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Developing Mind Mapping-Based Pocketbook with Augmented Reality to Support Creative Thinking Skills in Pre-Service Mathematics Teachers

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ABSTRACT
Enhancing creative thinking skills (CTSs) is a critical competency for pre-service mathematics teachers, especially in responding to the demands of 21st-century learning. This study aims to develop a pocketbook based on mind mapping and supported by Augmented Reality (AR), integrated within a Project-Based Learning (PjBL) framework, to support creative thinking skills. The development process adopted the Plomp model, consisting of preliminary investigation, design, realization, testing, evaluation, revision, and implementation phases. The resulting instructional pocketbook focuses on secondary school mathematics content and includes a series of questions enhanced with AR features to support CTSs. The findings demonstrate that the developed mind mapping based pocketbook with AR effectively improves students' ability to think creatively and solve complex mathematical problems. This research contributes to the field of mathematics education by offering an innovative tool that combines visual mapping strategies, immersive technology, and active learning to better prepare future mathematics educators.

ABSTRAK
Meningkatkan keterampilan berpikir kreatif (CTSs) merupakan aspek penting bagi calon guru matematika dalam menghadapi tantangan pembelajaran abad ke-21. Penelitian ini bertujuan mengembangkan buku saku berbasis mind mapping yang didukung oleh Augmented Reality (AR) dan diintegrasikan dalam model Project-Based Learning (PjBL) guna mendukung pengembangan CTSs. Pengembangan buku ini menggunakan model Plomp yang meliputi tahap investigasi awal, desain, realisasi, pengujian, evaluasi, revisi, dan implementasi. Buku saku ini memuat materi matematika tingkat sekolah menengah dan dilengkapi dengan soal-soal serta fitur AR untuk meningkatkan daya tarik dan pemahaman konsep. Hasil penelitian menunjukkan bahwa penggunaan buku saku ini secara signifikan membantu meningkatkan CTSs siswa serta keterampilan dalam menyelesaikan masalah matematika kompleks. Dengan menggabungkan pendekatan visual, teknologi imersif, dan pembelajaran berbasis proyek, penelitian ini memberikan kontribusi inovatif dalam pendidikan matematika. Alat bantu pembelajaran ini tidak hanya meningkatkan CTSs, tetapi juga mempersiapkan calon guru matematika untuk menjadi pendidik yang adaptif dan inovatif di era digital.

INTRODUCTION

Creative thinking skills (CTSs) have emerged as one of the most essential 21st-century skills, increasingly demanded in both academic and professional domains (Kennedy & Sundberg, 2020; Wahyuningsih et al., 2025). For pre-service teachers, particularly in the field of mathematics education, fostering creative thinking is not only critical for their personal development but also fundamental for preparing students to meet complex, real-world challenges (Albay & Eisma, 2024; Bicer et al., 2022; Sevinc & Lesh, 2022). Teachers who can think creatively tend to implement more engaging instructional practices, design meaningful learning experiences, and integrate technology effectively to make learning more enjoyable and student-centered (Boom-Cárcamo et al., 2024).

Despite its importance, numerous studies have indicated that pre-service mathematics teachers often exhibit low levels of creative thinking (Baumanns & Rott, 2024; Bicer et al., 2023; Kuscu & Erdogan, 2024). Empirical data have shown that their performance in tasks such as problem formulation, innovation in digital media use, and the design of learning tools remains inadequate (Abdullah et al., 2015; Suherman & Vidákovich, 2024; Zhan et al., 2024; Meryansumayeka et al., 2025). These shortcomings are frequently attributed to a lack of diverse teaching strategies, limited exposure to creative learning models, and insufficient training in educational media development (Abdullah et al., 2016; Mustaqim et al., 2025; Nusantara et al., 2024a; Sitorus & Masrayati, 2016). Several studies have emphasized the need to address these gaps by incorporating pedagogical strategies that explicitly promote creativity and problem-solving in teacher education (Bozkurt & Tan, 2021; Kaufman & Beghetto, 2009; Kim, 2006; Nusantara et al., 2024b).

Project-Based Learning (PjBL) is a widely adopted instructional model known for promoting critical and creative thinking. Numerous studies have demonstrated that PjBL encourages learners to apply theoretical knowledge in practical, real-world scenarios while fostering collaboration, innovation, and independent learning (Kokotsaki et al., 2016; Putri et al., 2021; Cruz et al., 2022; Nollmeyer & Torres, 2022). Within mathematics education, according to Holmes and Hwang (2016), PjBL has been found effective in enhancing conceptual understanding and motivating students to engage deeply in mathematical problems (Putri et al., 2021). However, the success of PjBL implementation depends heavily on the availability of structured, supportive learning tools that facilitate project planning, idea generation, and knowledge integration.

Mind mapping, as a visual and metacognitive learning strategy, has gained recognition for its ability to organize information hierarchically, highlight connections between concepts, and support the creative process (Evans & Jeong, 2023; Chiu & Hwang, 2024;). Prior research has confirmed that mind mapping can significantly improve students' creative thinking and problem-solving skills across disciplines, including mathematics (Cendros & Gadanidis, 2020; Loc & Loc, 2020). Moreover, its application within PjBL contexts has shown promising results in helping learners scaffold their ideas and manage complex tasks more effectively.

Augmented Reality (AR) has emerged as a powerful tool in educational settings. AR overlays digital information—such as 3D objects, animations, or interactive content—onto the physical environment through mobile devices or tablets, thereby creating immersive and interactive learning experiences (Wahab et al., 2017; Medina et al., 2019; Bertrand et al., 2024; Meryansumayeka et al., 2025). Studies have highlighted AR's potential in enhancing learner engagement, visualization of abstract concepts, and retention of information (AlGerafi et al., 2023; Sutomo et al., 2025). In mathematics education, AR has been particularly useful in illustrating complex geometrical figures and abstract relationships that are otherwise difficult to conceptualize (Wang et al., 2025).

