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The Trend of Gamification in Mathematics Learning: A Problem-Based Instruction Approach with AI Integration

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Abstract: The integration of gamification, problem-based instruction (PBI), and artificial intelligence (AI) in mathematics learning represents a contemporary pedagogical trend aimed at enhancing student engagement, critical thinking, and learning outcomes. This study aims to develop and implement a gamified PBI model with AI assistance to improve mathematics learning outcomes among senior high school students. The research employed a Research and Development (RD) approach using the ADDIE model (Analyze, Design, Development, Implementation, Evaluation). The study involved 180 Grade XI students from six classes (XI-MIPA-A–F) at SMA Negeri 2 Padangsidimpuan, North Sumatra, Indonesia, during the odd semester of the 2025/2026 academic year (January–June 2026). The instruments included a mathematics achievement test, gamification engagement questionnaire, AI literacy scale, and PBI perception survey. Expert validation (n=5) indicated high content validity (Vexp > 0.85). Empirical validity showed that all 35 items had r-calculated > r-table (0.148, p<0.05). Reliability coefficients (Cronbach's alpha) ranged from 0.78 to 0.89 across instruments. The implementation results showed a significant increase in mathematics learning outcomes (pre-test mean = 58.4; post-test mean = 84.7; t = 21.34, p < 0.001). Gamification engagement was high (mean = 4.2/5), and AI integration improved problem-solving efficiency by 32%. The findings indicate that the gamified PBI model with AI integration is feasible, valid, and effective in improving mathematics learning outcomes. This study contributes to the growing body of literature on technology-enhanced mathematics education in the context of the Merdeka Curriculum.

Keywords: Gamification, Mathematics Learning, Problem-Based Instruction, AI Integration, Senior High School, ADDIE

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1. Introduction

The rapid advancement of digital technology has fundamentally reshaped the landscape of mathematics education. In the 21st century, students are expected not only to master mathematical concepts but also to develop critical thinking, collaboration, creativity, and problem-solving skills [1]. However, traditional mathematics instruction often fails to engage students actively, leading to low motivation and poor learning outcomes [2]. In response, educators and researchers have explored innovative pedagogical approaches, including gamification, problem-based instruction (PBI), and artificial intelligence (AI) integration [3].

The rapid advancement of digital technology has fundamentally reshaped the landscape of mathematics education in profound and far-reaching ways. In the contemporary era, often associated with the demands of the 21st century, learning is no longer confined to traditional classrooms but is increasingly mediated by digital platforms and intelligent systems [4]. Students are now expected not only to master mathematical concepts but also to develop higher-order skills such as critical thinking, collaboration, creativity, and complex problem-solving abilities. These competencies are essential for navigating an increasingly data-driven and technology-oriented world, as highlighted in recent studies such as those by [1]. Furthermore, the integration of digital tools has opened new possibilities for visualizing abstract mathematical concepts, making them more accessible and meaningful for learners [5]. Despite these opportunities, many educational institutions still rely heavily on conventional teaching methods that emphasize rote learning and procedural knowledge. This mismatch between technological advancement and pedagogical practice often results in a learning environment that fails to fully engage students [6]. As a consequence, students may struggle to see the relevance of mathematics in real-life contexts. Therefore, there is a pressing need to align instructional practices with the evolving digital landscape to foster more meaningful and engaging learning experiences. The transformation of mathematics education must be guided by innovative approaches that leverage technology to enhance both understanding and motivation [7].

Traditional mathematics instruction often fails to actively involve students in the learning process, which can lead to disengagement and reduced academic performance. Teacher-centered approaches, which dominate many classrooms, tend to position students as passive recipients of knowledge rather than active participants in constructing their own understanding. This lack of engagement can significantly impact students' motivation, especially in a subject like mathematics that is frequently perceived as difficult and abstract [7]. As a result, many students develop negative attitudes toward mathematics, which further hinders their learning outcomes. In addition, traditional methods often do not provide sufficient opportunities for students to develop essential skills such as collaboration and problem-solving. The limited use of interactive and contextual learning strategies can make mathematical concepts appear disconnected from real-world applications [8]. Consequently, students may fail to appreciate the practical value of mathematics in everyday life. Recent educational research has emphasized the importance of student-centered learning environments that promote active participation and meaningful interaction. Without such approaches, the gap between expected competencies and actual student performance is likely to persist. Therefore, rethinking traditional instructional strategies is critical to addressing these challenges and improving overall learning effectiveness [7].

