International Journal of Learning, Teaching and Educational Research
Vol. 25, No. 3, pp. 162-193, March 2026
https://doi.org/10.26803/ijlter.25.3.8
Received Dec 30, 2025; Revised Feb 19, 2026; Accepted Feb 20, 2026

Enhancing Mathematical Motivation, Problem-Solving, and Cognitive Engagement of Pre-Service Teachers: A Metaverse-Based Adaptive Gamification Research and Development Study

Erna Yayuk*, Daroe Iswatiningsih and Agung Deddiliawan Ismail
University Muhammadiyah of Malang,
East Java, Indonesia

Abstract. This study aimed to develop and evaluate a metaverse-based adaptive gamified learning game to enhance mathematical motivation, problem-solving skills, and cognitive engagement of teacher education students. The research specifically sought to produce a valid, practical, and effective learning system that addresses low motivation, mathematics anxiety, and limited higher-order thinking skills commonly found in teacher education. Using a research and development (R&D) approach with a 4D model (define, design, develop, disseminate), the study integrated immersive digital environments with adaptive gamification strategies. The adaptive mechanism personalizes learning by dynamically adjusting task difficulty, feedback, and learning pathways based on students' performance and progression. The learning content focuses on core elementary mathematics topics, particularly geometry and basic problem-solving concepts. The system was implemented over a six-week intervention period and evaluated using a quasi-experimental one-group pretest–posttest design involving 60 teacher education students. Data were collected through expert validation, black box testing, practicality testing, and pre–post assessments. Validation results indicated high validity for material (90.90%), media (89.94%), and instructional design (90.40%). Black box testing achieved a 100% success rate, and practicality testing yielded an overall score of 90.17%, demonstrating strong usability. Effectiveness analysis revealed significant improvements across all measured outcomes ($p < 0.001$). The disseminate stage resulted in a finalized and classroom-ready learning product that is feasible for broader implementation in teacher education programs. These findings confirm

*Corresponding author: Erna; *ernayayuk17@umm.ac.id*

that metaverse-based adaptive gamified learning can effectively enhance mathematics learning outcomes while strengthening digital pedagogical competencies aligned with Education 4.0.

Keywords: Adaptive gamification; Education 4.0; mathematical motivation; metaverse; pre-service teachers

1. Introduction

The rapid advancement of immersive technologies, such as virtual reality (VR), augmented reality (AR), and the metaverse, has transformed higher education by creating interactive, immersive, and collaborative learning environments that go beyond traditional classrooms. Through three-dimensional (3D) visualization, avatar-based interaction, and real-time collaboration, the metaverse enables learners to engage with abstract concepts through authentic simulations and gamified tasks, making learning more meaningful (Hong Lin et al., 2022; Wu et al., 2023; Zhang et al., 2022).

Research shows that such environments enhance motivation, engagement, and knowledge retention through experiential learning (López-Belmonte et al., 2023; Sin et al., 2023). This shift aligns with the goals of Education 4.0, which emphasize adaptability, creativity, problem-solving, and digital literacy as essential skills for a technology-driven world (Dwivedi, 2022; Hartina et al., 2024; Jagatheesaperumal et al., 2024). For students in elementary teacher education programs, mastering both mathematics and innovative digital pedagogy is essential to prepare future generations for this landscape (Rungrapeepornphong et al., 2023; Yayuk & Ekowati, 2022). Integrating metaverse-based learning into teacher education strengthens professional readiness and fosters the competencies needed to thrive in 21st-century education (Lee, 2021; Meena, 2023).

Despite these advances, mathematics learning among prospective elementary teachers still faces challenges in sustaining motivation, enhancing problem-solving skills, and promoting deep cognitive engagement, despite strong evidence that immersive environments can positively influence learning processes (Cheng et al., 2015; Radianti et al., 2020). While gamification and metaverse-based learning are widely recognized as promising approaches, prior studies rarely integrate adaptive gamification within immersive metaverse environments using a systematic research and development framework. This gap underscores the need for a pedagogically grounded metaverse-based adaptive gamification model targeting pre-service mathematics teacher education.

In the Indonesian context, challenges in mathematics education remain evident. The OECD Program for International Student Assessment 2022 reports that Indonesia scored 366 in mathematics, substantially below the OECD average of 472, indicating persistent weaknesses in mathematical reasoning and problem-solving. National data from Indonesia’s minimum competency assessment (Asesmen Kompetensi Minimum) further show that a large proportion of students remain at a basic or below basic numeracy level, particularly in higher-order and contextual problem-solving tasks. These findings raise concerns for teacher education programs, as pre-service teachers with limited mathematical competence may face difficulties in effectively developing numeracy skills in future classrooms (Tyaningsih et al., 2022).

Mathematics is often perceived as abstract, rigid, and disconnected from real-life contexts, leading to low motivation and underachievement among students, including those in elementary teacher education programs (Setyaningrum et al., 2023). This low motivation is particularly concerning for pre-service teachers, as limited mastery of mathematical concepts can hinder their ability to teach numeracy skills effectively to young learners (Yayuk & Ekowati, 2022). The issue is not only due to disinterest but also linked to mathematics anxiety and a lack of engaging instructional strategies, which undermine their confidence (Vankúš, 2021; Yulianto et al., 2024).

Conventional approaches such as lectures and repetitive exercises often fail to sustain engagement or develop higher-order thinking skills. Therefore, innovative pedagogical strategies are needed to make mathematics learning more meaningful and motivating (Rungrapeepornphong et al., 2023; Wu et al., 2023). Immersive technologies, particularly gamified educational games in the metaverse, offer promising solutions by contextualizing abstract concepts and promoting active participation, collaboration, and persistence (Fang et al., 2024; López-Belmonte et al., 2023).

Gamification is increasingly recognized as an effective pedagogical approach to boost students' motivation, persistence, and engagement by transforming routine learning activities into enjoyable, goal-oriented experiences through elements such as rewards, challenges, levels, and progress tracking (da Silva & Rodrigues, 2023). In this study, the term *adaptive* refers to the system's ability to personalize learning by dynamically adjusting task difficulty, feedback, and learning pathways based on students' performance and progression. Such adaptive mechanisms aim to accommodate individual differences and ensure that learners remain optimally challenged throughout the learning process. These elements activate both intrinsic and extrinsic motivation, encouraging active participation and a sense of achievement through incremental progress (Aguiar-Castillo, 2022; Solekhah et al., 2023).

In mathematics education, gamification has been shown to reduce anxiety and improve attitudes toward problem-solving, particularly through interactive quizzes, point systems, and competition-based tasks (Setyaningrum et al., 2023; Tyaningsih et al., 2022). It also sustains attention and promotes collaboration, which is essential for elementary teacher education students as future facilitators of engaging learning environments (Yayuk & Ekowati, 2022; Yulianto et al., 2024).

However, traditional gamification remains limited due to its reliance on two-dimensional and static designs, which often fail to develop higher-order skills such as critical thinking and reasoning (Vankúš, 2021; Wu et al., 2023). To address this, adaptive gamification has emerged, providing personalized learning by adjusting task difficulty, feedback, and pathways to match learner performance

(Costa et al., 2024; Fang et al., 2024). When combined with immersive technologies such as the metaverse, adaptive gamification creates personalized, context-rich experiences that enhance motivation and cognitive skill development through real-time simulations and problem-based tasks (López-Belmonte et al., 2023; Rungrapeepornphong et al., 2023). This integration equips future elementary teachers with both strong content knowledge and innovative pedagogical strategies.

The metaverse provides distinct advantages over conventional learning platforms by offering 3D, avatar-based, and interactive environments that foster immersive and collaborative learning experiences. These spaces enable real-time interaction, personalization, and social presence, allowing learners to explore knowledge in engaging ways (Hong Lin et al., 2022; Zhang et al., 2022). Avatar representation supports identity formation, communication, and community building, which are crucial for enhancing collaboration and learner engagement (López-Belmonte et al., 2023; Sin et al., 2023).

Immersive simulations also promote experiential learning by replicating authentic contexts while overcoming the physical limitations of traditional classrooms (Dwivedi, 2022; Lee, 2021). For students in elementary teacher education programs, these features not only increase motivation and interest but also build essential digital competencies needed for their future roles as educators (Meena, 2023). Metaverse-based learning supports project-based learning (PBL) by enabling collaborative, long-term tasks based on authentic problems. Through virtual projects, students develop mathematical understanding while experiencing innovative instructional practices relevant to future teaching.

In mathematics education, the metaverse has emerged as an innovative platform that enables visualization of abstract concepts, making them more accessible and meaningful (Fang et al., 2024; Wu et al., 2023). Immersive simulations allow learners to experiment, explore strategies, and receive immediate feedback, fostering critical thinking and deeper understanding (Park, 2022; Rungrapeepornphong et al., 2023). When integrated with gamification, the metaverse combines motivational elements such as rewards, progress tracking, and adaptive challenges, creating personalized and engaging learning pathways (da Silva & Rodrigues, 2023). This integration not only enhances motivation and engagement but also supports cognitive development by aligning learning experiences with individual needs (Costa et al., 2024; López-Belmonte et al., 2023). As such, the metaverse functions as a comprehensive educational ecosystem in which immersive technologies and gamification converge to transform mathematics learning and teacher preparation.

