education reform in many countries, including Indonesia. This condition highlights the necessity of designing mathematics instruction that promotes conceptual understanding, reasoning, and meaningful application rather than emphasizing procedural computation alone.

Numeracy development is closely related to mathematical problem-solving because both competencies require students to use mathematical knowledge to understand, analyze, and resolve unfamiliar situations. Mathematical problem-solving encourages learners to identify relevant information, formulate appropriate strategies, implement solutions systematically, and evaluate the correctness of their reasoning (Szabo et al., 2020; Torres-Peña et al., 2025). These processes support the development of critical thinking, logical reasoning, and decision-making, which are indispensable competencies in contemporary education (Dumitru & Halpern, 2023; Raj et al., 2022; Rivas et al., 2022). Nevertheless, many elementary students still encounter substantial challenges when mathematical tasks require reasoning beyond routine computational procedures. Learning difficulties become particularly evident in fraction topics because students often memorize algorithms without fully understanding the underlying concepts. As a consequence, they struggle to transfer procedural knowledge into meaningful problem-solving situations involving authentic contexts. Such learning difficulties gradually accumulate and negatively influence students' readiness to learn more advanced mathematical concepts in higher grades. One major factor contributing to this condition is the continued dominance of teacher-centered instruction that emphasizes formula memorization and repetitive practice. Although this instructional approach may improve procedural fluency, it often provides limited opportunities for students to develop conceptual understanding and flexible mathematical reasoning. Therefore, mathematics instruction should be transformed into a more contextual and student-centered learning experience that enables students to construct mathematical understanding through meaningful exploration and authentic problem-solving activities.

Project-Based STEM learning has emerged as one of the promising instructional approaches capable of addressing these educational challenges by integrating science, technology, engineering, and mathematics into authentic learning experiences. Rather than treating mathematics as an isolated subject, this approach positions mathematical knowledge as a practical tool for investigating problems, designing solutions, and evaluating outcomes within meaningful projects. Through project-based activities, students actively participate in inquiry, collaboration, experimentation, and reflective thinking while applying mathematical concepts to solve real-world problems (Rehman et al., 2024). Such learning experiences provide opportunities for students to connect abstract mathematical ideas with concrete situations that are relevant to their daily lives. One authentic context that can facilitate this integration is the design and construction of a vertical garden, where students apply fraction operations, measurement, estimation, and quantitative reasoning to complete engineering design tasks. This environmental project not only strengthens students' mathematical understanding but also introduces sustainability-related issues that encourage responsible decision-making and interdisciplinary thinking. The Engineering Design Process embedded in Project-Based STEM learning further supports systematic reasoning by guiding students through identifying problems, generating ideas, constructing prototypes, testing solutions, and improving their designs (Abdurrahman et al., 2023; Jiang & Pang, 2023; Lin et al., 2021; Syukri et al., 2026; Vistara et al., 2022). Consequently, mathematics becomes an integral component of the

design process rather than merely a collection of abstract procedures. This learning environment encourages students to understand why mathematical concepts are needed and how they function in solving authentic problems. Therefore, integrating Project-Based STEM learning with vertical garden design offers considerable potential to enhance both numeracy and mathematical problem-solving in elementary mathematics education.

Recent studies have consistently demonstrated the educational benefits of project-based STEM learning in improving students' learning outcomes across mathematics and science education. Previous research has primarily examined the implementation of project-based STEM learning from the perspectives of instructional effectiveness, student engagement, creativity, and twenty-first-century skills, while also identifying various pedagogical opportunities and implementation challenges (Baran et al., 2021; Chistyakov et al., 2023; Lee & Lee, 2025; Wilson, 2021). In parallel, numerous studies have emphasized the growing importance of numeracy and mathematical problem-solving as essential competencies for elementary students, highlighting their roles in supporting mathematical reasoning, decision-making, and lifelong learning (Geiger & Schmid, 2024; Grotlüschen et al., 2020; Hoogland, 2023; Olivares et al., 2021; Reyna & Brainerd, 2023). Furthermore, innovative mathematics learning approaches, including project-based learning and realistic mathematics education, have been reported to improve students' mathematical achievement, numeracy, and problem-solving abilities in elementary classroomsc (Fauzan et al., 2024; Lazi et al., 2021; Pellegrini et al., 2021). Nevertheless, several important research gaps remain. Most previous studies have investigated numeracy and mathematical problem-solving as separate learning outcomes, providing limited evidence regarding the simultaneous development of both competencies within a single project-based STEM intervention. Moreover, authentic engineering design activities situated in environmental sustainability contexts, such as vertical garden design, have rarely been integrated into elementary mathematics instruction, despite their potential to provide meaningful opportunities for applying mathematical concepts in real-world situations. In addition, comparative evidence examining the effectiveness of project-based STEM learning against a well-established instructional approach such as Direct Instruction remains scarce, making it difficult to determine whether the advantages of STEM are competency-specific or consistently superior across different mathematical outcomes. Therefore, this study addresses these gaps by integrating project-based STEM learning with a vertical garden design project and simultaneously examining its effects on elementary students' numeracy and mathematical problem-solving in comparison with Direct Instruction, thereby providing more comprehensive empirical evidence regarding the instructional value of contextual STEM learning in elementary mathematics education. Despite the growing body of research demonstrating the educational benefits of Project-Based STEM learning, important gaps remain regarding its application in elementary mathematics education.

Previous studies have generally investigated numeracy and mathematical problem-solving as separate learning outcomes, providing limited evidence concerning their simultaneous development within a single instructional intervention. Furthermore, many existing STEM projects employ general engineering activities that are not explicitly connected to environmental sustainability or authentic mathematical applications encountered by elementary students. Comparative studies evaluating Project-Based STEM learning against well-established instructional approaches such as Direct Instruction are also relatively limited, making it difficult to determine the specific instructional advantages of each approach for different mathematical competencies. Addressing these limitations is important for developing more comprehensive evidence regarding effective mathematics instruction at the elementary level. Therefore, this study investigates the effectiveness of Project-Based STEM learning through vertical garden design in enhancing elementary students' numeracy and mathematical problem-solving. Specifically, the study examines

the effects of the instructional intervention on students' numeracy achievement and mathematical problem-solving performance following the learning process. It also compares students' learning improvements with those achieved through Direct Instruction to determine whether Project-Based STEM learning provides greater educational benefits. Furthermore, the study seeks to identify the competency-specific contribution of Project-Based STEM learning in supporting meaningful mathematics learning through authentic engineering design experiences. The findings are expected to provide empirical evidence that contributes to the advancement of contextual mathematics instruction and supports the implementation of innovative STEM-based pedagogies in elementary education.