While previous studies have examined PjBL (Kokotsaki et al., 2016; Putri et al., 2021; Cruz et al., 2022; Nollmeyer & Torres, 2022, mind mapping (Cendros & Gadanidis, 2020; Loc & Loc, 2020), and AR (Medina et al., 2019; Bertrand et al., 2024) independently, there is a clear research gap in integrating all three into a single instructional tool tailored for pre-service mathematics teachers. This study offers a novel approach by combining these elements into a mind mapping-based pocketbook enhanced with AR, designed to support CTSs. The objective is to develop a mind mapping based pocketbook with AR to support CTSs among prospective teachers through the PjBL learning model.

METHOD

This study employed a research and development (R&D) approach using the Plomp model (Plomp, 2013), which is widely recognized for the systematic development and evaluation of educational tools and innovations. The model consists of five iterative phases: (1) preliminary investigation, (2) design, (3) realization/construction, (4) testing, evaluation, and revision, and (5) implementation. This approach was selected to ensure that the resulting instructional tool—namely, a mind mapping-based pocketbook enhanced with AR and integrated within a PjBL framework—was developed through a valid, practical, and effective process.

The study was conducted in the Department of Mathematics Education at Universitas Jambi, Indonesia. Participants consisted of 38 pre-service mathematics teachers enrolled in a course titled Selected Topics in Secondary School Mathematics. This course was selected due to its complex content, which demands higher order thinking and provides ample opportunities for the implementation of creative instructional strategies. A purposive sampling technique was used to select participants based on their enrollment in the course and consent to participate in the research.

The development of the mind mapping based pocketbook with AR in this study followed the Plomp model of educational design research, which includes five key phases: preliminary investigation, design, realization/construction, testing and revision, and implementation (See Figure 1). These phases were carried out iteratively to ensure the production of a valid, practical, and effective learning tool that integrates mind mapping, PjBL, and AR in a cohesive manner.

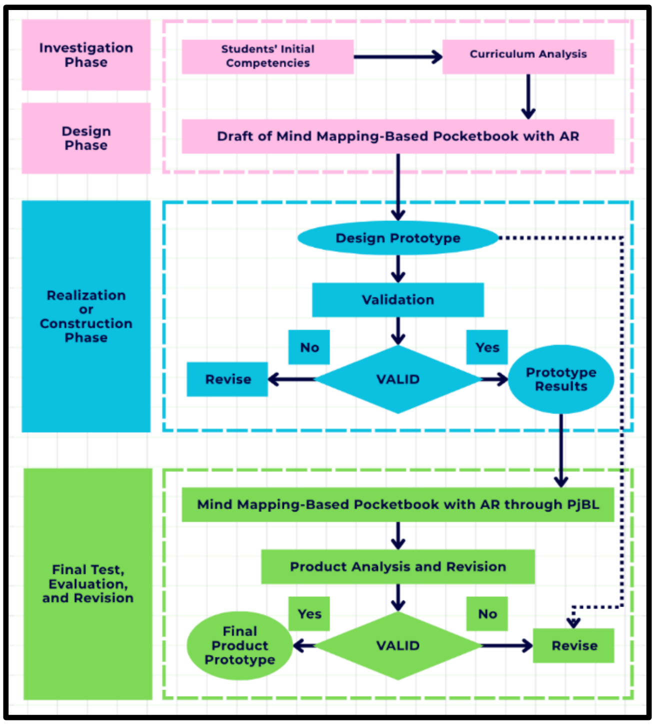


Figure 1. Research Procedure on Developing Mind Mapping Based Pocketbook with AR

Figure 1 depicts the process of developing mind mapping based pocketbooks with AR through an investigation phase, which involved comprehensive needs analysis, curriculum review, and literature study to identify problems related to the low creative thinking abilities among pre-service mathematics teachers. Following this, the design phase focused on developing the conceptual and structural framework of the pocketbook. It included the design of mind mapping templates, the integration of PjBL stages, and the planning of AR content.

In the realization/construction phase, the first prototype of the pocketbook was developed. This included content writing, graphic design, creation of mind maps, and the development of AR components using Assemblr EDU. The AR elements were linked to specific QR code embedded in the pocketbook, enabling users to access the question in the form of interactive 3D models. The prototype was then subjected to testing and revision. Expert validation through Focus Group Discussion (FGD) was conducted by experts in mathematics education to assess content, construct, language, and visual design. Feedback from the experts informed a series of revisions to enhance clarity, interactivity, and instructional effectiveness. A small group user trial was also conducted with a group of students to evaluate the practicality of the mind mapping based pocketbook with AR and identify technical or instructional issues from the user's perspective.

Finally, the implementation phase involved the application of the revised pocketbook in an actual classroom setting over several instructional sessions. Students used the pocketbook as a core learning resource during PjBL-based instruction, working individually and in groups to complete tasks and solve problems creatively. Data on student performance and engagement were collected throughout this phase to evaluate the impact of the mind mapping based pocketbook with AR on students' CTSs.

To collect valid and reliable data for this study, multiple instruments were employed, each aligned with the research objectives and designed to measure different aspects of the development and implementation process. The primary instrument was a CTSs Test, adapted from Torrance's framework, which assessed four key indicators: fluency, flexibility, originality, and elaboration. This test was administered after the intervention to evaluate changes in students' creative thinking performance. The test items were designed to reflect open-ended mathematical tasks that encouraged diverse and innovative responses on CTSs. Scoring was conducted using an analytical rubric as seen in Table 1.

Table 1. Assessment Rubric for Creative Thinking Skills

Indicator	Level 1 (Low)	Level 2 (Adequate)	Level 3 (High)	Level 4 (Very High)
Fluency *(The number of ideas expressed)*	Few responses, lacks variety of ideas (only 1 idea)	Provides 2–3 ideas, but still limited	Provides many ideas (>3) related to the question	Provides many ideas and can connect them systematically
Flexibility *(The variety of approaches used)*	Only one point of view	Includes several different points of view	Shows a variety of approaches and ways of thinking	Demonstrates multiple perspectives with innovative and varied solutions
Originality *(The uniqueness of the ideas presented)*	Common, predictable responses	Somewhat unique responses	Unique and rarely found responses	Highly original, creative, and unexpected ideas
Elaboration *(The detail and depth of the explanation)*	Short answer, no explanation	Basic explanation, but not detailed	Clear explanation with examples and reasoning	In-depth, detailed explanation with reasoning and step-by-step description

Table 1 outlines a rubric for assessing creative thinking skills based on four indicators: fluency, flexibility, originality, and elaboration. Each indicator is rated on a four-level scale, from low (Level 1) to very high (Level 4). Fluency refers to the number of ideas generated, progressing from a single idea to multiple, systematically connected ideas. Flexibility assesses the range of perspectives, from a single viewpoint to diverse and innovative approaches. Originality measures the uniqueness of ideas, ranging from common to highly original and unexpected responses. Elaboration evaluates the depth of explanation, from brief and undeveloped answers to detailed, reasoned, and well-structured explanations. This rubric provides a clear framework for evaluating the development of students' creative thinking in a structured and measurable way.