In response to these limitations, educators and researchers have increasingly explored innovative pedagogical approaches that aim to enhance student engagement and learning outcomes. Among these approaches, gamification has emerged as a powerful strategy for making learning more interactive and enjoyable. By incorporating game elements such as points, badges, leaderboards, and challenges, gamification can motivate students to participate more actively in the learning process [9]. In addition, problem-based instruction (PBI) emphasizes the use of real-world problems as a context for learning, encouraging students to develop critical thinking and analytical skills. This approach allows students to construct knowledge through exploration and inquiry rather than passive reception. Furthermore, the integration of artificial intelligence (AI) in education has introduced adaptive learning systems that can personalize instruction based on individual student needs [8]. According to [3], the combination of these approaches has the potential to significantly improve both engagement and achievement in mathematics learning. AI-powered tools can provide immediate feedback, track student progress, and offer tailored learning pathways. When combined with gamification and PBI, these technologies create a dynamic and interactive learning environment. Such an environment supports not only cognitive development but also emotional and motivational aspects of learning. Therefore, the integration of these innovative strategies represents a promising direction for the future of mathematics education [8].

The synergy between gamification, problem-based instruction, and AI-based educational tools offers a comprehensive framework for addressing the challenges of modern mathematics education. This integrated approach aligns well with the needs of digital-native students who are accustomed to interactive and technology-rich environments. By embedding game mechanics within problem-based learning scenarios, educators can create immersive experiences that stimulate curiosity and sustained engagement [10]. At the same time, AI technologies can enhance this process by providing data-driven insights and personalized support. For instance, AI can analyze student performance patterns and recommend specific interventions to improve understanding. This level of personalization is difficult to achieve through traditional teaching methods alone. Additionally, the use of gamified elements can foster a sense of achievement and competition, which further motivates students to excel [11]. The incorporation of real-world problems ensures that learning remains relevant and meaningful. As a result, students are more likely to develop a deeper understanding of mathematical concepts and their applications. Ultimately, this integrated approach not only improves academic performance but also prepares students with the skills needed for lifelong learning. Therefore, embracing these innovations is essential for creating a more effective and future-ready mathematics education system [11].

Gamification—the application of game design elements in non-game contexts—has emerged as a powerful strategy to increase student motivation and engagement in mathematics learning [12]. Elements such as points, badges, leaderboards, and challenges transform abstract mathematical concepts into enjoyable and competitive activities. Nevertheless, gamification alone may not sufficiently develop higher-order thinking skills. Therefore, combining gamification with problem-based instruction (PBI) offers a promising synergy: PBI provides authentic, ill-structured problems that require deep reasoning, while gamification sustains motivation throughout the problem-solving process [13].

In recent years, educational researchers have highlighted how gamification can transform traditionally rigid learning environments into dynamic and interactive experiences. According to Yan and Matore (2023) [12], the integration of game elements into academic contexts has shown significant potential in improving students' interest and persistence in learning mathematics. By embedding elements such as points, badges, leaderboards, and structured challenges, educators can create an atmosphere that mirrors the excitement of digital games [10]. This transformation is particularly important in mathematics, a subject that is often perceived by students as abstract, difficult, and less engaging. Gamification helps bridge this gap by presenting mathematical problems in a more approachable and stimulating format. As a result, students become more willing to participate actively in classroom activities. Moreover, gamified environments often promote a sense of achievement and progress, which can reinforce positive learning behaviors. Students are encouraged to set goals, track their performance, and strive for improvement. Consequently, gamification not only enhances engagement but also contributes to sustained motivation over time [11].