LITERATURE REVIEW

Numeracy is widely recognized as a fundamental competency that enables learners to interpret, analyze, and apply mathematical knowledge in diverse real-life situations. Unlike traditional computational proficiency, numeracy emphasizes the meaningful use of mathematical concepts, reasoning, and quantitative information to make informed decisions and solve authentic problems (Hoogland, 2023; Reyna & Brainerd, 2023; Torres-Peña et al., 2025). Contemporary mathematics education views numeracy as a multidimensional construct encompassing conceptual understanding, procedural fluency, strategic reasoning, and the ability to communicate mathematical ideas effectively (Adeleke et al., 2025; Asmara et al., 2026; Barham et al., 2026; Proshkin & Astafieva, 2025). Developing numeracy during elementary education is particularly important because it establishes the cognitive foundation required for learning more advanced mathematical concepts in subsequent educational levels. Students who develop strong numeracy skills at an early age generally demonstrate greater confidence in mathematical reasoning and exhibit higher achievement across various academic disciplines. Conversely, inadequate numeracy often results in persistent misconceptions that hinder students from applying mathematical knowledge beyond routine classroom exercises. This condition becomes increasingly problematic when students encounter contextual mathematical tasks that require interpretation, estimation, comparison, and decision-making rather than direct computation. Consequently, mathematics instruction should provide meaningful learning experiences that encourage students to connect mathematical concepts with authentic situations encountered in their daily lives. Contextual learning environments facilitate conceptual understanding because students construct mathematical meaning through active interaction with realistic problems rather than through memorization of isolated procedures. Therefore, strengthening numeracy requires instructional approaches that integrate conceptual understanding, authentic problem contexts, and active student engagement within meaningful mathematical experiences.

Mathematical problem-solving is considered one of the central objectives of mathematics education because it enables students to utilize mathematical knowledge strategically when confronted with unfamiliar situations. Effective problem-solving extends beyond obtaining correct answers and involves understanding problems, selecting appropriate strategies, implementing mathematical procedures, and evaluating the validity of solutions (Leavy & Hourigan, 2020; Szabo et al., 2020). These cognitive processes encourage students to develop logical reasoning, analytical thinking, creativity, and reflective judgment throughout the learning process. The well-established problem-solving framework proposed by Polya continues to provide a comprehensive foundation for understanding how students approach mathematical problems systematically. Students who actively engage in structured problem-solving activities generally demonstrate stronger conceptual understanding because they continuously connect prior knowledge with newly encountered

mathematical situations. However, many elementary students experience considerable difficulties in solving contextual mathematical problems because classroom instruction frequently emphasizes procedural practice rather than strategic reasoning. Such instructional conditions often encourage students to memorize algorithms without understanding why particular mathematical procedures are appropriate for solving specific problems. As a result, students become dependent on familiar procedures and struggle when mathematical tasks require flexible reasoning or multiple solution strategies. Providing authentic learning experiences that encourage investigation, exploration, and collaborative reasoning can substantially improve students' mathematical problem-solving abilities. Therefore, instructional approaches that integrate meaningful contexts with active learning experiences are expected to strengthen both students' problem-solving competence and their overall mathematical understanding.

Project-Based STEM learning has emerged as an interdisciplinary instructional approach that integrates science, technology, engineering, and mathematics within authentic learning experiences designed to solve real-world problems. This approach encourages students to construct knowledge actively by participating in inquiry, collaboration, experimentation, and engineering design activities rather than passively receiving information from teachers (Awwad, 2025; Bhaumik et al., 2024; Gillies, 2023; Morris, 2025). Mathematics serves as an essential component of STEM learning because quantitative reasoning supports decision-making throughout the process of identifying problems, generating ideas, evaluating alternatives, and refining solutions. The Engineering Design Process provides a systematic framework that guides students through identifying problems, designing possible solutions, constructing prototypes, testing outcomes, and improving their designs based on evidence and reflection (Arce et al., 2022; Arık & Topçu, 2022; Lin et al., 2021; Subramaniam et al., 2025). Through these iterative learning experiences, students develop conceptual understanding while simultaneously strengthening higher-order thinking, creativity, communication, and collaboration. Project-based learning further enhances the effectiveness of STEM education because students work on meaningful projects that require sustained investigation and authentic application of disciplinary knowledge. In elementary mathematics education, project-based STEM learning enables students to apply mathematical concepts within realistic situations where calculations directly influence design decisions and project outcomes. One authentic example is the design of a vertical garden, where students employ fraction operations, measurement, proportional reasoning, and estimation to determine planting arrangements, material requirements, and spatial organization. Such activities transform mathematics from an abstract school subject into a practical tool for solving meaningful environmental challenges. Consequently, Project-Based STEM learning supported by the Engineering Design Process provides a strong theoretical foundation for enhancing elementary students' numeracy and mathematical problem-solving through contextual and interdisciplinary mathematics instruction.