To assess the validity of the developed pocketbook, an expert validation sheet was used. This instrument was completed by subject matter experts in mathematics education. The experts reviewed the content, construct, language, and visual design of the mind mapping based pocketbook with AR. Their feedback was essential in guiding revisions during the testing phase.

In addition, a practicality questionnaire was administered to students and lecturers after the initial implementation. This instrument captured user perceptions of the ease of use, accessibility, content clarity, visual quality, and overall usefulness of the pocketbook in supporting learning through PjBL. The questionnaire used a Likert scale format and was analyzed using descriptive statistics.

To gain deeper insights into how the pocketbook influenced student learning and engagement, qualitative data were collected through classroom observations and semi-structured interviews. Observations focused on student interactions, engagement levels, and use of the AR features during project work. Interviews were conducted with selected students and the course instructor to capture their perceptions of the learning experience, challenges encountered, and suggestions for improvement. All qualitative data were audio-recorded, transcribed, and thematically analyzed to complement the quantitative findings.

The data analysis in this study combined both quantitative and qualitative approaches to evaluate the validity, practicality, and effectiveness of the developed mind mapping-based pocketbook with AR. Validity was assessed through expert judgment using a structured questionnaire, with results analyzed quantitatively to ensure the content, construct, language, and visual design; qualitative feedback from experts further supported the validity by offering suggestions for refinement and improvement. Practicality was determined through student and lecturer responses collected via questionnaires and semi-structured interviews, revealing that the pocketbook was easy to use, engaging, and supportive of student learning in a project-based environment. Effectiveness was measured quantitatively through a CTSs test administered after the intervention, with student responses evaluated against four key indicators—fluency, flexibility, originality, and elaboration—using a standardized rubric.

RESULTS AND DISCUSSIONS

The results of the study are descriptions based on the types of data collected according to research methods based on R&D Plomp's model.

In this R&D study, the first phase of Plomp's model is the preliminary investigation. During this stage, the researchers conducted several preparatory activities, including the analysis of students' initial competencies and a curriculum review, to determine the mathematical content that would be the focus of the instructional material to be developed.

Students' Initial Competencies Analysis

As part of the initial stage of the R&D process using the Plomp model, an analysis of students' initial competencies was conducted to ensure the instructional material would be developed in alignment with students' existing knowledge and skill levels. This analysis involved students enrolled in the Selected Topics in Mathematics course across three classes (R001, R002, and R003). A group of participants was purposively selected to be involved in the product evaluation stages: one-to-one, small group, and field testing. The purpose of this selection was not only to identify suitable subjects but also to clarify the research procedures and plan the implementation timeline for each development phase.

The one-to-one phase involved three students from R001 who provided direct individual feedback on the clarity and feasibility of the early draft. The small group phase included six students from R002 who worked collaboratively, offering input on the usability and effectiveness of the prototype in a more interactive setting. The field test was conducted with the entire R003 class to evaluate the learning material in a real instructional context. Through this staged involvement, researchers gained valuable insights into how students interpreted, interacted with, and responded to the learning materials, thus allowing for informed revisions that targeted both pedagogical effectiveness and learner engagement.

Curriculum Analysis

The present study analyzes mathematics content based on Indonesia's Kurikulum Merdeka (Independent Curriculum), which structures secondary school mathematics into four key domains: Numbers, Algebra, Geometry and Measurement, and Data Analysis and Uncertainty. By the end of Phase D (typically Grade 9), students are expected to master essential mathematical operations with rational numbers, including integer exponents and factorization, apply concepts such as proportional reasoning and rates of change, and recognize patterns in numerical and object arrangements. They also begin to understand irrational numbers as part of the extended number system.

In the algebra strand, students are expected to model real-life situations using algebraic expressions, transform algebraic forms using standard properties, and solve both linear equations and inequalities in one variable, as well as systems of linear equations in two variables. Their learning extends to understanding and representing functions and solving contextual problems through these concepts. In the geometry domain, students explore relationships among angles, properties of congruence and similarity, the Pythagorean theorem, and geometric transformations on the Cartesian plane. For data and uncertainty, students learn data representation techniques, descriptive statistics (mean, median, mode, range), sampling strategies, and basic probability, including expected values from simple experiments.

Although the curriculum spans a broad range of topics, this mind mapping based pocketbook with AR specifically targets the development of instructional materials focused on six core mathematical topics at the secondary school level. These include: (1) Integer Exponents, Fractional Powers, and Roots; (2) Algebraic Operations on Radicals and Rationalizing Denominators; (3) Linear Equations in Two Variables; (4) Quadratic Equations; (5) Quadratic Functions; and (6) Points, Lines, Planes, and Angles. These topics are selected to align with key curriculum competencies while providing structured content that supports deeper conceptual understanding and mathematical reasoning at the middle school level.

In the design phase of this research, the development team created a prototype instructional instrument in the form of a pocketbook, which includes components such as mind mapping, instructional content, and a series of AR assisted-practice questions (See Figure 1). The pocketbook addresses six core mathematics topics commonly taught at the secondary school (SMP) level: (1) Integer Exponents, Fractional Powers, and Roots; (2) Algebraic Operations on Radicals and Rationalizing Denominators; (3) Linear Equations in Two Variables; (4) Quadratic Equations; (5) Quadratic Functions; and (6) Points, Lines, Planes, and Angles. The first version of the pocketbook, referred to as Prototype 1, was designed to undergo evaluation through expert review/FGD, one-to-one testing, small group trials, and field testing.