Motivation plays a crucial role in mathematics learning as it enhances persistence, reduces anxiety, and builds confidence when students encounter challenging tasks. Research shows that motivational beliefs such as self-efficacy and goal orientation are positively linked to better performance and a greater willingness to engage with complex problems (Yunus & Wan Ali, 2009). Experiencing incremental successes reinforces positive learning experiences and strengthens motivation for future tasks (Daly, 2019). Adopting a growth mindset encourages students to view difficulties as opportunities to grow rather than signs of failure, which increases perseverance and reduces avoidance (Boaler, 2016). In immersive digital environments, adaptive gamification can further boost mathematical motivation by providing timely feedback, incremental rewards, and clear progress tracking, fostering greater interest and confidence in learning mathematics (Schunk et al., 2014).

Problem-solving in mathematics involves analyzing problems, selecting appropriate strategies, and applying logical reasoning to reach solutions. Technologically enriched learning environments, such as immersive or virtual platforms, allow learners to experiment with multiple strategies, test their reasoning, and refine their approaches dynamically (Schoenfeld, 2016). Engaging in interactive, problem-based tasks in such settings helps develop higher-order thinking and adaptive reasoning more effectively than traditional methods (Chasokela, 2025). Real-time feedback supports learners in adjusting strategies, thereby improving their critical thinking and creativity. For students in elementary teacher education programs, mastering problem-solving is essential not only for their own mathematical proficiency but also for their ability to teach and model reasoning processes for young learners (Polya, 2004; Schoenfeld, 2016). Integrating adaptive gamification into metaverse-based activities ensures appropriately challenging tasks, supporting continuous growth in problem-solving competence.

Cognitive engagement refers to mental effort, attention, and immersion learners invest in educational activities. Immersive technologies such as extended reality (XR) and VR have been shown to enhance emotional and cognitive engagement significantly compared to conventional methods (Hmoud et al., 2025). These environments foster sustained attention, deeper reflection, and active participation through multisensory and interactive learning experiences. Achieving a state of 'flow', in which learners are optimally challenged and focused, further promotes engagement (Csikszentmihalyi, 2014). This is particularly valuable in mathematics, in which abstract concepts often demand prolonged concentration. Adaptive gamification within metaverse contexts supports this by offering personalized challenges, instant feedback, and interactive tasks, which stimulate deeper cognitive processing and active participation (Fredricks et al., 2004).

Although research on gamification and metaverse-based learning has expanded considerably, important gaps remain that underscore the novelty of this study. Many existing studies examine gamification as a motivational tool or the metaverse as an immersive learning platform separately, without integrating adaptive gamification mechanisms within metaverse-based mathematics education (da Silva & Rodrigues, 2023; Wu et al., 2023). Additionally, most research focuses on general learners in secondary or higher education, with limited attention to students in elementary teacher education programs—future educators who play a crucial role in shaping mathematical literacy at the primary level (Rungrapeepornphong et al., 2023; Yayuk & Ekowati, 2022). Another gap concerns learning outcomes: previous studies often emphasize short-term engagement or achievement, rather than simultaneously examining motivation, problem-solving skills, and cognitive engagement, which are essential for preparing adaptive and innovative pre-service teachers (Fang et al., 2024; López-Belmonte et al., 2023).

2. Research Objectives

This study aimed to develop, validate, and evaluate a metaverse-based adaptive gamified learning game for teacher education students. The research objectives are structured into technical and pedagogical objectives as follows.

2.1 Technical Objectives

1) To develop a metaverse-based adaptive gamified learning game that integrates immersive 3D environments, adaptive learning mechanisms, and gamification features for mathematics instruction.
2) To validate the developed system in terms of content, instructional design, and technical functionality through expert review and system testing.
3) To evaluate the effectiveness of the developed system based on measurable improvements in mathematical motivation, problem-solving skills, and cognitive engagement.

2.2 Pedagogical Objectives

4) To enhance teacher education students' mathematical motivation through adaptive and immersive learning experiences.
5) To improve problem-solving skills and cognitive engagement by engaging students in interactive and project-oriented mathematical tasks within the metaverse environment.
6) To strengthen teacher education students' digital pedagogical competency by modeling the effective use of adaptive, immersive, and gamified technologies aligned with the principles of Education 4.0.

3. Literature Review

3.1 Grand Theories: Integrating Self-Determination Theory and Cognitive Theory of Multimedia Learning to Frame Metaverse-Based Education

The theoretical framework integrates the self-determination theory (SDT) and the cognitive theory of multimedia learning (CTML) to explain how metaverse-based adaptive gamified learning environments influence key educational outcomes in mathematics. The SDT, developed by Ryan and Deci (1985), emphasizes the fulfillment of three basic psychological needs (autonomy, competence, and relatedness) which drive intrinsic motivation, persistence, and confidence in learning (López-Belmonte et al., 2023). Gamification elements such as meaningful choice, feedback, and social interaction are instrumental in supporting these needs within digital environments.

The CTML, proposed by Mayer (1997), focuses on how learners process information through dual channels (visual and verbal), limited working memory, and active processing involving selecting, organizing, and integrating information (Mayer, 2022). The design principles of signaling, coherence, personalization, and segmenting help reduce cognitive load and enhance comprehension, aligning well with immersive 3D environments. The metaverse-based adaptive gamified educational game combines these motivational and cognitive mechanisms through its features 3D environments, avatar-based interactions, and immersive simulations and mechanisms such as adaptive challenges, real-time feedback, and reward systems (Fang et al., 2024; Hong Lin et al., 2022; López-Belmonte et al., 2023). This integration is theorized to enhance mathematical motivation, problem-solving skills, and cognitive engagement, particularly for elementary teacher education students who must master both content and innovative pedagogy for future classrooms.

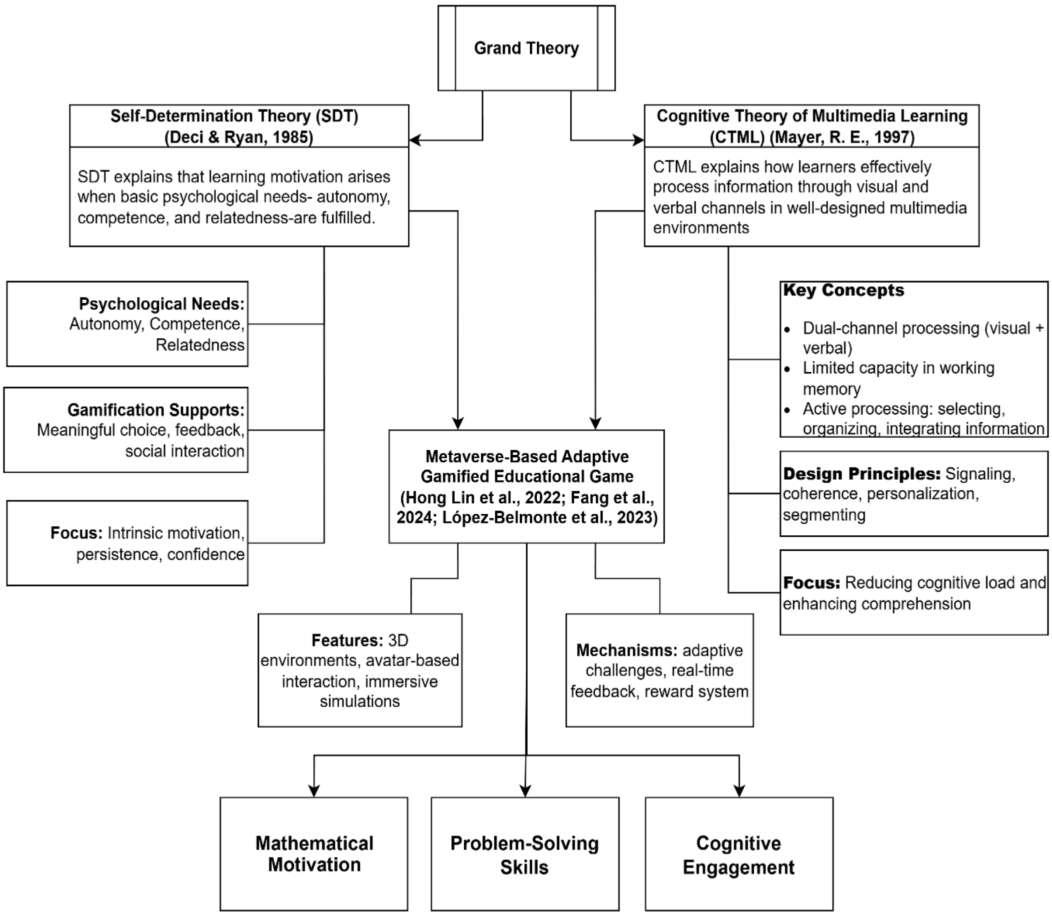

Figure 1: Theoretical framework

This study empirically tested the proposed theoretical framework by operationalizing the core constructs of the SDT and the CTML within a metaverse-based adaptive gamified learning environment. Specifically, the research examined how gamification features and adaptive multimedia design influence the fulfillment of psychological needs, cognitive processing, and learning experiences, and how these mechanisms subsequently affect mathematical motivation, problem-solving skills, and cognitive engagement among pre-service elementary teachers. By adopting a systematic research and development approach, this study extended prior theoretical and conceptual work by providing empirical evidence on the combined motivational–cognitive pathways underpinning metaverse-based mathematics education (Mayer, 2022; López-Belmonte et al., 2023).