Authentic learning contexts have become increasingly important in contemporary mathematics education because they enable students to experience mathematics as a meaningful tool for solving practical problems rather than as a collection of isolated procedures. Environmental sustainability projects provide valuable opportunities for integrating mathematical concepts with scientific inquiry and engineering design in ways that are relevant to students' everyday experiences (Abdurrahman et al., 2023; Alkair et al., 2023; Djam'an, 2025; Nguyen et al., 2020; Solihah et al., 2024). Among various sustainability-oriented learning contexts, vertical garden design offers a practical project that requires students to apply mathematical reasoning throughout the planning and implementation process. Students are required to measure available space, determine planting layouts, estimate material requirements, and calculate fractional quantities when organizing planting media and arranging containers. These activities naturally encourage learners to use

mathematical concepts in authentic situations where every calculation directly influences the success of the engineering design. In addition to strengthening conceptual understanding, the project encourages students to collaborate, communicate ideas, and evaluate alternative solutions based on quantitative evidence (Naseer et al., 2025; Retno et al., 2025). Integrating environmental issues into mathematics instruction also helps students recognize the social relevance of mathematical knowledge and fosters greater learning motivation. Furthermore, sustainability-oriented projects promote interdisciplinary thinking by encouraging students to connect mathematical reasoning with environmental awareness, scientific knowledge, and technological problem-solving. Such contextual experiences contribute to deeper conceptual understanding because mathematical ideas are learned through purposeful investigation rather than through repetitive procedural exercises. Therefore, vertical garden design represents an authentic and meaningful instructional context for strengthening elementary students' numeracy and mathematical problem-solving within Project-Based STEM learning.

The theoretical relationship between Project-Based STEM learning, numeracy, and mathematical problem-solving can be understood through the integration of contextual learning, constructivist learning theory, and interdisciplinary education. Project-Based STEM learning encourages students to construct mathematical understanding actively through investigation, collaboration, and engineering design experiences that require continuous reasoning and reflection (Lee & Lee, 2025; Retno et al., 2025; Vistara et al., 2022). Within this learning environment, numeracy develops as students repeatedly apply mathematical concepts, quantitative reasoning, and procedural knowledge to make informed decisions during project completion. At the same time, mathematical problem-solving evolves because students are continuously challenged to identify problems, formulate strategies, test alternative solutions, and evaluate the effectiveness of their decisions. The Engineering Design Process functions as a cognitive framework that systematically connects mathematical reasoning with authentic problem-solving activities throughout each stage of project development. Unlike conventional teacher-centered instruction, Project-Based STEM learning positions students as active problem solvers who construct knowledge through meaningful interactions with real-world situations. This student-centered learning environment provides greater opportunities for developing conceptual understanding, critical thinking, creativity, and adaptive reasoning simultaneously. Consequently, improvements in numeracy and mathematical problem-solving are expected to occur as complementary learning outcomes rather than as separate educational objectives. Nevertheless, empirical evidence remains limited regarding whether Project-Based STEM learning produces comparable improvements across these two mathematical competencies when implemented in elementary classrooms. Therefore, investigating the competency-specific contribution of Project-Based STEM learning through vertical garden design is expected to enrich the theoretical understanding of contextual mathematics instruction while providing empirical evidence for improving mathematics education at the elementary level.

METHOD

Research Design

This study employed a quantitative approach with a quasi-experimental method. The quantitative approach was chosen because the study aims to test the effect of a treatment on the dependent variables through measurable measurement and statistical analysis. The quasi-experimental method was used because the study was conducted on naturally formed classes, so the researcher could not randomly assign subjects to groups. The design used was a Nonequivalent Control Group Design, involving an experimental group with STEM learning and a control group with

the Direct Instruction model. Both groups were given a pretest before the treatment and a posttest after the treatment.

Participants

The population was all fifth-grade students at one public elementary school in Bandung. Sampling was carried out using a nonprobability sampling technique because the classes used were intact classes that did not permit individual randomisation. The subjects whose data were analysed numbered 46 students, divided into an experimental class (STEM, n=23) and a control class (Direct Instruction, n=23). Class selection considered the equivalence of characteristics and learning achievement in both groups.

Instruments and Data Collection

The research instruments consisted of a number-domain numeracy test and a mathematical problem-solving test. Each test comprised five essay items with a total score range of 0 to 20 (maximum 4 points per item). The numeracy test was developed based on the indicators of understanding mathematical information, using number concepts and operations, and interpreting results, whereas the problem-solving test was developed based on Polya's four stages. The measurement context was the addition and subtraction of fractions linked to the vertical garden project. Content validity was established through expert judgment by a Professor in Mathematics Education. Empirical validity was tested through a trial on 74 sixth-grade students using Pearson Product Moment correlation. All items were declared valid, with correlation coefficients of 0.451 to 0.896 on the numeracy test and 0.665 to 0.922 on the problem-solving test (all $p<0.05$). Internal consistency reliability showed a Cronbach's Alpha of 0.859 (high category) for the numeracy test and 0.919 (very high category) for the problem-solving test. Test–retest reliability was 0.968 and 0.955 respectively (very strong category), so both instruments were suitable for use.

Data Analysis

Data were analysed with the aid of IBM SPSS Statistics 29. The analysis comprised descriptive statistics, calculation of N-Gain using formula together with its categories, and prerequisite tests in the form of the Shapiro–Wilk normality test and Levene's homogeneity test at a significance level of 0.05. Testing the pretest–posttest difference in the experimental class used a paired sample t-test if the data were normal or the Wilcoxon test if not normal, whereas testing the difference in improvement (N-Gain) between groups used an independent sample t-test. The effect size was computed using Cohen's d.

Research Procedure

Learning in the experimental class was conducted through the Engineering Design Process (EDP), simplified into five stages. In the Identify stage, students recognised real problems related to the need for green space, planting media, and plant arrangement, giving rise to a need for calculation. In the Design stage, students designed the vertical garden by calculating the need for, and the division of, materials using the addition and subtraction of fractions. In the Build stage, students constructed a vertical garden prototype based on the design. In the Test stage, students tested the prototype and evaluated the conformity of the calculation results to the objective. In the Redesign stage, students refined the design and calculations based on the test results and then communicated their work. At each stage, fraction concepts were used functionally to make real decisions. Learning in the control class was conducted with the Direct Instruction model, which emphasises stating objectives, teacher demonstration and explanation, worked examples, guided practice, feedback, and independent practice in a systematic manner. The implementation of learning in both classes was monitored through an observation sheet completed by an observer at each meeting.