The development process included thorough review and refinement of the pocketbook in terms of content accuracy, construct validity, linguistic clarity, and visual design. We collaborated to revise and improve aspects such as terminology, grammar, and layout design as needed.

Figure 2. A Display of Mind-Mapping Based Pocketbook with AR

Figure 2 depicts the cover of the mind mapping based pocketbook with AR. The content of the pocketbook was carefully structured to reflect the six mathematics topics using a blend of mind mapping, instructional explanations, worked examples, and AR-assisted Higher-Order Thinking Skills (HOTs) or Program for International Student Assessment (PISA)-oriented problems. The use of mind maps at the beginning of each chapter aligns with Ausubel's theory of meaningful learning, facilitating the integration of new information with prior knowledge. Instructional explanations and worked examples are included to reduce cognitive load (Torre at al., 2023) and support schema development, particularly for novice learners. Summary sections enhance metacognitive reflection (Moritz & Lysaker, 2018), reinforcing key concepts. At the end of each chapter, AR-based questions are provided to encourage higher-order thinking and application in real-life contexts, consistent with Vygotsky's social constructivism and the revised Bloom's Taxonomy (Krathwohl, 2002). This design also promotes transfer of learning across contexts (Van den Heuvel-Panhuizen & Drijvers, 2020), making the pocketbook a pedagogically sound tool for mathematics education.

The visual presentation of the book was designed to be modern and appealing. The cover features a bold, clean layout with dominant maroon and white colors. The title "KAPITA SELEKTA MATEMATIKA" is prominently displayed, with "MATEMATIKA" in bright red for emphasis. Key visual elements include: (1) 3D geometric shapes (prisms and cubes) representing geometry; (2) colored bar and line graphs representing data analysis and functional relationships; (3) mathematical formulas on a chalkboard symbolizing algebra and problem-solving; and (4) game elements such as dice, reflecting probability and practical applications of mathematics. A dynamic circular graphic is positioned at the bottom left, while the logos of the Ministry of Education and Universitas Jambi are placed in the top left corner to add formality. The bottom right includes a red circle labeled "SMP" to indicate the educational level.

During the realization/construction phase, the developed product—Prototype 1—was subjected to parallel testing that included expert review through a FGD, one-to-one testing, and small group trials. These steps were aimed at assessing and refining the quality of the instructional material from various perspectives, including content, structure, language, and visual design.

Expert Review through FGD

Prototype 1 underwent expert validation through an FGD involving four university lecturers specializing in mathematics education. These experts, from Universitas Sriwijaya (HR), Universitas PGRI Yogyakarta (LS), Universitas Tridinanti Palembang (DR), and STKIP Muhammadiyah OKU Timur (FY), evaluated the prototype in terms of its content accuracy, conceptual structure, linguistic clarity, and visual appeal.

The validation process was conducted via an online platform, using a dedicated WhatsApp group for communication. The prototype and validation sheets were distributed to experts for a one-week review period. Feedback was then shared both in written form and orally during scheduled virtual discussions. Table 2 summarizes the comments and suggestions provided by the validators.

Table 2. Summary of Expert Feedback on Prototype of Mind Mapping Based Pocketbook

Name of Experts	Feedback
HS	Refining learning objectives, improving access to AR content, and standardizing mind map orientation
LS	Categorizing question difficulty, updating the book title to reflect its mind mapping focus, refining cover illustrations, and ensuring logo and layout consistency
DR	Improving image alignment, adding page numbers, figure/table lists, and including clearer mind mapping layouts and learning objectives in each chapter
FY	Appreciating the contextual problems and diverse question types but suggested enhancing accessibility by including non-AR versions of practice items and improving text formatting

Table 2 summarizes expert feedback on the mind mapping-based pocketbook prototype. Suggestions included refining learning objectives, improving AR content access, standardizing mind map layouts, and enhancing visual elements such as cover design, image alignment, and formatting. Experts also recommended categorizing question difficulty, adding non-AR alternatives, and ensuring consistency in layout and structure. Overall, the feedback supports improving clarity, accessibility, and instructional design.

The one-to-one testing phase involved three students from Class R001—CS, RJ, and IA—representing varying academic abilities based on teachers' daily score. The session was conducted virtually via Zoom to ensure accessible and collaborative interaction. Students were guided through each chapter using a walkthrough approach and asked to provide feedback on content, structure, language, and visual design aspects.

Students generally responded positively to the prototype, particularly praising its comprehensive content, clarity of explanations, and the use of mind mapping, which they found helpful for grasping key mathematical concepts quickly. They also appreciated the contextualized examples and visually consistent themes, noting that the red design motif lent the material a professional feel.

However, students also noted several technical issues. The most prominent concern was the readability of some mind maps, which appeared blurry even when zoomed in. Additionally, students faced difficulties accessing AR-based practice problems using a single device. They recommended including QR codes as a secondary access method rather than the sole option.

Students proposed digitizing unclear mind maps to improve clarity and suggested a more consistent layout, including spacing adjustments for better readability. They also requested that all practice questions be visible in the book, not just accessible through AR, to ensure usability across devices. Feedback and Suggestions from the students are tabulated in Table 3.

Table 3. Summary of Students' Feedback and Suggestions

Aspect	Feedback	Suggestion
Mind Mapping	- Helpful for understanding the materials - Innovative visual integration	- Some diagrams/figures are blurry - Recommend digital versions for clarity
Design and Theme	- Appealing visuals - Consistent red theme	- Choose one main mind map per chapter - Link additional ones via QR code
Practice Questions	- Comprehensive material - Well-explained examples	- Issues with single-device access - Include printed questions with optional QR
Accessibility	- Easy to access some links	- AR-only access limits usability
Text Formatting	- Clear structure overall	- Improve spacing for readability

The feedback from both experts and students from the Table 3 informed key revisions to Prototype 1. Improvements were made to enrich content depth, enhance logical sequencing (construct), refine linguistic accuracy, and optimize layout and accessibility. Suggestions regarding mind map resolution, practice question accessibility, and formatting consistency were prioritized to increase readability and learning effectiveness. Quantitative validation was performed using a Likert scale across four dimensions: content, construct, language, and appearance.