3.2 Conceptual Framework and Variables

The conceptual framework of this study integrated motivational and cognitive perspectives to examine how metaverse-based adaptive gamified educational games influence key learning outcomes in mathematics among elementary teacher education students. Grounded in the SDT and the CTML, this framework positioned the metaverse environment as an innovative pedagogical tool that combines immersive technology with adaptive gamification to address both learners' psychological needs and cognitive processing demands.

The independent variable focused on the integration of metaverse features and adaptive gamification mechanisms, while the dependent variables reflected essential educational outcomes: mathematical motivation, problem-solving skills, and cognitive engagement. These three constructs were selected because they represent critical competencies for future elementary school teachers who must develop not only mathematical proficiency but also effective digital pedagogy to foster 21st-century learning (Fang et al., 2024; López-Belmonte et al., 2023; Rungrapeepornphong et al., 2023).

Recent studies have highlighted that adaptive learning in metaverse-based environments is driven by algorithmic and artificial intelligent-based logic that personalizes learning through dynamic adjustment of task difficulty, feedback, and learning pathways based on learners' performance and engagement data (Katona & Gyonyoru, 2025; Parthasarathy et al., 2025; Strielkowski et al., 2025). However, many existing metaverse studies in education emphasize immersive visualization and engagement, while offering limited critical discussion of adaptive instructional logic and its pedagogical implications, which constrain scalability and instructional depth.

Within the SDT framework, the *relatedness* component is strengthened through avatar-based interaction and collaborative problem-solving, fostering social presence and a sense of belonging among learners. For teacher education students, such environments also support teacher readiness by developing digital pedagogical competency, enabling future educators to design and implement effectively adaptive, immersive, and gamified learning experiences aligned with the demands of Education 4.0.

Table 1: Conceptual framework and variables

Variable Type	Variable Name	Definition / Focus	Indicators	Reference
Independent Variable (X)	Metaverse-Based Adaptive Gamified Educational Game	Integration of metaverse features and adaptive gamification mechanisms	1) 3D environment, avatars, immersive simulation 2) Adaptive challenges 3) Real-time feedback 4) Reward systems	(Fang et al., 2024; Hong Lin et al., 2022; López-Belmonte et al., 2023)
Dependent Variable (Y_1)	Mathematical Motivation	Students' persistence, confidence, and interest in mathematics learning	1) Interest 2) Persistence 3) Self-efficacy 4) Reduced anxiety	(Daly., 2019; Setyaningrum et al., 2023; Tyaningsih et al., 2022)
Dependent Variable (Y_2)	Problem-Solving Skills	Ability to analyze problems, select strategies, and apply reasoning	1) Problem analysis 2) Strategy selection 3) Reasoning 4) Solution evaluation	(Fang et al., 2024; Rungrapeepornphong et al., 2023; Schoenfeld, 2016)
Dependent Variable (Y_3)	Cognitive Engagement	Level of mental effort, attention, and active participation during learning	1) Sustained attention 2) Deep reflection 3) Active participation	(Fredricks et al., 2004; Hmoud et al., 2025)

3.3 Hypotheses Framework

These hypotheses reflect the idea that integrating motivational and cognitive design principles in the metaverse can create transformative learning experiences that support both affective and cognitive learning dimensions (Fang et al., 2024; López-Belmonte et al., 2023; Mayer, 2022; Ryan & Deci, 2017). Adaptive gamified games in the metaverse are designed to fulfill learners' psychological needs for autonomy, competence, and relatedness through meaningful choices, personalized challenges, real-time feedback, and social interaction. When these needs are satisfied, students experience higher levels of intrinsic motivation, persistence, and confidence, which are crucial for sustaining interest in mathematics learning (Ryan & Deci, 2017).

By providing an engaging and supportive environment, adaptive gamification within the metaverse helps reduce anxiety and fosters a sense of ownership over the learning process, thereby increasing students' overall mathematical motivation (López-Belmonte et al., 2023). Interactive visualization combined with adaptive feedback in metaverse environments allows learners to explore mathematical problems dynamically, test multiple strategies, and refine their reasoning through immediate guidance. Such environments make abstract mathematical concepts more concrete, enabling deeper cognitive processing and supporting the development of analytical and strategic thinking (Fang et al., 2024). As learners receive adaptive feedback, they are able to adjust their approaches in real time, which enhances their problem-solving skills and encourages flexible, higher-order thinking (Rungrapeepornphong et al., 2023).

Immersive metaverse environments, enhanced by gamification mechanics such as challenges, rewards, and progress tracking, create multisensory and interactive experiences that promote a state of flow, which is a deep sense of focused engagement in which learners are fully absorbed in the task. This combination stimulates sustained attention, active participation, and reflective thinking, which are central components of cognitive engagement (Mayer, 2022). By integrating immersive features and motivational elements, the metaverse enables learners to become mentally and emotionally invested in mathematical activities, leading to richer and more meaningful learning experiences (Hmoud et al., 2025).

Table 2: Hypotheses framework

Code	Hypothesis Statement
H1	Metaverse-based adaptive gamified educational games have a significant positive effect on students' mathematical motivation.
H2	Metaverse-based adaptive gamified educational games have a significant positive effect on students' problem-solving skills.
H3	Metaverse-based adaptive gamified educational games have a significant positive effect on students' cognitive engagement.

4. Methodology

4.1 Research Design

This study employed a research and development (R&D) approach using the 4D model (define, design, develop, disseminate), which was adapted to develop a metaverse-based adaptive gamified educational game as an innovative learning technology product. The research design integrated the development process with a quasi-experimental one-group pretest–posttest model to evaluate the effectiveness of the developed game on three key dependent variables: (Y_1) mathematical motivation, (Y_2) problem-solving skills, and (Y_3) cognitive engagement of elementary teacher education students. The use of a one-group design was chosen due to practical and institutional constraints, including limited class availability, curriculum scheduling, and ethical considerations that required equal access to the developed learning innovation for all students enrolled in the course.

This design was considered feasible and appropriate for early-stage evaluation of educational technology products within R&D studies, particularly when the primary focus is product validation and initial effectiveness testing. The 4D model was implemented systematically through the following stages:

1) The defined stage involved needs analysis and literature review to identify learning problems and set development goals.
2) The design stage focused on conceptualizing the game, creating adaptive gamification mechanisms, and designing storyboards and game flow.

3) The develop stage included prototype creation, alpha and beta testing, and product refinement based on feedback and usability trials.
4) The disseminate stage finalized the product and published the findings for broader implementation.

4.2 Research Setting and Participants

This study was conducted within the Elementary Teacher Education Program (Pendidikan Guru Sekolah Dasar), in the Faculty of Teacher Training and Education, at the Universitas Muhammadiyah Malang, Indonesia. The program is equipped with computer laboratories, stable internet access, and adequate technological infrastructure to support the implementation of metaverse-based learning environments, making it an appropriate research setting. The research participants consist of 60 undergraduate students enrolled in the Elementary Teacher Education Program during the 2023/2024 academic year, all of whom were taking the Basic Mathematics course. A purposive sampling technique was employed to select the participants based on their learning needs, technological readiness, and willingness to participate in the study.

The overall research process, including needs analysis, design, development, implementation and evaluation phases, was conducted over a six-month period. The implementation of the metaverse-based adaptive gamified educational game was over one month, comprising eight instructional sessions. Each session lasted approximately 90 minutes, resulting in a total of 12 hours of structured game-based learning. The intervention was primarily conducted in a computer laboratory setting under lecturer guidance, with students engaging in the metaverse-based activities during scheduled class sessions. In addition, limited independent exploration was encouraged outside class to reinforce learning outcomes. Ethical considerations were strictly observed throughout the study, including informed consent and voluntary participation, ensuring that students clearly understood the research objectives, procedures, and potential benefits of their involvement.

4.3 Adaptive Similarity Calculation and Learning Mechanism

The adaptive mechanism of the system was based on an adaptive similarity calculation, which analyzed learners' pretest scores, task performance accuracy, completion time, and engagement indicators. Learner profiles were compared using similarity metrics to identify performance patterns, which were then used to recommend appropriate learning scenarios. Based on this calculation, the system dynamically adjusted task difficulty levels, feedback intensity, and learning pathways, ensuring that students received personalized challenges aligned with their current competence level. This adaptive logic allowed the system to respond continuously to learner progression, rather than delivering uniform content.