The use of gamification elements such as points, badges, leaderboards, and challenges plays a crucial role in reshaping students' learning experiences. Points provide immediate feedback and reward incremental progress, helping students recognize their achievements in real time. Badges serve as symbols of accomplishment, offering recognition for mastering specific skills or completing particular tasks. Leaderboards introduce a competitive dimension that can motivate students to improve their performance relative to their peers [10]. Meanwhile, challenges stimulate curiosity and encourage students to solve problems in a structured yet enjoyable manner. These elements collectively transform abstract mathematical concepts into more concrete and engaging learning activities. Students are no longer passive recipients of information but active participants in a game-like learning environment. Furthermore, gamification can foster collaboration when designed to include group challenges or team-based competitions [14]. This collaborative aspect is essential in developing communication and teamwork skills among students. However, it is important to note that the effectiveness of gamification depends on thoughtful design and alignment with learning objectives. Poorly implemented gamification may lead to superficial engagement without meaningful learning. Therefore, educators must carefully integrate these elements to ensure they support deeper understanding [14].

Despite its many advantages, gamification alone may not be sufficient to develop higher-order thinking skills required in mathematics education. While it effectively enhances motivation and engagement, it often focuses more on external rewards rather than deep cognitive processes. Students may become more interested in earning points or badges than in truly understanding the underlying mathematical concepts [14]. This limitation highlights the need for complementary instructional approaches that emphasize critical thinking and problem-solving. Higher-order thinking skills, such as analysis, evaluation, and synthesis, require learners to engage with complex and meaningful problems. Traditional gamification strategies may not always provide the depth needed to cultivate these abilities. As a result, relying solely on gamification could lead to an imbalance between motivation and cognitive development. Educational researchers have therefore advocated for the integration of gamification with other pedagogical models. This integration aims to combine the motivational benefits of gamification with the intellectual rigor of more cognitively demanding approaches. In doing so, educators can create a more balanced and effective learning environment. Thus, the role of gamification should be viewed as supportive rather than standalone [15].

One promising approach to addressing this limitation is the integration of gamification with problem-based instruction (PBI). Problem-based instruction emphasizes learning through engagement with authentic, real-world problems that are often complex and ill-structured. This approach encourages students to think critically, explore multiple solutions, and develop a deeper understanding of mathematical concepts [16]. When combined with gamification, PBI can create a learning environment that is both intellectually challenging and highly motivating. According to [13], this combination offers a powerful synergy that enhances both engagement and cognitive development. Gamification elements can be used to maintain student interest and motivation throughout the problem-solving process. At the same time, PBI ensures that students are actively engaged in meaningful learning tasks that require deep reasoning. This integration allows students to experience the best of both approaches. They are motivated to participate while also being challenged to think critically and solve complex problems. Furthermore, this approach aligns well with the goals of 21st-century education. It prepares students not only to understand mathematical concepts but also to apply them in real-life situations [15].

The synergy between gamification and problem-based instruction ultimately creates a more holistic and effective mathematics learning experience. By combining motivational strategies with cognitively demanding tasks, educators can address both the affective and intellectual needs of students. Gamification sustains students' enthusiasm and engagement, while PBI fosters deep understanding and critical thinking skills [15]. This integrated approach also supports the development of independent learning, as students take greater responsibility for solving problems and achieving learning goals. In addition, it encourages perseverance, as students are motivated to overcome challenges and improve their performance. The use of real-world problems further enhances the relevance of mathematics, helping students see its practical applications. As a result, students are more likely to develop a positive attitude toward mathematics [15]. This positive attitude can lead to improved learning outcomes and long-term academic success. Moreover, the combination of these approaches provides opportunities for differentiated instruction, allowing educators to cater to diverse student needs. Ultimately, integrating gamification with problem-based instruction represents a forward-thinking strategy in mathematics education. It offers a balanced approach that not only engages students but also equips them with essential skills for the future [16].

Furthermore, the integration of artificial intelligence (AI) into mathematics learning opens new possibilities for personalized and adaptive instruction. AI tools can provide real-time feedback, generate adaptive problem sets, and assist students in visualizing complex mathematical structures [17]. When embedded within a gamified PBI framework, AI can scaffold student learning, reduce cognitive load, and enhance problem-solving efficiency. However, few studies have systematically examined the combined effect of gamification, PBI, and AI in senior high school mathematics [16].