Table 4. Quantitative Validation Results

Aspect	Score (%)	Category	Notes
Content	83%	Fairly valid	Minor revisions suggested
Construct	84%	Fairly valid	Logical flow to be improved
Language	84%	Fairly valid	Minor linguistic adjustments
Appearance	85%	Fairly valid	Layout and clarity to refine

The quantitative validation results presented in Table 4 indicate that the developed instructional material demonstrates an overall level of "fairly valid" across all assessed aspects: content, construct, language, and appearance. Specifically, the content validity received a score of 83%, suggesting that the material adequately reflects the intended curriculum, with only minor revisions recommended to enhance alignment. The construct validity scored 84%, indicating that while the logical structure is mostly sound, improvements in coherence and flow could strengthen the material's effectiveness. Language also scored 84%, implying that the instructional text is generally clear, though minor linguistic refinements are advised for greater clarity and precision. The highest score was in the appearance aspect at 85%, showing that the visual layout is functional, but slight enhancements in design and presentation may improve usability. These findings collectively suggest that the material is appropriate for classroom use following targeted revisions.

Based on these findings, the pocketbook was deemed suitable for further testing, with several refinements needed to optimize its usability and instructional impact. The next phase will involve small group trials to evaluate the practicality of the pocketbook in actual learning environments. Students will be asked to engage with the materials in the context of PjBL, followed by questionnaires to assess the book's effectiveness, clarity, and ease of use. Insights from this phase will support final revisions before broader implementation.

Small Group Trials

The small group trials were conducted involving nine undergraduate students with varied academic abilities to assess and provide feedback on the mind mapping-based pocketbook. This phase was conducted virtually via Zoom, facilitating remote access and enabling collaborative discussions.

During the session, students were asked to read each chapter of the developed pocketbook, which integrates mind mapping, core concepts, example problems, and AR-based exercises accessible via walkthrough features. This multimodal approach aimed to support self-directed learning, enhance visual conceptualization, and provide an interactive learning experience.

Participants were also invited to share their reflections and feedback based on their experiences using the pocketbook. The evaluation focused on three key dimensions: 1) content relevance; 2) ease of use; and 3) students' engagement. The insights gathered from student feedback are summarized in Table 5.

Table 5. Summary of Student Feedback from the Small Group During Interview

Aspect	Feedback
Language Clarity and Comprehension	Most students reported that the language used in the pocketbook was clear and easy to understand. However, several students noted the presence of minor typographical errors and ineffective phrasing in certain practice problems. While these issues did not hinder overall comprehension, they suggest a need for linguistic refinement to ensure optimal readability.
Visual Aid Relevance and Effectiveness	Visual elements, particularly those in the mind maps and practice questions, were generally viewed as beneficial for conceptual understanding. Students found the mind maps to be creative and informative, aiding the retention of complex concepts. However, some visuals were flagged as inconsistent with the question context, such as images that did not match real-life scenarios described in the problems (e.g., a garden fence illustrated as a house fence). Additional suggestions included improving layout consistency and supplementing images with relevant contextual details (e.g., object dimensions or labels) to enhance clarity.

Aspect	Feedback
Problem Difficulty Level	Students acknowledged that the problems varied in difficulty—from basic to more complex questions requiring advanced reasoning. Although some found the higher-order problems challenging, the integrated materials, mind maps, and worked examples within the pocketbook were deemed helpful in facilitating problem-solving and review.
Impressions	Students expressed overall positive perceptions of the pocketbook, describing it as engaging, innovative, and pedagogically valuable. The inclusion of AR-based exercises was highlighted as a novel feature that enhanced visualization and learning efficiency. Nevertheless, recommendations were made to ensure consistency between AR content and illustrations in the printed book for a smoother user experience.

Based on student feedback from the small group interviews (Table 5), it indicates that the pocketbook was generally well received. Students found the language clear, though minor typographical and phrasing issues were noted. Visual aids, particularly mind maps, were considered effective, but some inconsistencies between images and contextual problems were identified. The variation in problem difficulty was appreciated, with students valuing the support provided through worked examples and visual summaries. Overall, the pocketbook was viewed as engaging and innovative, especially with the integration of AR features, though suggestions were made to improve consistency between AR content and printed visuals.

The practicality of the pocketbook was further assessed using a quantitative Likert-scale questionnaire, evaluating the same three core dimensions. The results are presented in Table 6.

Table 6. Practical Assessment of the Prototyping the Mind Mapping Based Pocketbook

Dimensions	Score (%)	Category	Interpretation
Content Relevance	83%	Highly Practical	Usable without revisions
Ease of use	79%	Moderately Practical	Useable with minor adjustments
Student Engagement	84%	Highly Practical	Usable without revisions

Table 6 indicates that the pocketbook demonstrates a high degree of practicality overall, particularly in terms of content alignment and student engagement. The content relevance score (83%) suggests strong compatibility with course objectives, particularly in enhancing students' understanding of Selected Topics in Mathematics. The ease-of-use dimension (79%)—while approaching the "highly practical" threshold—indicates room for minor improvements, particularly concerning: 1) Correction of typographical and grammatical issues; 2) Refinement of images and their alignment with question contexts; 3) Improved layout for better aesthetic and navigational quality; and 4) Simplification of complex or ambiguous sentences. These refinements are expected to further improve usability and user satisfaction, particularly in supporting independent learning. The highest score was recorded in the student engagement dimension (84%), underscoring the book's effectiveness in promoting active learning. Features such as mind mapping and AR integration were considered motivating and conducive to creative thinking. No revisions are deemed necessary in this dimension.

Following the small group trial, revisions will be focused on improving usability, especially in language precision, layout, and image clarity. Once completed, the revised pocketbook will proceed to the large-scale field test phase, involving its use in broader instructional settings.