4.4. Data Collection Techniques and Instruments

Data collection included expert validation, system functionality testing, practicality testing, and effectiveness testing. Effectiveness evaluation focused on mathematical motivation, problem-solving skills, and cognitive engagement using validated instruments aligned with the conceptual framework.

Table 3: Data collection techniques and instruments

No	Data Type / Purpose	Technique - Instrument	Indicators	N item	Respondents
1	Expert validation—Material	Material Expert Questionnaire	• Curriculum alignment • Mathematical content accuracy • Content depth and coverage • Relevance to learner context • Clarity of language and examples • Cognitive level appropriateness • Integration of metaverse and gamification • Learning objectives and assessment quality	22	Two subject-matter experts
2	Expert validation—Learning media	Media Expert Questionnaire	• User interface and navigation • Design consistency and accessibility • Multimedia quality • System performance and stability • Device compatibility • Interactivity and feedback • Data security • Technical support	24	Two media/ technology experts
3	Expert validation—Instructional design	Instructional Design Expert Questionnaire	• Alignment of objectives, activities, and assessments • Pedagogical strategies and scaffolding • Adaptive personalization • Feedback and sequencing • Authentic learning tasks • Cognitive load management • Engagement and motivational strategies • Implementation readiness	24	Two instructional design experts
4	System functionality	Black Box Test Scenarios	• User registration and login • Navigation in 3D environment • Avatar functionality • Adaptive feedback • Data saving and error handling • Cross-device compatibility	15	Research team
5	Practicality (usability)	Student Practicality Questionnaire	• Ease of use • Clarity of instructions • Technical smoothness • Time efficiency • Integration with learning • Usefulness • Willingness for future use	14	60 students

No	Data Type / Purpose	Technique - Instrument	Indicators	N item	Respondents
6a	Effectiveness — Mathematical Motivation	Pre–post questionnaire — Mathematical Motivation Scale	• Interest in mathematics • Persistence in learning • Self-efficacy • Reduced anxiety	20	60 students
6b	Effectiveness — Problem-Solving Skills	Pre–posttest-Mathematical Problem-Solving Test	• Problem analysis • Strategy selection • Reasoning ability • Solution evaluation	10	60 students
6c	Effectiveness — Cognitive Engagement	Questionnaire (self-report) Cognitive Engagement Scale	• Sustained attention • Deep reflection and metacognition • Active participation in learning activities	12	60 students

4.5 Data Analysis
The data analysis in this study consisted of descriptive and inferential statistical methods. Descriptive analysis was employed to summarize expert validation results, practicality testing, and system functionality testing by converting questionnaire scores into percentages, with a minimum validity and practicality threshold of ≥70%. Prior to the main analysis, a pilot test was conducted to examine the quality of the research instruments. Exploratory factor analysis was used to assess construct validity, followed by confirmatory factor analysis (CFA) to confirm the factor structure of the measurement scales.

Instrument reliability was evaluated using Cronbach's alpha coefficient. For the problem-solving skills assessment, item validity, reliability, and difficulty levels were analyzed to ensure test quality. Inferential analysis applied a paired sample t-test to evaluate the effectiveness of the metaverse-based adaptive gamified educational game on mathematical motivation, problem-solving skills, and cognitive engagement. All statistical analyses were conducted using SPSS software.

Table 4: Data analysis techniques

No	Data Type / Purpose	Analysis Technique	Description of Analysis	Decision Criteria
1	Expert Validation—Material	Descriptive statistics (percentage)	Convert total expert scores to percentages to determine the validity level of the learning material.	≥ 70% = Valid; < 70% = Revise
2	Expert Validation—Learning Media	Descriptive statistics (percentage)	Calculate media expert ratings in percentage to assess usability and technical quality.	≥ 70% = Valid; < 70% = Revise
3	Expert Validation—Instructional Design	Descriptive statistics (percentage)	Assess instructional design alignment and quality using percentage conversion.	≥ 70% = Valid; < 70% = Revise
4	System Functionality (Black Box)	Functional suitability testing	Evaluate whether each system feature operates according to design scenarios.	≥ 90% success = Functional
5	Practicality (Usability)	Descriptive statistics (percentage)	Convert student questionnaire results into percentages to assess ease of use, clarity, and usefulness.	≥ 70% = Practical; < 70% = Revise
6a	Effectiveness—Mathematical Motivation	Inferential statistics (paired sample t-test)	Compare pretest and posttest scores to identify significant changes in mathematical motivation.	Sig. (p) < 0.05 = Significant improvement
6b	Effectiveness—Problem-Solving Skills	Inferential statistics (paired sample t-test)	Compare pretest and posttest scores to assess the development of problem-solving abilities.	Sig. (p) < 0.05 = Significant improvement
6c	Effectiveness—Cognitive Engagement	Inferential statistics (paired sample t-test)	Compare pretest and posttest cognitive engagement scores to determine engagement changes.	Sig. (p) < 0.05 = Significant improvement

5. Results and Findings

5.1 Design and Development Results

5.1.1 Metaverse-Based Adaptive Gamified Learning System Design

The design of the metaverse-based adaptive gamified learning system integrates immersive technologies, adaptive mechanisms, and gamification strategies to support mathematics learning for elementary teacher education students. The system consists of eight core components that function together to create secure, personalized, and interactive learning experiences. Each component includes specific roles and practical applications in mathematics learning. The detailed system design is presented in Table 5.

Table 5: Metaverse-based adaptive gamified learning system design

No	Component	Description	Implementation in Learning
1	Management and Support	Admin control for user management, activity monitoring, and learning analytics.	Lecturers manage student access, monitor activity logs, and analyze learning progress through dashboards.
2	Security and Privacy	Ensures secure login, data protection, and authentication.	Students log in with verified accounts; data and activities are stored securely during learning sessions.
3	Assessment and Feedback	Adaptive quizzes, real-time feedback, and progress tracking.	Students receive instant feedback on quiz results and task completion; lecturers track improvement.
4	Collaboration and Social	Avatar-based interaction, group tasks, and peer support.	Students work together in virtual 3D spaces using avatars, collaborating on problem-solving activities.
5	Personalizatio n and Accessibility	Adaptive challenges, role selection, and device compatibility.	Tasks adjust to student ability levels; learners can join via laptops, VR headsets, or mobile devices.
6	Content and Interaction	3D immersive environments, simulations, and gamified learning tasks.	Students explore 3D math scenarios, manipulate objects, and engage with interactive simulations.
7	Gamification and Adaptive Mechanisms	Adaptive challenges, reward systems, and avatar interaction.	Students earn badges, points, and rewards for solving math problems; tasks adapt to their performance.
8	Infrastructure	Cloud-based servers, stable internet, and VR/AR support.	The system runs smoothly during class activities, enabling real-time multiplayer learning experiences.

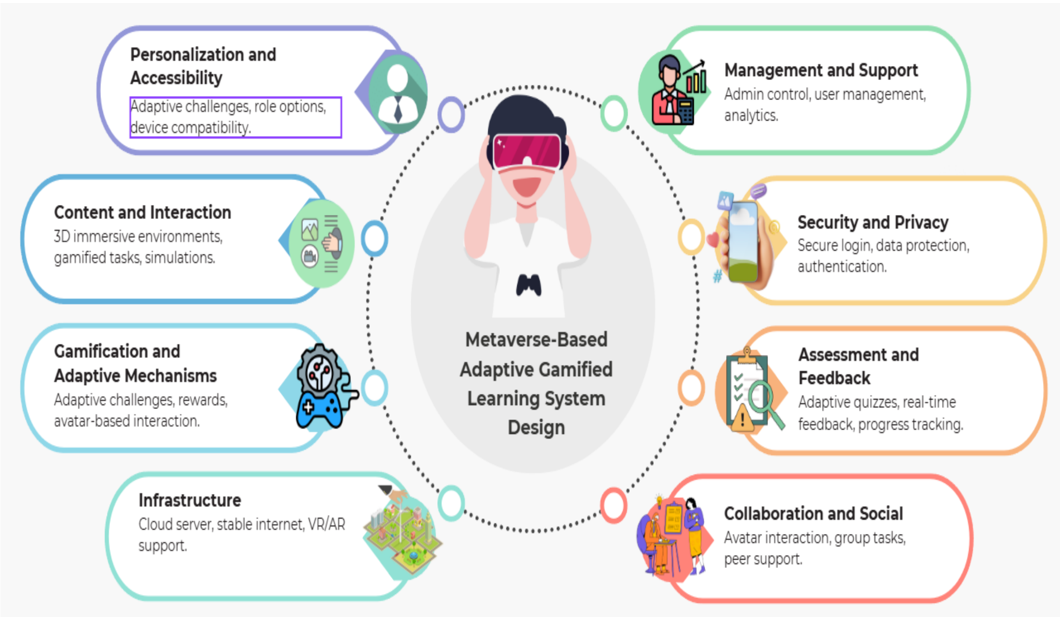

Figure 2: Metaverse-based adaptive gamified learning system design

5.1.2 System Process Flow

The system process flow illustrates the operational sequence of the metaverse-based adaptive gamified learning environment. It integrates adaptive recommendation mechanisms, immersive visualization, and gamification features to support personalized and engaging mathematics learning for elementary teacher education students.