In recent years, AI has emerged as a powerful tool capable of reshaping how students interact with mathematical content and how teachers facilitate learning. Unlike traditional instructional methods, AI-driven systems can analyze individual learning patterns and tailor content to meet each student's specific needs. This personalization ensures that students receive appropriate levels of challenge and support, thereby optimizing their learning experiences. According to [17], AI tools are particularly effective in enhancing the quality and responsiveness of mathematics instruction. These technologies enable a shift from one-size-fits-all teaching approaches to more individualized learning pathways. As a result, students can progress at their own pace without feeling overwhelmed or left behind [18]. Furthermore, AI integration aligns with the broader goals of digital transformation in education. It supports the development of data-driven decision-making in teaching and learning processes. Therefore, AI has the potential to significantly improve both the efficiency and effectiveness of mathematics education [16]. One of the key advantages of AI in mathematics learning lies in its ability to provide real-time feedback and generate adaptive problem sets. Immediate feedback is essential for helping students identify and correct misconceptions before they become deeply ingrained [19]. AI systems can instantly evaluate student responses and offer explanations or hints that guide learners toward the correct solution. In addition, adaptive problem sets allow students to engage with tasks that are aligned with their current level of understanding. This dynamic adjustment ensures that students are neither bored by tasks that are too easy nor frustrated by those that are too difficult. Moreover, AI can assist students in visualizing complex mathematical structures through interactive simulations and graphical representations. These visualizations make abstract concepts more concrete and easier to comprehend [19]. For example, topics such as calculus, geometry, and algebra can be explored through dynamic models that respond to student input. This interactive engagement enhances conceptual understanding and retention. Consequently, AI not only supports procedural learning but also deepens students' conceptual insights. The combination of feedback, adaptability, and visualization makes AI an invaluable tool in modern mathematics education [19].

When embedded within a gamified problem-based instruction (PBI) framework, AI can further enhance the overall learning experience by providing structured support and scaffolding. In such a framework, students are presented with meaningful, real-world problems that require critical thinking and analytical reasoning. Gamification elements maintain motivation and engagement, while AI acts as an intelligent guide throughout the learning process. AI can break down complex problems into manageable steps, offering hints and suggestions that reduce cognitive overload [19]. This scaffolding is particularly beneficial for students who may struggle with challenging mathematical tasks. By reducing cognitive load, AI allows students to focus more on understanding concepts rather than being overwhelmed by complexity. Additionally, AI can monitor student progress and adjust the level of support as needed. This ensures that learners gradually develop independence and confidence in their problem-solving abilities. The integration of AI in this context creates a balanced learning environment that supports both engagement and cognitive development. Therefore, combining AI with gamified PBI represents a highly effective instructional strategy [20].

Despite these promising advantages, research on the combined implementation of gamification, problem-based instruction, and AI remains relatively limited, particularly at the senior high school level. Most existing studies tend to focus on these approaches in isolation rather than examining their integrated impact. As a result, there is a lack of comprehensive understanding regarding how these strategies interact to influence student learning outcomes [20]. This gap in the literature highlights the need for more systematic and empirical investigations. In particular, studies are needed to explore how the integration of these approaches affects students' motivation, critical thinking skills, and overall academic performance. Additionally, there is a need to examine the practical challenges associated with implementing such integrated models in real classroom settings. Factors such as teacher readiness, technological infrastructure, and curriculum alignment must be considered. Without addressing these factors, the potential benefits of integration may not be fully realized. Therefore, further research is essential to provide evidence-based guidelines for effective implementation [21].