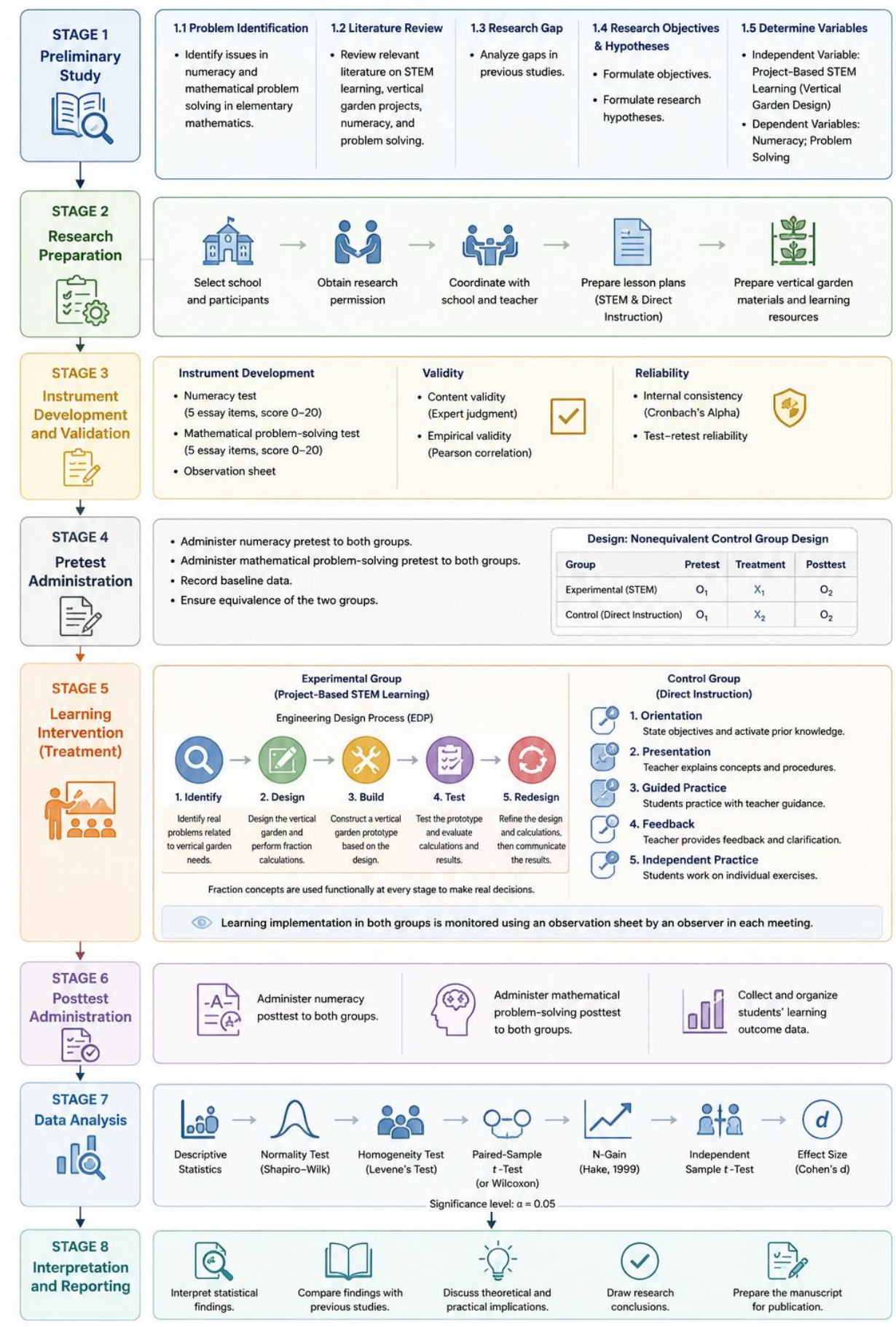


Figure 1. Research Method Flow

RESULTS AND DISCUSSION

Results

The descriptive statistics of the pretest and posttest scores for both abilities in the experimental (STEM) and control (Direct Instruction/DI) classes are presented in Table 1. For numeracy, the mean score of the DI class rose from 10.09 to 15.35, while that of the STEM class rose from 12.61 to 17.61. For mathematical problem solving, the mean score of the DI class rose from 8.57 to 16.09, while that of the STEM class rose from 13.78 to 18.04. Both classes improved, with the experimental class's posttest mean higher on both abilities. It should be noted that the STEM class's problem-solving pretest mean was already relatively high (13.78 of 20), while the control class started from a lower initial ability (8.57).

Table 1. Descriptive Statistics of Numeracy and Mathematical Problem-Solving

Ability	Class	Data	N	Max	Mean	SD
Numeracy	DI	Pretest	23	20	10.09	1.564
	DI	Posttest	23	20	15.35	1.112
	STEM	Pretest	23	20	12.61	1.530
	STEM	Posttest	23	20	17.61	1.644
Problem Solving (PS)	DI	Pretest	23	20	8.57	2.313
	DI	Posttest	23	20	16.09	1.905
	STEM	Pretest	23	20	13.78	1.650
	STEM	Posttest	23	20	18.04	1.918

Source: Data processed with IBM SPSS Statistics 29

Improvement was computed using N-Gain. As presented in Table 2, the mean numeracy N-Gain of the STEM class (0.68; medium category) was higher than that of the DI class (0.52; medium category). For problem solving, the mean N-Gain of the STEM class was 0.70 and that of the DI class 0.65, with a much smaller difference. This pattern provides an initial picture that STEM's superiority is more evident in numeracy improvement than in problem solving.

Table 2. Mean N-Gain of Both Abilities

Ability	Class	N-Gain	Category	Diff.
Numeracy	STEM	0.68	Medium	0.16
	DI	0.52	Medium	
Problem Solving (PS)	STEM	0.70	High	0.05
	DI	0.65	Medium	

Source: Data processed with IBM SPSS Statistics 29

The Shapiro–Wilk normality test results (Table 3) show that all numeracy data were normally distributed (Sig.>0.05). For problem solving, two data sets were not normal, namely the DI pretest (Sig.=0.004) and the STEM posttest (Sig.=0.003), while the N-Gain scores of both abilities in both classes were normally distributed. Levene's homogeneity test showed that the variances of the numeracy posttest (Sig.=0.063) and the problem-solving posttest (Sig.=0.541) were homogeneous. Based on these results, testing the pretest–posttest numeracy difference in the experimental class used a paired sample t-test, testing the pretest–posttest problem-solving difference used the Wilcoxon test, and testing the between-group N-Gain difference used an independent sample t-test.