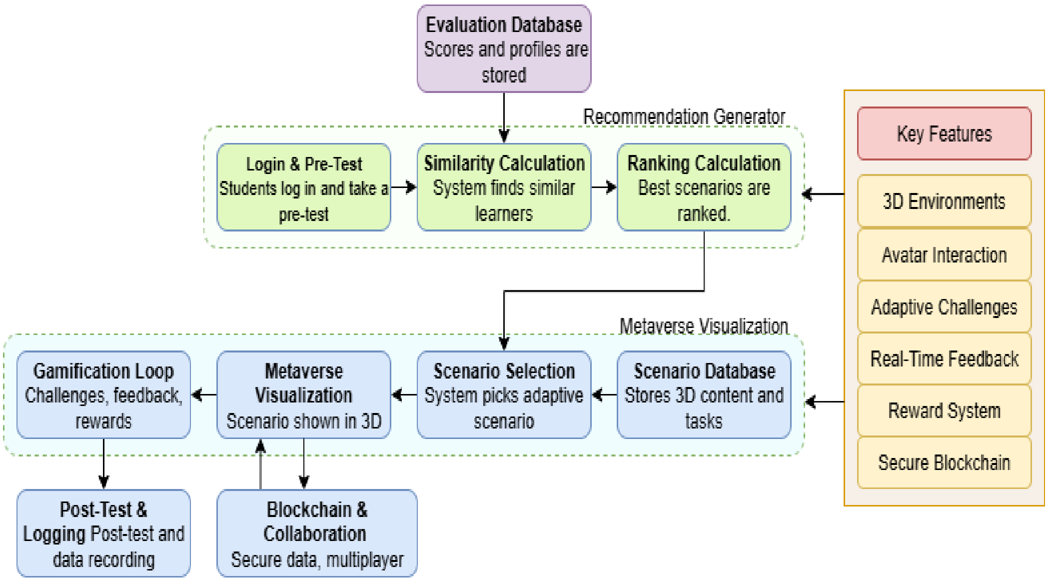

Figure 3: System process flow

The process starts with login and pre-test, where students access the platform and complete an initial assessment to determine their prior knowledge. The results are stored in the evaluation database, which serves as the foundation for generating adaptive learning pathways. The similarity calculation module analyzes stored data to find learners with comparable profiles, while the ranking calculation module determines the most appropriate learning scenarios based on similarity scores.

Next, the system proceeds to scenario selection, where an adaptive learning scenario is chosen automatically from the scenario database, which contains 3D content, mathematical challenges, and problem-solving missions. The selected scenario is then presented through metaverse visualization, enabling learners to enter an immersive 3D environment which supports exploration and interaction via avatars. Within this space, the gamification loop provides adaptive challenges, real-time feedback, and reward mechanisms to maintain student engagement and motivation. Blockchain and collaboration features are integrated to ensure secure data management, user authentication, and multiplayer interaction between students.

Finally, the post-test and logging stage records students' performance and activity data, allowing for progress tracking and evaluation of learning effectiveness. Throughout this process, key features (including 3D environments, avatar-based interaction, adaptive challenges, real-time feedback, reward systems, and a secure blockchain layer) are embedded to create a dynamic and personalized learning ecosystem. This systematic flow ensures that each learner experiences tailored mathematical activities, immediate adaptive support, and secure collaborative engagement, thereby enhancing motivation, problem-solving abilities, and cognitive involvement in mathematics learning.

5.1.3 Metaverse Learning Material and Environment Design

The metaverse visualization class functions as the central interactive space in which learning activities take place in an immersive 3D environment. Within this virtual classroom, students engage with various instructional components such as mathematics learning materials, adaptive quizzes, interactive games, and problem-solving simulations designed to reinforce conceptual understanding. The environment allows students to navigate through different learning zones using avatars, fostering a sense of presence and active participation. Real-time feedback and adaptive challenges are integrated into the activities, enabling personalized learning experiences that adjust to students' performance levels. Collaborative features, such as group tasks and peer discussions, are also embedded to encourage communication and teamwork. This metaverse classroom is supported by gamification mechanics including reward systems, points, and badges that sustain motivation and engagement while promoting deeper cognitive involvement with mathematical content. Overall, this visualization class transforms traditional mathematics instruction into an interactive, exploratory, and student-centered learning experience.

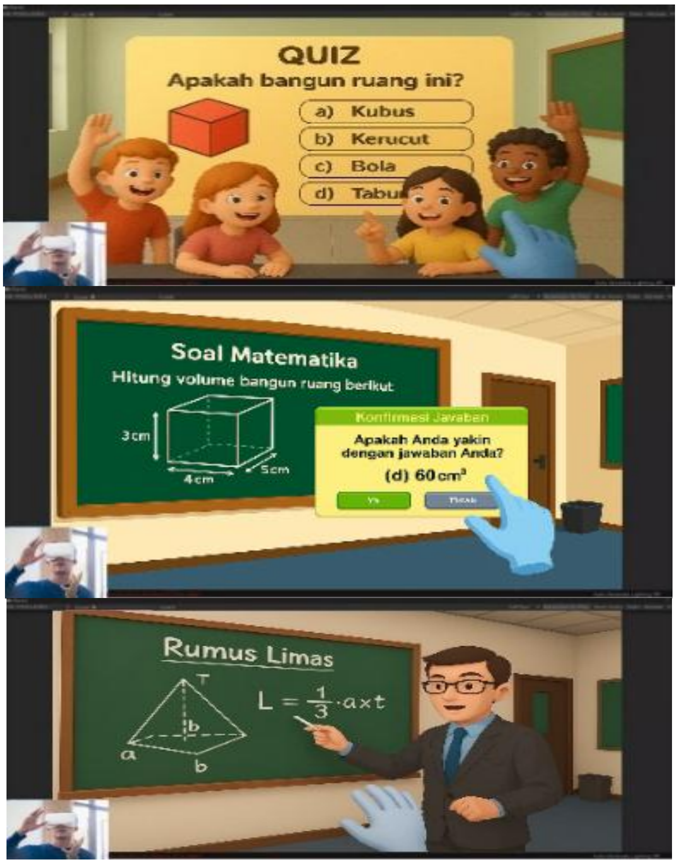

Figure 4: Metaverse visualization design

5.1.4 Expert Validation Results

Expert validation was conducted to ensure the quality, validity, and feasibility of the metaverse-based adaptive gamified educational game before implementation. The three types of expert validation performed were material validation, learning media validation, and instructional design validation, involving subject-matter experts, media/technology experts, and instructional design experts. Each expert assessed specific indicators related to curriculum relevance, media functionality, and pedagogical design. The validation results were converted into percentages, with a minimum validity criterion of 70%, indicating that the product was appropriate for use in the next stages of practical and effectiveness testing.

Table 6: Expert validation results

No.	Type of Validation	Indicators	Result (%)	Category
1	**Material Expert Validation**	Curriculum alignment	92.00	Valid
		Mathematical content accuracy	90.50	Valid
		Content depth and coverage	91.20	Valid
		Relevance to learner context	89.80	Valid
		Clarity of language and examples	93.40	Valid
		Cognitive level appropriateness	90.00	Valid
		Integration of metaverse and gamification	88.70	Valid
		Learning objectives and assessment quality	91.60	Valid
	Total Material Expert Validation		**90.90**	**Valid**
2	**Learning Media Expert Validation**	User interface and navigation	90.80	Valid
		Design consistency and accessibility	89.20	Valid
		Multimedia quality	92.50	Valid
		System performance and stability	88.00	Valid
		Device compatibility	91.30	Valid
		Interactivity and feedback	89.70	Valid
		Data security	90.10	Valid
		Technical support	87.90	Valid
	Total Learning Media Expert Validation		**89.94**	**Valid**
3	**Instructional Design Expert Validation**	Alignment of objectives, activities, and assessments	91.70	Valid
		Pedagogical strategies and scaffolding	90.20	Valid
		Adaptive personalization	88.50	Valid
		Feedback and sequencing	89.60	Valid
		Authentic learning tasks	92.00	Valid
		Cognitive load management	90.40	Valid
		Engagement and motivational strategies	91.00	Valid
		Implementation readiness	89.80	Valid
	Total Instructional Design Expert Validation		**90.40**	**Valid**

The material expert validation achieved an overall score of 90.90%, indicating that the developed content strongly aligned with the curriculum, maintained mathematical accuracy, and effectively integrated metaverse and gamification elements. High scores in language clarity and cognitive appropriateness also showed that the content was well-structured and suitable for learners at the elementary teacher education level. The learning media expert validation reached 89.94%, demonstrating that the platform was technically reliable, visually consistent, and accessible across different devices. Indicators such as user interface, multimedia quality, and data security received high ratings, indicating that the system's design was user-friendly, interactive, and safe for implementation in educational environments. Finally, the instructional design expert validation obtained 90.40%, reflecting strong alignment between learning objectives, activities, and assessments. High scores in pedagogical strategies, cognitive load management, and engagement strategies confirmed that the game was well-designed to support meaningful learning. Overall, the validation results across all three expert groups exceeded the 70% threshold, confirming that the product was valid and ready for practical trials and effectiveness testing.