In the Test, Evaluation, and Revision phase, the final prototype of the pocketbook was implemented and tested within a classroom setting using the Project-Based Learning (PjBL) model. All activities in this phase—ranging from classroom instruction and product development to exhibition, reflection, and final evaluation—were systematically designed and executed in accordance with the six core stages of the PjBL framework: (1) determining basic questions, (2) designing project planning, (3) arranging a schedule, (4) monitoring and evaluating students and project progress, (5) testing results, and (6) evaluation of experience. This alignment was intended to ensure a pedagogical flow that supports inquiry, collaboration, creativity, and reflective learning, which are essential for developing skills needed in mathematics education.

The implementation of PjBL began with identifying essential questions that would guide students throughout the project. The instructional design was centered on two fundamental inquiries: (1) How can complex mathematical concepts be represented visually to enhance comprehension? (2) How can creative tools such as mind mapping and AR support students in developing CTSs?. These questions served not only to stimulate students' curiosity but also to anchor their exploration in authentic mathematical problems relevant to secondary school curricula. By rooting the project in real-world classroom challenges, the learning process became both meaningful and applicable.

Following the formulation of guiding questions, the instructor facilitated a structured planning session. Students were introduced to the project's objectives, expected outcomes, and the assessment rubrics. They were instructed to create mathematical mind maps on selected topics, including integer exponents, radical and fractional forms, linear and quadratic equations, quadratic functions, and geometric constructs such as points, lines, and angles. Each group was tasked with designing a mind map that visually communicated their understanding of these concepts and included at least one HOTS or PISA-like problem to be enhanced through AR. The use of AR was intended to increase engagement and interactivity, further deepening students' cognitive involvement. The planning stage also included guidelines for logical organization, clarity of content, linguistic precision, and visual appeal, ensuring the final product met academic and communicative standards.

A detailed project timeline was developed collaboratively between the instructor and the students. Over the course of one week, students were given time to conceptualize, draft, and finalize their mind maps. The schedule allocated specific days for content development, visual design, peer consultation, and integration of AR components. Regular check-ins were scheduled to provide formative feedback and ensure that the project remained on track. The structured timeframe balanced independent inquiry and collaborative learning, allowing students to experience authentic project management while honing their academic skills.

Throughout the mind mapping process, the instructor adopted a formative evaluation approach to monitor student progress. Group activities were closely observed, with the instructor providing scaffolding where necessary. Peer feedback was encouraged during in-class consultations, which helped students refine their work before the final presentation. Assessment criteria focused on the accuracy of mathematical content, logical structure of the mind map, language appropriateness, and overall creativity. Furthermore, students demonstrated their problem-design capabilities by incorporating original HOTs/PISA problems, which were later evaluated for cognitive complexity and clarity. By maintaining consistent engagement, the instructor ensured that the learning process was both reflective and iterative, in line with the six stages of PjBL.

The culmination of the project was marked by a mind mapping exhibition, where students presented their final products to peers and faculty members. This exhibition functioned as both a formative assessment and an opportunity for peer learning. Each group explained their mind map, discussed their problem design, and demonstrated how AR was utilized to enhance understanding. During the exhibition, an observer rotation system was employed, allowing students to engage with other groups' work, provide feedback, and evaluate presentations using a star-based appreciation system. The three groups receiving the highest number of stars were recognized and invited to re-present their work for deeper discussion. This public sharing not only reinforced content mastery but also developed students' communication and critical reflection skills.

Following the exhibition and testing phase, a structured reflection activity was conducted. Students completed an online evaluation form that allowed them to assess their own and others' mind maps based on predefined quality indicators. Students were encouraged to provide constructive feedback, identifying strengths (tops) and areas for improvement (tips). The instructor facilitated an open discussion to gather qualitative insights into students' experiences throughout the project. Responses indicated that students found the process engaging and intellectually stimulating, with appreciation for the visual and collaborative aspects of the learning design.

The reflections underscored those students not only deepened their understanding of mathematics but also developed skills in project management, teamwork, and creative communication—core competencies in 21st-century learning. A post-test was administered to assess the development of students' CTSs. The test measured four dimensions: fluency, flexibility, elaboration, and originality. One item, for instance, asked students to determine the area of irregularly shaped leaves using innovative estimation methods (See Figure 3).

CONTEXT: TYPES OF LEAVES

The image below shows three types of leaves: papaya leaf, teak leaf, and cassava leaf.

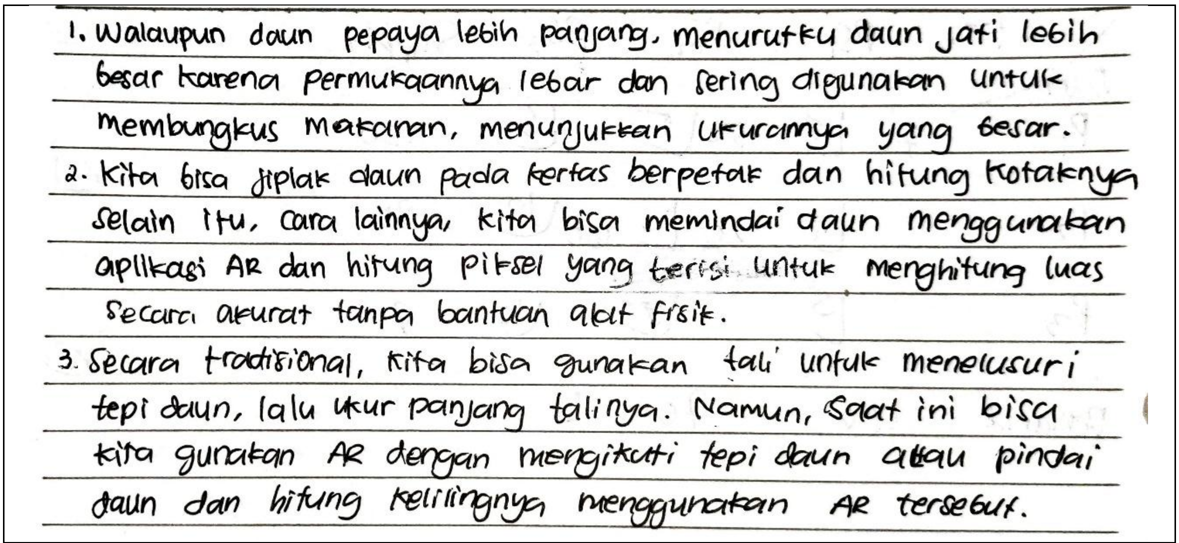
Question 1.
Among the three leaves, which one has the largest area? Explain your answer clearly.
Question 2.
How would you measure or estimate the area of the papaya leaf? Explain your reasoning.
Question 3.
How would you measure or estimate the perimeter of the papaya leaf? Explain your reasoning.