Table 3. Shapiro–Wilk Normality Test Results

Ability	Data	Class	Sig.	Remark
Numeracy	Pretest	DI	0.268	Normal
	Pretest	STEM	0.225	Normal
	Posttest	DI	0.061	Normal
	Posttest	STEM	0.104	Normal
	N-Gain	DI	0.161	Normal
	N-Gain	STEM	0.260	Normal
PS	Pretest	DI	0.004	Not Normal
	Pretest	STEM	0.492	Normal
	Posttest	DI	0.105	Normal
	Posttest	STEM	0.003	Not Normal
	N-Gain	DI	0.130	Normal
	N-Gain	STEM	0.088	Normal

Source: Data processed with IBM SPSS Statistics 29

The hypothesis testing results are presented in Table 4. The paired sample t-test showed a significant improvement in the experimental class's numeracy ($t=14.284$; $p<0.001$). The Wilcoxon test showed a significant improvement in the experimental class's problem solving ($Z=-4.222$; $p<0.001$), with all 23 students obtaining higher posttest than pretest scores. The independent sample t-test on numeracy N-Gain showed a significant difference in improvement between the STEM class (0.683) and the DI class (0.522), with $t=3.098$; $p=0.003$ and a large effect size (Cohen's $d=0.914$). Conversely, the independent sample t-test on problem-solving N-Gain showed no significant difference between the STEM class (0.702) and the DI class (0.652), with $t=0.800$; $p=0.428$ and a small effect size (Cohen's $d=0.236$).

Table 4. Summary of Hypothesis Testing

Hypothesis	Test	Statistic	Sig.	Decision
Pre–post numeracy (STEM)	Paired t-test	t=14.284	<0.001	Significant
Pre–post PS (STEM)	Wilcoxon	Z=−4.222	<0.001	Significant
Gain numeracy (STEM vs DI)	Independent t-test	t=3.098; d=0.914	0.003	Significant
Gain PS (STEM vs DI)	Independent t-test	t=0.800; d=0.236	0.428	Not significant

Source: Data processed with IBM SPSS Statistics 29

Discussion

The findings confirm that vertical garden project-based STEM learning significantly improved the number-domain numeracy of fifth-grade students. This improvement must be read as more than an increase in scores. In essence, numeracy is the ability to formulate, use, and interpret mathematics across a variety of contexts to solve real-life problems. The posttest score increase in the experimental class indicates that students not only mastered the procedures of adding and subtracting fractions but also began to be able to use those operations to read situations and solve meaningful problems; the intervention thus appears to have reached the interpretive dimension of numeracy, not merely its computational surface. The numeracy advantage of the STEM class can be explained through the characteristics of STEM learning, which position mathematics as a thinking tool for solving real problems. In the vertical garden project, fraction concepts were used to calculate material needs, divide planting media, and determine leftover materials, so that fraction operations became meaningful because they had a real purpose and real consequences for the product created.

This explanation is reinforced by cognitive development theory because fifth-grade students, who are at the concrete operational stage, more easily grasp abstract concepts such as fractions when those concepts are presented in concrete activities that can be observed and manipulated. Our finding aligns with studies reporting STEM's advantage in developing the numeracy of elementary students (Nurwijaya, 2024), which suggests that the effect is not incidental but a recurring pattern across contexts.

The significant superiority of the STEM class's numeracy over the DI class (a large effect size, $d = 0.914$) provides strong empirical evidence. This advantage stems from the nature of numeracy, which demands the functional use of mathematics in real contexts. STEM learning gives students broader room to use fraction concepts in authentic situations, whereas Direct Instruction emphasises the explicit delivery of material that is relatively detached from context (Grundy & Koretsky, 2025; Oyovwe & Oyovwi, 2026; Zhu et al., 2023). Although DI is effective in building procedural mastery, its emphasis on decontextualised drill makes students less accustomed to interpreting and using number in real situations. This is consistent with the view that numeracy develops more optimally through contextual, problem-based learning rather than procedural drill (Torres-Peña et al., 2025). STEM learning also significantly improved the experimental class's mathematical problem-solving ability. The authentic project context gave students a compelling reason to truly understand the problem before acting. Unlike routine procedural problems, the problems within the project required students to interpret situations, select relevant information, and evaluate solutions against a real objective, in line with the view that problem solving develops when students are confronted with problems that demand the deployment of strategy. Our finding strengthens the results of studies concluding that STEM learning can improve students' mathematical problem-solving ability.

An intriguing finding emerges precisely in the between-group comparison of problem-solving improvement, which showed no significant difference ($p = 0.428$; $d = 0.236$). This result must be interpreted cautiously and cannot be read as evidence that STEM is less effective. At least two explanations exist. First, a ceiling effect: the STEM class's problem-solving pretest mean was already relatively high (13.78 of 20), while the control class started from a lower score (8.57). Because N-Gain is computed relative to the difference between the maximum score and the pretest score, a group with high initial ability has narrower room for improvement, so the chance of showing a gain surge becomes mathematically limited, regardless of the quality of the learning. The second explanation concerns the effectiveness of Direct Instruction in building structured skills. Polya's sequential problem-solving stages can be taught explicitly and systematically, making them highly compatible with the characteristics of Direct Instruction. From the perspective of cognitive load theory, structured guided practice helps students manage cognitive load when learning new problem-solving procedures. Thus, for a clearly structured skill such as Polya's stages, a highly guided model can yield results comparable to an open approach such as STEM. The absence of a significant difference in fact reflects that both forms of learning are equally effective for that purpose, not that one of them failed.

The differing pattern between numeracy and problem solving offers valuable information. STEM's distinctive advantage appears strongest in numeracy, which demands the use of mathematics in context, whereas in the more structured problem solving, STEM and Direct Instruction yielded comparable improvement. This finding aligns with the awareness in the literature that the advantage of an approach is specific to the type of competency developed. This moves the present study beyond the general claim that STEM is always superior and instead offers a more nuanced understanding of the limits of its advantage.