5.2 Construct Validity and Reliability of Measurement Instruments

To ensure the psychometric quality of the research instruments, CFA and reliability testing were conducted for all study variables. Additionally, CFA was employed to examine the construct validity of the measurement model by assessing the standardized factor loadings of each indicator, while internal consistency reliability was evaluated using Cronbach's alpha coefficients. The analysis examined three main constructs, mathematical motivation, problem-solving skills, and cognitive engagement, and each measured using multiple indicators and items.

Table 7: Results of confirmatory factor analysis and reliability testing

Variable	Indicators	Number of Items	Standardized Factor Loading (λ)	Cronbach's Alpha
Mathematical Motivation	Interest	5	0.63 – 0.82	**0.88**
	Persistence	5	0.66 – 0.85	
	Self-efficacy	5	0.69 – 0.87	
	Reduced anxiety	5	0.58 – 0.76	
Problem-Solving Skills	Problem analysis	3	0.61 – 0.79	**0.84**
	Strategy selection	3	0.64 – 0.81	
	Reasoning	2	0.59 – 0.74	
	Solution evaluation	2	0.62 – 0.83	
Cognitive Engagement	Sustained attention	4	0.67 – 0.86	**0.86**
	Deep reflection	4	0.65 – 0.84	
	Active participation	4	0.60 – 0.81	

5.3 Black Box Testing Result

Black box testing was conducted to evaluate the functional reliability of the metaverse-based adaptive gamified learning system before classroom implementation. The testing was divided into six main scenarios with a total of 15 detailed indicators, examining key functions such as authentication, 3D navigation, avatar interaction, adaptive mechanisms, data handling, and multi-device compatibility. Each indicator was assessed based on expected and actual results to ensure all features operated smoothly.

Table 8: Black box testing results

No.	Test Scenario	Indicator	Expected Result	Actual Result	Status
1	User registration and login	a. Account creation	Users can create accounts successfully.	Account creation worked correctly without errors.	Pass ☑
		b. Secure login	Users can log in securely.	Login was smooth and properly authenticated.	Pass ☑
		c. Dashboard access	Dashboard appears after login.	Dashboard loaded correctly after authentication.	Pass ☑
2	Navigation in a 3D environment	a. Navigation controls	Users can move freely using keyboard/mouse or VR.	Navigation was smooth and intuitive.	Pass ☑
		b. Object interaction	Users can interact with 3D objects.	Object interaction worked responsively.	Pass ☑
3	Avatar functionality	a. Avatar movement	Avatars can walk, run, and jump.	Avatar's movement was fluid and accurate.	Pass ☑
		b. Avatar customization	Users can change their avatar appearance.	Customization features worked properly.	Pass ☑
4	Adaptive feedback	a. Real-time feedback	Immediate feedback after answering quizzes.	Feedback appeared instantly and accurately.	Pass ☑
		b. Adaptive sequencing	Challenges adjust based on performance.	Adaptive sequencing functioned correctly.	Pass ☑
		c. Reward system	Points/badges given after tasks.	Rewards were displayed correctly and on time.	Pass ☑
5	Data saving and error handling	a. Automatic data saving	User progress is saved automatically.	Data saved successfully without loss.	Pass ☑
		b. Error message handling	System displays clear error messages and recovers smoothly.	Errors were handled properly with notifications.	Pass ☑
6	Cross-device compatibility	a. PC compatibility	The platform works on PC browsers.	The system ran smoothly on the PC.	Pass ☑
		b. Laptop compatibility	The platform works on standard laptops.	The system was stable on laptops.	Pass ☑
		c. VR headset compatibility	Platform functions in a VR environment.	VR ran smoothly and interactions were stable.	Pass ☑

The black box testing results demonstrated that the system met all functional expectations across six scenarios and 15 indicators. The user registration and login process was fully operational, ensuring secure access and smooth dashboard loading. The 3D navigation and object interaction worked responsively, enabling learners to explore the metaverse environment easily. Avatar functionality allowed fluid movement and customization, enhancing user engagement and identity within the virtual space. The adaptive feedback scenario, including real-time responses, adaptive sequencing, and reward systems, worked seamlessly, supporting personalized learning experiences. Data saving and error handling were stable and reliable, ensuring that user progress was recorded accurately and system errors were managed appropriately. Finally, cross-device compatibility was confirmed across PC, laptop, and VR devices, ensuring the platform's accessibility and flexibility in various learning contexts.

Overall, all 15 indicators passed successfully, confirming that the metaverse-based adaptive gamified learning system is functionally ready for classroom use and capable of delivering immersive and adaptive mathematics learning experiences. The error-handling mechanisms addressed common system issues such as invalid login attempts, unstable network connections, incomplete data submissions, and unexpected user exits. In all cases, the system successfully displayed clear error messages, preserved user progress, and recovered without data loss, confirming system robustness and reliability.

5.4 Practicality (Usability) Test Results

A student practicality (usability) test was conducted to evaluate the ease of use, clarity, usefulness, and overall user experience of the metaverse-based adaptive gamified learning system. A practicality questionnaire consisting of 14 items, across seven key indicators, was distributed to 60 students after using the system during mathematics learning sessions. The results were converted into percentages to determine the level of practicality, with a minimum criterion of 70% to be considered practical.

Table 9: Practicality (usability) test results

No.	Indicator	Practicality Score (%)	Category
1	Ease of use	91.20	Practical
2	Clarity of instructions	89.50	Practical
3	Technical smoothness	87.80	Practical
4	Time efficiency	88.90	Practical
5	Integration with learning	90.30	Practical
6	Usefulness	92.10	Practical
7	Willingness for future use	93.40	Practical
	Total Practicality Score	**90.17**	**Practical**

The practicality test results indicate that the metaverse-based adaptive gamified learning system demonstrated a high level of usability across all evaluated indicators. The highest score was found in willingness for future use (93.40%), showing that students were highly motivated to continue using the platform in future learning sessions. Ease of use (91.20%) and usefulness (92.10%) also received strong ratings, indicating that students found the platform intuitive and beneficial for their mathematics learning experience. Indicators related to clarity of instructions, technical smoothness, and time efficiency scored between 87–90%, reflecting that the system operated smoothly, was easy to understand, and supported efficient learning activities. Furthermore, the strong score for integration with learning (90.30%) confirmed that the platform effectively supports mathematical concepts and classroom learning objectives. Overall, the total practicality score of 90.17% exceeded the minimum criterion, demonstrating that the platform was highly practical and user-friendly for elementary teacher education students, making it suitable for continued implementation and scaling in mathematics education.

The qualitative feedback from the students' responses further supported the quantitative findings. Students reported that the immersive 3D environment made mathematics learning more engaging and reduced anxiety. Several participants highlighted that adaptive challenges helped them learn at their own pace, while avatar-based collaboration increased motivation and peer interaction. These comments indicated the positive perceptions of usability, engagement, and instructional value of the system.

5.5 Effectiveness Test Results

5.5.1 Mathematical Motivation

The effectiveness of the metaverse-based adaptive gamified educational game on mathematical motivation was evaluated using a pre–post questionnaire administered to 60 students. The questionnaire measured four key indicators of mathematical motivation: interest, persistence, self-efficacy, and reduced anxiety. Paired sample t-tests were performed to compare pretest and posttest scores, and the gain scores were calculated to determine the magnitude of improvement.

Table 10: Paired sample t-test results for mathematical motivation

No.	Indicator	Pretest (Mean ± SD)	Posttest (Mean ± SD)	Gain	t-statistic	Sig. (p)	Cohen's d (dz)	Effect Size
1	Interest in mathematics	67.5 ± 8.2	94.3 ± 6.5	26.8	12.45	0.000	1.61	Large
2	Persistence in learning	63.2 ± 7.5	88.6 ± 6.9	25.4	11.87	0.000	1.53	Large
3	Self-efficacy	59.4 ± 8.7	84.2 ± 7.1	24.8	10.96	0.000	1.41	Large
4	Reduced anxiety	46.5 ± 9.3	77.8 ± 8.0	31.3	13.02	0.000	1.68	Large

The paired sample t-test results demonstrated statistically significant improvements across all indicators of mathematical motivation following the intervention. Interest in mathematics ($t = 12.45$, $p < 0.001$), persistence in learning ($t = 11.87$, $p < 0.001$), self-efficacy ($t = 10.96$, $p < 0.001$), and reduced anxiety ($t = 13.02$, $p < 0.001$) all showed substantial gains. Effect size analysis revealed large effects across all motivational indicators (Cohen's *d* > 1.40), indicating that the metaverse-based adaptive gamified learning system produced strong and educationally meaningful improvements in students' motivation toward mathematics.