Scan the barcode to help you visualize the leaves more clearly

https://asblr.com/YElc3m

Figure 3. Creative Thingking Test Give to Students with Types of Leaves Context

Figure 3 presents a CTSs task in which students are shown three different types of leaves: papaya, teak, and cassava. Students are asked to determine which leaf has the largest area, followed by estimating the area and the perimeter of the papaya leaf. The task encourages visual comparison and spatial reasoning, guiding students to apply estimation strategies based on observed dimensions. Each problem is supported by AR features that allow students to visualize the leaves in 3D, enhancing their ability to make accurate estimations and deepening their conceptual understanding through interactive learning. Figure 4 is one example of a solution provided by a student for a question assessing creative thinking skills using the context of different types of leaves.


1. Walaupun daun pepaya lebih panjang. menurutku daun jati lebih besar karena permukaannya lebar dan sering digunakan untuk membungkus makanan, menunjukkan ukurannya yang besar.
2. Kita bisa jiplak daun pada kertas berpetak dan hitung kotaknya selain itu, cara lainnya, kita bisa memindai daun menggunakan aplikasi AR dan hitung piksel yang terisi untuk menghitung luas secara akurat tanpa bantuan alat fisik.
3. Secara tradisional, kita bisa gunakan tali untuk menelusuri tepi daun, lalu ukur panjang talinya. Namun, saat ini bisa kita gunakan AR dengan mengikuti tepi daun atau pindai daun dan hitung kelilingnya menggunakan AR tersebut.

English version

1. *Although papaya leaves are longer, I think teak leaves are larger because their surface area is wider and they are often used to wrap food, which indicates their large size.*
2. *We can trace the leaf onto graph paper and count the squares. Alternatively, we can scan the leaf using an AR application and count the filled pixels to accurately calculate the area without using physical tools.*
3. *Traditionally, we can use a string to trace the edge of the leaf, then measure the length of the string. However, nowadays we can use AR to follow the leaf's edge or scan the leaf and calculate its perimeter using the AR tool.*

Figure 4. One example of a student's solution demonstrating creative thinking skills using the context of different types of leaves

Figure 4 depicts the student's answers demonstrate a strong level of creative thinking through several key aspects. In response to question 1, the student goes beyond simply observing the length of the leaves by considering additional characteristics such as surface area and practical use (wrapping food). This shows the student's ability to analyze and compare objects from multiple perspectives, reflecting critical observation and conceptual connection skills. For question 2, the student proposes two distinct methods for measuring leaf area: a traditional approach using graph paper and a modern technological solution involving an AR application. This dual-method approach highlights innovation and adaptability in problem-solving by integrating both analog and digital techniques. In question 3, the student similarly combines a conventional method (using a string to measure perimeter) with a digital alternative (AR scanning), demonstrating flexibility and openness to technology as a tool for enhancing accuracy and efficiency. Overall, the student exhibits analytical thinking, problem-solving creativity, and the ability to apply technology innovatively in practical contexts.

Student responses reflected a variety of problem-solving approaches, including geometric breakdown methods and hands-on techniques such as using string for measurement. These findings highlight students' progress in applying creative thinking skills to mathematical problems. Table 7 presents a categorization of student answers along with their corresponding scores, based on specific indicators of creative thinking ability.

Table 7. Analysis of CTSs from Students' Answers

Question	Creativity Level	Sample Answer	Assessment Explanation
1. Among the three leaves, which one has the largest area?	Level 1 (Low)	*"The teak leaf is the largest."*	Short answer, no explanation (Fluency 1, Elaboration 1)
	Level 2 (Moderate)	*"Papaya leaves are usually big, but I have also seen large cassava leaves."*	Two ideas, some variation (Fluency 2, Flexibility 2)
	Level 3 (High)	*"The teak leaf looks wider, while the papaya leaf is longer but narrower."*	Clear reasoning and comparison (Elaboration 3, Flexibility 3)
	Level 4 (Very High)	*"Although the papaya leaf is longer, I think the teak leaf is largest because of its wide surface and it is often used to wrap food, indicating its large size."*	Detailed explanation with logic and unique context (Originality 4, Elaboration 4)
2. How would you measure or estimate the area of the papaya leaf?	Level 1 (Low)	*"Use a ruler."*	Simple answer (Fluency 1)
	Level 2 (Moderate)	*"Trace the leaf on grid paper and count the squares."*	Simple but somewhat varied method (Flexibility 2)
	Level 3 (High)	*"Divide the leaf into simple shapes like triangles and rectangles, calculate each area, then add them."*	Logical, structured approach (Elaboration 3, Flexibility 3)
	Level 4 (Very High)	*"Scan the leaf using a computer app and count the filled pixels to calculate the area accurately without physical tools."*	Innovative and creative use of technology (Originality 4, Elaboration 4)
3. How would you measure or estimate the perimeter of the	Level 1 (Low)	*"Measure with a ruler."*	Simple answer (Fluency 1)
	Level 2 (Moderate)	*"Use a string to trace the leaf edge, then measure the string."*	Practical and varied method (Flexibility 2)
	Level 3 (High)	*"Trace the leaf outline on transparent paper, then measure the outline with a ruler."*	Systematic approach (Elaboration 3)

Question	Creativity Level	Sample Answer	Assessment Explanation
papaya leaf?	Level 4 (Very High)	*"Use a digital measuring tool that follows the leaf contour or scan the leaf and calculate the perimeter using software."*	Creative technology-based method (Originality 4)

The analysis of students' CTSs reveals a clear progression in the depth and complexity of responses across the assessed questions (See Table 7). At the lowest creativity level, answers tend to be brief and lack explanation, reflecting limited elaboration and fluency. For example, many students simply identify which leaf is largest without justification or suggesting basic measurement tools without detailing procedures.