Implications

The effectiveness of STEM in this study can be explained through the integration of its four components within a single project. The science component appears when students recognise real problems related to plant and green-space needs, making learning begin from a context close to life and fostering engagement. The technology and engineering components appear through designing, building, testing, and refining the prototype within the Engineering Design Process flow. The mathematics component appears through the use of fraction operations to make real decisions. The functional use of mathematics within the project supports the development of numeracy, while the systematic EDP flow supports the development of problem-solving ability. The strength of STEM lies in integration, not in the separate juxtaposition of four fields (Ardianti et al., 2020). Theoretically, this finding enriches the understanding of the specific limits and advantages of STEM and strengthens the framework that contextual, integrated learning supports the development of numeracy and problem solving. Practically, the finding provides a basis for teachers to choose an approach according to their objective: for strengthening number-domain numeracy that requires using number in context, project-based STEM is an effective choice; whereas for training clearly structured problem-solving skills, both STEM and Direct Instruction can be used, giving teachers the latitude to adjust to the availability of time and resources. This implication is important because implementing STEM demands more complex planning and pedagogical readiness on the part of teachers.

Limitations and Suggestions for Future Research

This study has several limitations that should be considered when interpreting its findings and planning future investigations. First, the study involved a relatively small sample of 46 fifth-grade students from a single public elementary school, which may limit the generalizability of the findings to broader educational settings with different demographic and instructional characteristics. Second, the quasi-experimental design relied on intact classrooms rather than random assignment, making it difficult to completely eliminate the influence of pre-existing differences between the experimental and control groups. Third, the relatively high initial mathematical problem-solving performance of the experimental group created a ceiling effect that may have reduced the sensitivity of the normalized gain analysis in detecting differences between instructional approaches. Fourth, the intervention focused exclusively on the addition and subtraction of fractions, and therefore the effectiveness of Project-Based STEM learning through vertical garden design cannot be directly generalized to other mathematical domains or grade levels. Fifth, the study primarily employed written achievement tests to evaluate learning outcomes, which may not have fully captured students' reasoning processes, collaborative interactions, creativity, or decision-making during the engineering design activities. Sixth, the duration of the intervention was limited to a single instructional unit, preventing the investigation of the long-term retention and transferability of numeracy and mathematical problem-solving skills. Future studies are therefore encouraged to involve larger and more diverse samples across multiple schools and educational contexts to enhance the external validity of the findings. Researchers are also recommended to employ randomized or longitudinal research designs to provide stronger causal evidence regarding the effectiveness of Project-Based STEM learning. In addition, future investigations should examine a wider range of mathematical topics and grade levels to determine whether the competency-specific advantages observed in this study remain consistent across different learning contexts. Incorporating qualitative approaches, such as classroom observations, learning analytics, interviews, or think-aloud protocols, would provide richer insights into students' cognitive processes and collaborative learning experiences during the Engineering Design Process. Finally, future research should explore additional contextual STEM projects related to environmental sustainability and compare their effectiveness with other innovative instructional approaches to establish a more

comprehensive understanding of how authentic interdisciplinary learning can foster elementary students' mathematical competencies.

CONCLUSION

This study concludes that the vertical garden project-based STEM approach effectively and significantly improves the number-domain numeracy and mathematical problem-solving ability of fifth-grade students. Compared with the Direct Instruction model, the STEM approach proved significantly superior in improving numeracy with a large effect size (d=0.914), but provided a relatively comparable improvement in mathematical problem solving that was influenced by a ceiling effect. This principal finding affirms that the advantage of a learning approach is specific to the type of competency developed. Theoretically, this study contributes to enriching the study of STEM effectiveness by demonstrating its specific limits and advantages, while strengthening the framework of contextual and integrated learning. Practically, it provides an empirical basis for teachers to choose a learning approach according to the target competency and shows that abstract fraction material can be learned meaningfully through a real project. Further research is advised to use larger and more varied samples, to address the ceiling effect through equalising initial ability or instruments with a wider range, to broaden coverage to other numeracy domains and mathematics materials, and to complement written-test measurement with process assessment in order to depict students' thinking as the project unfolds.

AUTHOR CONTRIBUTIONS STATEMENT

Cucu Maryam contributed to the conceptualization of the study, methodology development, investigation, data curation, instrument development and validation, formal analysis, visualization, writing of the original draft, project administration, and correspondence with the journal. Turmudi contributed to the conceptualization of the research, methodological refinement, supervision, validation of the research design and instruments, interpretation of the findings, critical review of the manuscript, and substantive editing of the final version. Sandi Budi Irawan contributed to the conceptualization, methodology, supervision, formal analysis, validation, visualization, interpretation of the results, critical review, and manuscript editing. All authors participated in discussing the results, approved the final version of the manuscript for publication, and agreed to be accountable for all aspects of the work, ensuring the accuracy and integrity of the research.

REFERENCES

Abdurrahman, A., Maulina, H., Nurulsari, N., Sukamto, I., Umam, A. N., & Mulyana, K. M. (2023). Impacts of integrating engineering design process into STEM makerspace on renewable energy unit to foster students' system thinking skills. Heliyon, 9(4). https://doi.org/10.1016/j.heliyon.2023.e15100

Adeleke, J. O., Balogun, H. A., & Ayanwale, M. A. (2025). Assessment of content and cognitive dimensions of learners' mathematics performance. STEM Education, 5(3), 383–400. https://doi.org/10.3934/steme.2025019

Alkair, S., Ali, R., Abouhashem, A., Aledamat, R., Bhadra, J., Ahmad, Z., Sellami, A., & Al-Thani, N. J. (2023). A STEM model for engaging students in environmental sustainability programs through a problem-solving approach. Applied Environmental Education & Communication, 22(1), 13–26. https://doi.org/10.1080/1533015X.2023.2179556

Arce, E., Suárez-García, A., López-Vázquez, J. A., & Fernández-Ibáñez, M. I. (2022). Design sprint: Enhancing STEAM and engineering education through agile prototyping and testing ideas. Thinking Skills and Creativity, 44, 101039. https://doi.org/10.1016/j.tsc.2022.101039

Ardianti, S., Sulisworo, D., Pramudya, Y., & Raharjo, W. (2020). The impact of the use of STEM education approach on blended learning to improve students' critical thinking skills. Universal Journal of Educational Research, 8(3B), 24–32. https://doi.org/10.13189/ujer.2020.081503