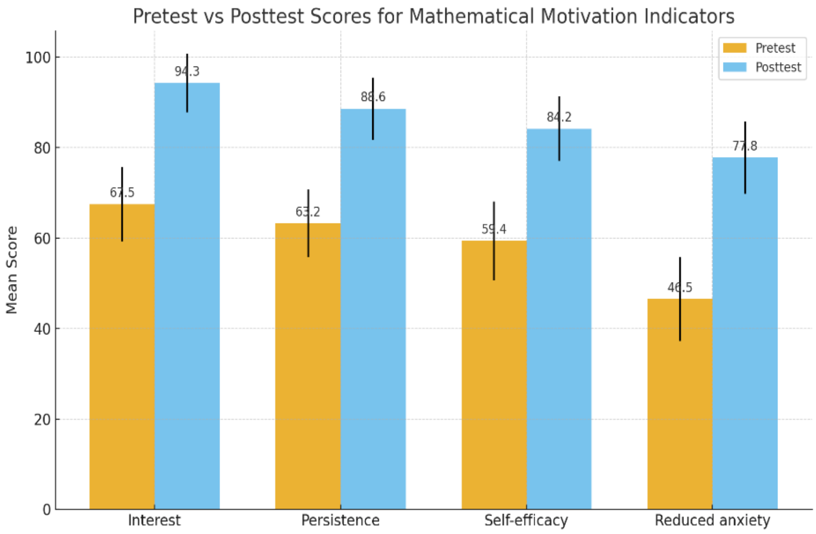

Figure 5: Pretest vs posttest scores for mathematical motivation

5.5.2 Effectiveness – Problem-Solving Skills

Paired pre–posttests measured four indicators of mathematical problem-solving. The results showed substantial gains after using the metaverse-based adaptive gamified learning system.

Table 11: Paired sample t-test results for problem-solving skills

No.	Indicator	Pretest (Mean ± SD)	Posttest (Mean ± SD)	Gain	t-statistic	Sig. (p)	Cohen's d (dz)	Effect Size
1	Problem analysis	61.3 ± 8.4	88.1 ± 7.2	26.8	12.21	0.000	1.58	Large
2	Strategy selection	58.7 ± 9.1	85.6 ± 7.5	26.9	11.74	0.000	1.51	Large
3	Reasoning ability	55.2 ± 8.9	84.7 ± 7.3	29.5	12.88	0.000	1.66	Large
4	Solution evaluation	52.6 ± 9.4	82.9 ± 7.8	30.3	13.05	0.000	1.68	Large

The paired sample t-test results showed statistically significant improvements across all four indicators of problem-solving skills after the intervention. Problem analysis increased with t = 12.21 ($p < 0.001$), while strategy selection showed improvement with t = 11.74 ($p < 0.001$). Reasoning ability also demonstrated a significant rise with t = 12.88 ($p < 0.001$), and solution evaluation achieved the greatest improvement with t = 13.05 ($p < 0.001$). Effect size analysis further indicated large practical effects across all indicators (Cohen's d > 1.50), suggesting that the observed improvements were not only statistically significant but also educationally meaningful. These findings demonstrate that the metaverse-based adaptive gamified learning system effectively supported higher-order mathematical thinking by enabling students to analyze problems, select appropriate strategies, apply logical reasoning, and evaluate solutions within an immersive and adaptive learning environment.

Figure 6: Paired sample t-test results for problem-solving skills

5.5.3 Effectiveness – Cognitive Engagement

The effectiveness of the metaverse-based adaptive gamified learning system on cognitive engagement was evaluated using a self-report cognitive engagement scale questionnaire administered before and after the intervention. The three key indicators assessed were sustained attention, deep reflection and metacognition, and active participation. Paired sample t-tests were performed to analyze changes between pretest and posttest scores.

Table 12: Paired sample t-test results for cognitive engagement

No.	**Indicator**	**Pretest (Mean ± SD)**	**Posttest (Mean ± SD)**	**Gain**	**t-statistic**	**Sig. (p)**	**Remark**
1	Sustained attention	60.8 ± 8.6	86.5 ± 7.4	25.7	11.92	0.000	Significant
2	Deep reflection & metacognition	57.9 ± 9.0	84.3 ± 7.2	26.4	12.38	0.000	Significant
3	Active participation	62.1 ± 8.1	89.2 ± 6.8	27.1	12.77	0.000	Significant

The paired sample t-test results indicated statistically significant improvements across all cognitive engagement indicators following the intervention. Sustained attention increased significantly ($t = 11.92$, $p < 0.001$), while deep reflection and metacognition showed a strong improvement ($t = 12.38$, $p < 0.001$). Active participation demonstrated the largest increase ($t = 12.77$, $p < 0.001$). Effect size analysis revealed large effects for all indicators (Cohen's $d > 1.50$), indicating that the metaverse-based adaptive gamified learning system produced substantial and practically meaningful gains in students' cognitive engagement through immersive, interactive, and personalized learning experiences.

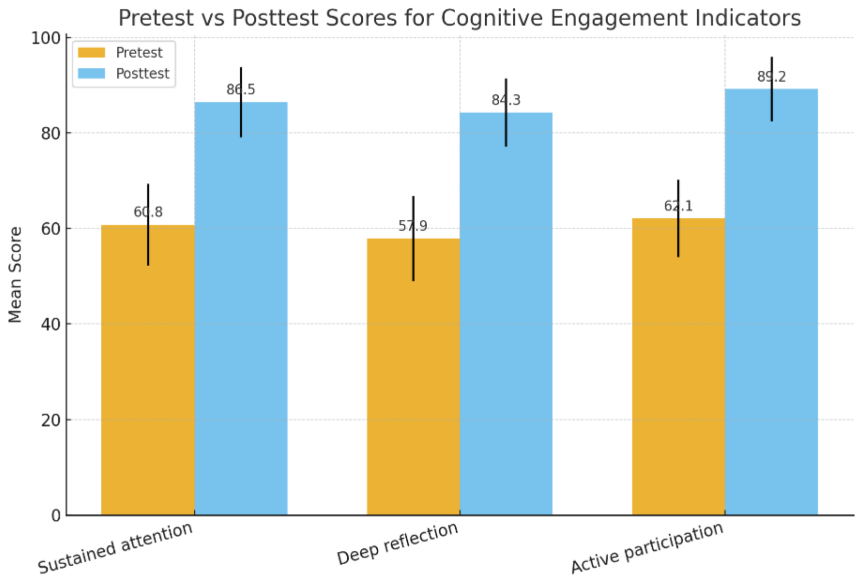

Figure 7: Pretest vs posttest scores for cognitive engagement

6. Discussion

6.1 Development Process

This study has produced significant findings related to the system development process, including design flow, expert validation, black box functional testing, and practicality evaluation. The development process followed the 4D model (define, design, develop, and disseminate) to ensure that the product was pedagogically sound, technically stable, and user-centered.

During the define stage, user needs and learning problems were analyzed, particularly regarding low motivation and difficulties in problem-solving among elementary teacher education students. In the design stage, a metaverse-based adaptive gamified learning system was conceptualized, featuring eight integrated components: management and support, security and privacy, assessment and feedback, collaboration and social interaction, personalization and accessibility, content and interaction, gamification and adaptive mechanisms, and infrastructure.

The system design flow was constructed to provide a seamless learning experience, starting from login and pre-test, similarity and ranking calculations, adaptive scenario selection, immersive 3D visualization, gamification loops with feedback and rewards, blockchain-supported collaboration, and ending with post-test and data logging. This structured flow ensured that the learning process within the metaverse environment was adaptive, interactive, and pedagogically aligned, reflecting recommendations from prior metaverse education research and immersive learning research (Fang et al., 2024; Jagatheesaperumal et al., 2024; López-Belmonte et al., 2023; Makransky et al., 2021; Radianti et al., 2020).

6.2 Teacher Readiness and PBL

An important implication of the findings relates to teacher readiness for implementing PBL. The metaverse-based adaptive gamified system exposed teacher education students to project-oriented, collaborative, and inquiry-driven learning experiences that mirror key PBL principles. Through long-term problem-solving missions, group-based avatar collaboration, and iterative feedback, students not only improved their mathematical competencies but also developed pedagogical readiness to design and facilitate PBL-oriented instruction. This experience is particularly valuable for future elementary teachers, as it models how technology-enhanced PBL can be implemented to promote active learning, collaboration, and authentic problem solving in primary mathematics classrooms (Jagatheesaperumal et al., 2024; López-Belmonte et al., 2023; Bond et al., 2020).