As the creativity level increases, students demonstrate greater flexibility and elaboration by providing comparative reasoning, considering multiple perspectives, and outlining more systematic approaches to estimate area and perimeter. This progression illustrates how students move beyond rote answers to incorporate analytical thinking and practical strategies. At the highest creativity levels, responses showcase originality and innovative thinking, often integrating technology and real-world contexts. Students at this level not only offer detailed logical explanations but also propose modern methods such as digital scanning and software-based calculations to improve accuracy and efficiency. According to Chiu and Hwang (2024) and Sutomo et al. (2025), creative thinking involves the ability to generate ideas that are both novel and useful, combining flexibility and originality to solve problems effectively. Furthermore, Zaremohzzabieh (2025) emphasizes that creative problem-solving is marked by the capacity to consider multiple perspectives and utilize diverse strategies, including technological tools, to enhance outcomes.

These findings highlight the importance of encouraging diverse problem-solving approaches and fostering creative use of resources in science education. The rubric-based assessment effectively captures variations in fluency, flexibility, elaboration, and originality, providing valuable insights for educators aiming to enhance students' CTSs.

The students' responses were subsequently analyzed and categorized according to their levels of CTSs. This detailed evaluation allowed for the identification of varying degrees of problem-solving skills demonstrated by students, providing valuable insights into their creative thinking development as seen in Table 8.

Table 8. Students' Creative Thingking Skills

Interval	Category	Number of Students
57-75	Very High	6
38-56	High	24
19-37	Moderate	8
1-18	Low	0

Table 8 illustrates the distribution of students' creative thinking abilities based on their post-test scores, categorized into four performance intervals: Very High, High, Moderate, and Very Low. Many students scored within the "High" category (24 students), while 6 students achieved the highest "Very High" category. Only 8 students fell into the "Moderate" category, and notably, no students were classified as "Low."

This distribution suggests a substantial improvement in students' CTSs after the instructional intervention. The increase in students scoring at higher categories reflects the effectiveness of the teaching model applied, likely fostering enhanced problem-solving and CTSs. The absence of students in the "Low" category post-intervention indicates that the learning process successfully supported by the designed pocketbook even the lower-performing students to improve. Overall, the data demonstrates that the pedagogical approach used was impactful in elevating CTSs across the student cohort. The development of a mind mapping-based pocketbook enhanced with AR within a PjBL framework has shown significant potential in supporting CTSs among pre-service mathematics teachers. This study demonstrated how the integration of visual learning tools and digital interactivity can serve as cognitive scaffolds to promote the development of fluency, flexibility, elaboration, and originality—dimensions critical to creative thinking (Kennedy & Sundberg, 2020; Bicer et al., 2022; Evans & Jeong, 2023; Wahyuningsih et al., 2025). By grounding the intervention in real-world classroom practices, the pocketbook helped bridge theoretical mathematical concepts with practical, innovative problem-solving tasks.

Mind mapping, as a visual-metacognitive strategy, supported students in organizing and connecting mathematical ideas meaningfully. The structured representations helped learners synthesize abstract content while facilitating the planning and articulation of complex problems, confirming prior findings that visual tools can enhance creativity in mathematics education (Loc & Loc, 2020; Chiu & Hwang, 2024). When combined with AR features, the pocketbook provided multisensory learning experiences that helped students conceptualize mathematical phenomena more effectively. These results echo earlier studies indicating that AR enhances visualization and student engagement in mathematics by making abstract content more concrete and interactive (Medina et al., 2019; AlGerafi et al., 2023; Bertrand et al., 2024).

The implementation of this pocketbook within the PjBL model not only encouraged independent inquiry and collaboration but also empowered students to create original HOTS and PISA-oriented problems. This outcome is particularly significant considering earlier research that identified limited creativity among pre-service mathematics teachers due to insufficient exposure to innovative pedagogies and technological tools (Sitorus & Masrayati, 2016; Baumanns & Rott, 2024; Kuscu & Erdogan, 2024). By addressing this gap through an integrated instructional design, the pocketbook contributed to improving students' problem formulation skills and fostering pedagogical creativity—essential competencies for future mathematics educators (Kim, 2006; Bozkurt & Tan, 2021; Boom-Cárcamo et al., 2024; Meryansumayeka et al., 2025).

Nevertheless, several limitations emerged. The pocketbook's reliance on AR requires digital infrastructure, which may not be equitably accessible to all learners. Additionally, some students found it challenging to balance detail and clarity in their mind maps, suggesting a need for more structured guidance on visual literacy. The content scope was also limited to selected mathematical topics, restricting broader curricular application without adaptation. Moreover, the short intervention period limited insights into the long-term development of CTSs. Addressing these issues in future research—by extending implementation time, expanding content scope, and developing offline-accessible AR—will strengthen the applicability and impact of such tools in diverse educational contexts. Despite these constraints, the pocketbook represents a valuable innovation for integrating visual, interactive, and project-based approaches to enhance creative thinking in mathematics education.

CONCLUSIONS

The development of a mind mapping-based pocketbook enhanced with Augmented Reality (AR) within the framework of Project-Based Learning (PjBL) effectively supports the enhancement of Creative Thinking Skills (CTSs) among prospective mathematics teachers. This pocketbook facilitates conceptual understanding through visual representations and interactive digital features, while also encouraging students to design innovative and contextually relevant solutions through project-based tasks. The quantitative results indicate a notable increase in students' CTSs, with the majority demonstrating high levels of creativity—24 students classified as "High" and 6 students reaching "Very High" creativity categories. This improvement reflects the pocketbook's success in fostering fluency, flexible, elaborate, and original thinking. The integration of mind mapping, AR, and PjBL into a single instructional tool successfully addresses existing pedagogical gaps in teacher education. However, the use of this pocketbook still presents certain limitations, such as technical constraints in accessing AR content and the need for more explicit visual guidance. Future studies should aim to address these limitations by improving the accessibility of AR features and exploring the tool's effectiveness across diverse educational contexts and long-term instructional practices.

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