Arık, M., & Topçu, M. S. (2022). Implementation of engineering design process in the K–12 science classrooms: Trends and issues. Research in Science Education, 52(1), 21–43. https://doi.org/10.1007/s11165-019-09912-x

Asmara, A. S., Yusuf, Y., Prawiyogi, A. G., Zonyfar, C., Alhamssyah, M. A., & Alfarid, M. N. (2026). Profiling numeracy literacy among ninth-grade students: Empirical evidence from junior secondary education. Infinity Journal, 15(1), 291–318. https://doi.org/10.22460/infinity.v15i1.p291-318

Awwad, F. (2025). Enhancing electronics courses education: Active learning strategies for undergraduate engineering students. International Journal of Engineering Pedagogy, 15(2), 42. https://doi.org/10.3991/ijep.v15i2.51739

Baran, M., Baran, M., Karakoyun, F., & Maskan, A. (2021). The influence of project-based STEM (PjBL-STEM) applications on the development of 21st-century skills. Journal of Turkish Science Education, 18(4), 798–815. https://doi.org/10.36681/tused.2021.104

Barham, A., Naccache, H., & Hasan, M. (2026). Assessing the reliability and validity of a numeracy test for pre-service mathematics teachers: Cultivating proficiency in mathematics education. Social Sciences & Humanities Open, 13, 102857. https://doi.org/10.1016/j.ssaho.2026.102857

Bhaumik, K., Reddy, S. S., Datta, A., Ismayel, G., & Sarif, B. M. (2024). Fostering higher-order thinking: Pedagogical strategies in engineering education. Journal of Engineering Education Transformations, 86–99. https://doi.org/10.16920/jeet/2024/v38i1/24177

Chistyakov, A. A., Zhdanov, S. P., Avdeeva, E. L., Dyadichenko, E. A., Kunitsyna, M. L., & Yagudina, R. I. (2023). Exploring the characteristics and effectiveness of project-based learning for science and STEAM education. Eurasia Journal of Mathematics, Science and Technology Education, 19(5), em2256. https://doi.org/10.29333/ejmste/13128

Christou, P. (2023). How to use artificial intelligence (AI) as a resource, methodological and analysis tool in qualitative research? The Qualitative Report. https://doi.org/10.46743/2160-3715/2023.6406

Djam'an, N. (2025). Examining the implementation of environmental education in the STEAM approach for sustainability. Discover Education, 4(1), 410. https://doi.org/10.1007/s44217-025-00837-4

Dumitru, D., & Halpern, D. F. (2023). Critical thinking: Creating job-proof skills for the future of work. Journal of Intelligence, 11(10). https://doi.org/10.3390/jintelligence11100194

Fauzan, A., Harisman, Y., Yerizon, Y., Suherman, S., Tasman, F., Nisa, S., Sumarwati, S., Hafizatunnisa, H., & Syaputra, H. (2024). Realistic mathematics education (RME) to improve literacy and numeracy skills of elementary school students based on teachers' experience. Infinity Journal, 13(2), 301–316. https://doi.org/10.22460/infinity.v13i2.p301-316

Geiger, V., & Schmid, M. (2024). A critical turn in numeracy education and practice. Frontiers in Education, 9. https://doi.org/10.3389/feduc.2024.1363566

Gerlich, M. (2025). AI tools in society: Impacts on cognitive offloading and the future of critical thinking. Societies, 15(1). https://doi.org/10.3390/soc15010006

Gillies, R. M. (2023). Using cooperative learning to enhance students' learning and engagement during inquiry-based science. Education Sciences, 13(12). https://doi.org/10.3390/educsci13121242

Grotlüschen, A., Desjardins, R., & Liu, H. (2020). Literacy and numeracy: Global and comparative perspectives. International Review of Education, 66(2), 127–137. https://doi.org/10.1007/s11159-020-09854-x

Grundy, L. S., & Koretsky, M. D. (2025). "More conceptual than actual": Epistemic metacognition in response to a non-numerical statics question. Journal of Engineering Education, 114(4), e70035. https://doi.org/10.1002/jee.70035

Hoogland, K. (2023). The changing nature of basic skills in numeracy. Frontiers in Education, 8. https://doi.org/10.3389/feduc.2023.1293754

Idrus, H., Rahim, S. S. A., & Zulnaidi, H. (2022). Conceptual knowledge in area measurement for primary school students: A systematic review. STEM Education, 2(1), 47. https://doi.org/10.3934/steme.2022003

Jiang, C., & Pang, Y. (2023). Enhancing design thinking in engineering students with project-based learning. Computer Applications in Engineering Education, 31(4), 814–830. https://doi.org/10.1002/cae.22608

Lazić, B. D., Knežević, J. B., & Maričić, S. M. (2021). The influence of project-based learning on student achievement in elementary mathematics education. South African Journal of Education, 41(3), 1–10. https://doi.org/10.15700/saje.v41n3a1909

Leavy, A., & Hourigan, M. (2020). Posing mathematically worthwhile problems: Developing the problem-posing skills of prospective teachers. Journal of Mathematics Teacher Education, 23(4), 341–361. https://doi.org/10.1007/s10857-018-09425-w

Lee, M. Y., & Lee, J. S. (2025). Project-based learning as a catalyst for integrated STEM education. Education Sciences, 15(7). https://doi.org/10.3390/educsci15070871

Lin, K.-Y., Wu, Y.-T., Hsu, Y.-T., & Williams, P. J. (2021). Effects of infusing the engineering design process into STEM project-based learning to develop preservice technology teachers' engineering design thinking. International Journal of STEM Education, 8(1), 1. https://doi.org/10.1186/s40594-020-00258-9

López-Meneses, E., Sirignano, F. M., Vázquez-Cano, E., & Ramírez-Hurtado, J. M. (2020). University students' digital competence in three areas of the DigComp 2.1 model: A comparative study at three European universities. Australasian Journal of Educational Technology, 36(3), 69–88. https://doi.org/10.14742/ajet.5583