The results of expert validation, black box testing, and practicality testing further confirmed the robustness of the developed system. Expert validation from material, media, and instructional design experts achieved average scores of 90.90%, 89.94%, and 90.40% respectively, all categorized as valid indicating strong curriculum alignment, technical reliability, and pedagogical soundness. Black box testing across six main scenarios and 15 detailed indicators confirmed that all system functions, including registration, 3D navigation, avatar interaction, adaptive feedback, data handling, and cross-device compatibility, worked as expected, achieving a 100% pass rate.

These results show that the platform is technically stable and functionally reliable for classroom use. Furthermore, student practicality testing involving 60 participants produced a total practicality score of 90.17%, with particularly high ratings in ease of use (91.2%), usefulness (92.1%), and willingness for future use (93.4%). These findings indicate that students perceived the system as highly user-friendly, engaging, and beneficial for mathematics learning. Collectively, these development and validation results confirm that the metaverse-based adaptive gamified learning system is pedagogically valid, technically functional, and practically feasible, aligning with recommendations for successful immersive technology integration in education (Dwivedi, 2022; Hong Lin et al., 2022; López-Belmonte et al., 2023; Meena, 2023; Schindler et al., 2017).

The findings of this study demonstrate that integrating metaverse-based adaptive gamified learning significantly improves students′ mathematical motivation, problem-solving skills, and cognitive engagement in mathematics courses for elementary teacher education students. These results align with previous studies that emphasize the transformative potential of immersive technologies in reshaping educational experiences through enhanced interaction, visualization, and personalization (Hong Lin et al., 2022; López-Belmonte et al., 2023; Zhang et al., 2022; Cheng & Tsai, 2020).

The statistically significant improvements in motivation indicators including interest, persistence, self-efficacy, and reduced anxiety highlight how immersive gamified environments can address long-standing challenges in mathematics education, in which abstract concepts often lead to disinterest and anxiety (Daly, 2019; Setyaningrum et al., 2023; Tyaningsih et al., 2022). These findings reinforce evidence that game immersion and challenge–skill balance play a critical role in sustaining learner motivation and performance (Cheng & Tsai, 2020; Makransky et al., 2021). By providing adaptive feedback, clear goals, and engaging learning scenarios, the metaverse platform successfully creates a learning context that fosters both intrinsic and extrinsic motivation, consistent with SDT (Ryan & Deci, 2017) and gamification research in mathematics (da Silva & Rodrigues, 2023; Sailer & Homner, 2020).

6.3 Comparison with Non-Adaptive (Static) Gamification Studies

Compared to studies employing non-adaptive or static gamification, which typically rely on fixed rewards, points, and levels, the findings of this study demonstrate stronger and more consistent improvements across motivation, problem-solving, and cognitive engagement. Previous research on static gamification has reported gains primarily in short-term motivation and engagement, often attributed to novelty effects, with limited impact on higher-order thinking skills.

In contrast, the adaptive gamification mechanism in this study dynamically adjusted task difficulty and feedback based on learners' performance, enabling sustained engagement and deeper cognitive processing. This comparison suggests that adaptivity plays a critical role in extending the pedagogical effectiveness of gamified learning beyond surface-level motivation (Daly, 2019; Setyaningrum et al., 2023; Tyaningsih et al., 2022). This finding supports broader reviews of gamified and immersive learning environments that emphasize adaptivity as a key determinant of long-term educational impact (Cheng & Tsai, 2020; Sailer & Homner, 2020).

The enhancement of cognitive engagement observed in this study is particularly noteworthy because engagement represents a critical mediating factor between instructional design and learning outcomes (Fredricks et al., 2004; Hmoud et al., 2025). In traditional mathematics classrooms, sustaining attention and active participation is challenging, especially when content is perceived as disconnected from real-world contexts (Boaler, 2016; Yunus & Wan Ali, 2009). By leveraging 3D immersive environments, avatar-based interaction, and adaptive gamification, the metaverse system created an experiential learning context that maintained students' sustained attention, encouraged deep reflection, and stimulated active participation.

This aligns with findings from immersive learning research which indicates that multisensory, interactive designs significantly enhance learners' cognitive investment and metacognitive engagement (Jagatheesaperumal et al., 2024). Importantly, the reported effect size for cognitive engagement falls within the large category based on Cohen's criteria, indicating that the observed improvement is not only statistically significant but also educationally meaningful. The adaptive feedback loop within the gamification mechanism further supports cognitive engagement by enabling students to track their progress and adjust learning strategies in real time, thereby fostering a reflective learning process (Mayer 2022; Garzón et al., 2019; Radianti et al., 2020).

Another important implication of these findings is their relevance to teacher education. Future elementary school teachers must not only master mathematical concepts but also be capable of designing and facilitating engaging, technology-enhanced learning experiences for their students (Rungrapeepornphong et al., 2023; Yayuk & Ekowati, 2022). The observed improvements in motivation, problem-solving, and cognitive engagement suggest that metaverse-based learning can serve as both a pedagogical tool and a professional development experience. By participating in immersive gamified learning, teacher education students develop digital competencies and pedagogical creativity that are essential for implementing innovative mathematics instruction in their future classrooms (Dwivedi, 2022; Hartina et al., 2024; Meena, 2023). This dual impact on both learning outcomes and professional readiness underscores the potential of immersive technologies to shape not only what pre-service teachers learn but also how they learn to teach (Bond et al., 2020).

These results contribute to ongoing discussions about the integration of gamification and metaverse technologies in education. Previous research often examined these two approaches separately: gamification focusing on motivation and engagement (Aguiar-Castillo, 2022; Solekhah et al., 2023), and metaverse studies emphasizing immersion and visualization (Fang et al., 2024; Sin et al., 2023). This study’s novelty lies in combining adaptive gamification with metaverse environments, thereby addressing both motivational and cognitive dimensions simultaneously.

The significant improvements across all measured outcomes provide empirical support for theoretical frameworks, such as SDT and CTML, which together explain how psychological needs, satisfaction, and optimized cognitive processing can lead to improved learning performance (Mayer, 2022; Ryan & Deci, 2017). Moreover, the findings align with the Education 4.0 vision, emphasizing adaptability, creativity, and digital literacy as essential competencies for future educators (Dwivedi, 2022; Jagatheesaperumal et al., 2024), while also extending empirical evidence from immersive and game-based learning research (Makransky et al., 2021; Radianti et al., 2020; Schindler et al., 2017).

Minor technical challenges, including temporary dizziness or eye strain during initial exposure to immersive environments, were reported by a small number of students; these issues were mitigated through gradual familiarization, flexible non-VR access, and optimized navigation to support inclusive system use. The blockchain component contributed primarily to secure authentication, reliable data logging, and transparent collaboration rather than direct instructional outcomes, thereby enhancing system reliability and user trust in adaptive and collaborative learning processes. In terms of sustainability, the platform demonstrates strong potential for long-term integration into standard curricula due to its modular design, device flexibility, and alignment with curricular objectives, although sustained implementation will require institutional support, teacher training, and ongoing technical maintenance (Mayer, 2022; Ryan & Deci, 2017).

7. Conclusion

This study concludes that the metaverse-based adaptive gamified learning system developed through the 4D model is valid, functional, practical, and effective in enhancing mathematics learning for elementary teacher education students. The system integrates immersive 3D environments, avatar-based interaction, adaptive challenges, and gamification mechanisms, resulting in significant improvements in mathematical motivation, problem-solving skills, and cognitive engagement. Expert validation scores exceeded 89% in all categories, black box testing achieved 100% functionality, and practicality testing showed a high usability score of 90.17%. The experimental results confirmed statistically significant increases across all indicators, demonstrating that adaptive gamification within a metaverse environment can simultaneously strengthen students' motivational, cognitive, and analytical capacities in mathematics learning.

7.1 Suggestions

Future implementations should consider integrating metaverse-based adaptive gamified learning systems more broadly into teacher education curricula to foster both mathematical competence and digital pedagogical skills. Educators are encouraged to use the system not only as a supplement but as part of their instructional strategies, promoting active learning and engagement. Educational technology developers should continue refining adaptive features such as real-time feedback and personalized challenge sequencing to improve learner support. Further research should involve larger and more diverse populations, explore different subjects, and examine long-term impacts to optimize scalability and institutional integration.

7.2 Limitations

This study has several limitations that should be acknowledged. The research was conducted within a single institutional context involving 60 students, which may limit the generalizability of the findings. The duration of the intervention was relatively short, focusing on immediate pretest–posttest outcomes, rather than long-term retention. The study relied mainly on quantitative methods; future studies could incorporate qualitative approaches for deeper insight into learning experiences. Additionally, while system functionality and validity were confirmed, further large-scale and stress testing are needed to examine performance across more varied and demanding educational settings.

Conflict of Interest

The author(s) declare no potential conflict of interest.

8. Acknowledgments

We thank the Directorate of Research and Community Service of the Ministry of Community Service of Higher Education, Science and Technology, University Muhammadiyah of Malang for supporting and facilitating this research.

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