Manfreda Kolar, V., & Hodnik, T. (2021). Mathematical literacy from the perspective of solving contextual problems. European Journal of Educational Research, 10(1), 467–483. https://doi.org/10.12973/eu-jer.10.1.467

Morris, D. L. (2025). Rethinking science education practices: Shifting from investigation-centric to comprehensive inquiry-based instruction. Education Sciences, 15(1). https://doi.org/10.3390/educsci15010073

Naseer, F., Tariq, R., Alshahrani, H. M., Alruwais, N., & Al-Wesabi, F. N. (2025). Project-based learning framework integrating industry collaboration to enhance student future readiness in higher education. Scientific Reports, 15(1), 24985. https://doi.org/10.1038/s41598-025-10385-4

Nguyen, T. P. L., Nguyen, T. H., & Tran, T. K. (2020). STEM education in secondary schools: Teachers' perspective towards sustainable development. Sustainability, 12(21). https://doi.org/10.3390/su12218865

Nurwijaya, S. (2024). Pengaruh pendekatan pembelajaran STEM terhadap kemampuan numerasi siswa SD di Kepulauan Aru. Pedagogy: Jurnal Pendidikan Matematika, 9(1), 56–62. https://doi.org/10.30605/pedagogy.v9i1.3604

Olivares, D., Lupiáñez, J. L., & Segovia, I. (2021). Roles and characteristics of problem solving in the mathematics curriculum: A review. International Journal of Mathematical Education in Science and Technology, 52(7), 1079–1096. https://doi.org/10.1080/0020739X.2020.1738579

Oyovwe, S. O., & Oyovwi, M. O. (2026). Unveiling the latent curriculum incidental mathematics through digital task integration in secondary education. Discover Education, 5(1), 286. https://doi.org/10.1007/s44217-026-01123-7

Pellegrini, M., Lake, C., Neitzel, A., & Slavin, R. E. (2021). Effective programs in elementary mathematics: A meta-analysis. AERA Open, 7, 2332858420986211. https://doi.org/10.1177/2332858420986211

Proshkin, V., & Astafieva, M. (2025). Implementation of a conceptual and procedural approach in university-level mathematics education using the Moodle LMS. International Journal for Technology in Mathematics Education, 32(3), 91–113. https://doi.org/10.1564/tme_v32.3.01

Raj, T., Chauhan, P., Mehrotra, R., & Sharma, M. (2022). Importance of critical thinking in education. World Journal of English Language, 12(3), 126. https://doi.org/10.5430/wjel.v12n3p126

Rehman, N., Huang, X., Mahmood, A., AlGerafi, M. A. M., & Javed, S. (2024). Project-based learning as a catalyst for 21st-century skills and student engagement in the math classroom. Heliyon, 10(23). https://doi.org/10.1016/j.heliyon.2024.e39988

Retno, R. S., Purnomo, P., Hidayat, A., & Mashfufah, A. (2025). Conceptual framework design for STEM-integrated project-based learning (PjBL-STEM) for elementary schools. Asian Education and Development Studies, 14(3), 579–604. https://doi.org/10.1108/AEDS-08-2024-0188

Reyna, V. F., & Brainerd, C. J. (2023). Numeracy, gist, literal thinking and the value of nothing in decision making. Nature Reviews Psychology, 2(7), 421–439. https://doi.org/10.1038/s44159-023-00188-7

Rivas, S. F., Saiz, C., & Ossa, C. (2022). Metacognitive strategies and development of critical thinking in higher education. Frontiers in Psychology, 13. https://doi.org/10.3389/fpsyg.2022.913219

Solihah, P. A., Kaniawati, I., Samsudin, A., & Riandi, R. (2024). Prototype of greenhouse effect for improving problem-solving skills in science, technology, engineering, and mathematics (STEM)-education for sustainable development (ESD): Literature review, bibliometric, and experiment. Indonesian Journal of Science and Technology, 9(1). https://doi.org/10.17509/ijost.v9i1.66773

Subramaniam, R. C., Morphew, J. W., Rebello, C. M., & Rebello, N. S. (2025). Presenting a STEM ways of thinking framework for engineering design-based physics problems. Physical Review Physics Education Research, 21(1), 010122. https://doi.org/10.1103/PhysRevPhysEducRes.21.010122

Syukri, M., Haya, F., Maghfirah, S., Herliana, F., Rasul, M. S., & Pratama, H. (2026). STEM-based engineering design process models in physics learning: Systematic literature review. European Journal of STEM Education, 11(1). https://doi.org/10.20897/ejsteme/17784

Szabo, Z. K., Körtesi, P., Guncaga, J., Szabo, D., & Neag, R. (2020). Examples of problem-solving strategies in mathematics education supporting the sustainability of 21st-century skills. Sustainability, 12(23). https://doi.org/10.3390/su122310113

Torres-Peña, R. C., Peña-González, D., Lara-Orozco, J. L., Ariza, E. A., & Vergara, D. (2025). Enhancing numerical thinking through problem solving: A teaching experience for third-grade mathematics. Education Sciences, 15(6). https://doi.org/10.3390/educsci15060667

Vistara, M. F., Rochmad, R., & Wijayanti, K. (2022). Systematic literature review: STEM approach through engineering design process with project-based learning model to improve

mathematical creative thinking skills. Mathematics Education Journal, 6(2), 140–156. https://doi.org/10.22219/mej.v6i2.21150

Wilson, K. (2021). Exploring the challenges and enablers of implementing a STEM project-based learning programme in a diverse junior secondary context. International Journal of Science and Mathematics Education, 19(5), 881–897. https://doi.org/10.1007/s10763-020-10103-8

Yi, S., Xu, X., Dai, J., & Hou, H. (2026). Improving elementary students' numerical operation abilities through knowledge building in China. The Journal of Educational Research, 1–19. https://doi.org/10.1080/00220671.2025.2607040

Zhu, C., Leung, C. O.-Y., Lagoudaki, E., Velho, M., Segura-Caballero, N., Jolles, D., Duffy, G., Maresch, G., Pagkratidou, M., & Klapwijk, R. (2023). Fostering spatial ability development in and for authentic STEM learning. Frontiers in Education, 8. https://doi.org/10.3389/feduc.2023.1138607