Given these considerations, the integration of gamification, PBI, and AI represents a promising yet underexplored frontier in mathematics education. This combined approach has the potential to create a highly engaging, adaptive, and intellectually stimulating learning environment. By leveraging the strengths of each component, educators can design instructional experiences that address both the motivational and cognitive needs of students. Gamification enhances engagement, PBI fosters deep understanding, and AI provides personalized support and feedback [20]. Together, these elements form a comprehensive framework for improving mathematics learning outcomes. Moreover, this approach aligns with the demands of 21st-century education, which emphasizes the integration of technology and the development of higher-order thinking skills. As educational systems continue to evolve, embracing such innovative strategies will be crucial for preparing students for future challenges. Therefore, advancing research and practice in this area is of great importance. It not only contributes to academic knowledge but also has practical implications for improving the quality of mathematics education at the senior high school level [21].

Indonesia, through the Merdeka Curriculum, encourages student-centered, technology-integrated learning. SMA Negeri 2 Padangsidimpuan, as a pilot school, faces challenges in implementing such innovations. Preliminary observations (January 2026) indicated that 68% of Grade XI students perceived mathematics as difficult and boring, and only 45% achieved the minimum competency criteria (KKM 75). Therefore, this study aims to develop and evaluate a gamified PBI model with AI integration to improve mathematics learning outcomes. The research questions are:

1. How is the validity and reliability of the developed gamified PBI-AI model?
2. What is the trend of gamification in mathematics learning through PBI with AI integration?
3. What is the effectiveness of the model in improving students' mathematics learning outcomes?
4. What are students' perceptions of engagement, AI usefulness, and problem-solving skills?

2. Literature Review

2.1. Gamification in Mathematics Education

Gamification refers to the use of game mechanics (points, badges, levels, feedback, competition) in educational settings to enhance motivation and learning [22]. In mathematics, gamification has been shown to increase student engagement, reduce anxiety, and improve performance [12]. A systematic literature review by Yan and Matore (2023) [12] found that most gamification studies in mathematics focused on primary school students (38%) and affective domains (motivation, attitude). However, there is a lack of research on senior high school students and the integration of gamification with problem-based learning and AI [21].

Gamification has gained widespread attention as an innovative pedagogical approach in various fields, including mathematics education [23]. In the context of mathematics learning, gamification aims to transform abstract and often challenging content into more engaging and interactive experiences. By incorporating elements commonly found in games, educators can create a learning environment that encourages active participation and sustained interest. Students are motivated to achieve specific goals, track their progress, and compete in a healthy and constructive manner [21]. This approach aligns with contemporary educational demands that emphasize student-centered learning and intrinsic motivation. Moreover, gamification provides immediate feedback, allowing students to recognize their strengths and areas for improvement in real time. Such feedback is crucial in mathematics, where misconceptions can easily hinder further understanding. As a result, gamification has become an increasingly popular strategy for enhancing both engagement and achievement in mathematics education [23].

In mathematics classrooms, gamification has been shown to significantly increase student engagement and reduce anxiety associated with learning complex concepts. Mathematics is often perceived as a difficult and intimidating subject, leading to negative attitudes and low self-confidence among students. Gamified learning environments help alleviate these issues by introducing elements of fun, challenge, and reward. According to Yan and Matore (2023) [12], students who engage in gamified mathematics activities tend to exhibit higher levels of motivation and more positive attitudes toward the subject. The use of points and badges provides a sense of accomplishment, while leaderboards can foster a spirit of friendly competition. Additionally, gamification can create a safe space for students to make mistakes and learn from them without fear of judgment [23]. This is particularly important in developing mathematical resilience and persistence. Interactive challenges and game-based tasks also encourage students to think critically and explore multiple solution strategies. Consequently, gamification not only improves affective outcomes but also contributes to cognitive development. These benefits highlight the potential of gamification as a valuable tool in modern mathematics education [24].

Despite its advantages, the implementation of gamification in mathematics education has primarily focused on certain educational levels and learning domains. A systematic literature review conducted by Yan and Matore (2023) [12] revealed that a significant proportion of gamification studies in mathematics are concentrated at the primary school level, accounting for approximately 38% of the research. This indicates a strong emphasis on younger learners, while relatively less attention has been given to secondary and senior high school students [24]. Furthermore, many of these studies tend to focus on affective domains, such as motivation, engagement, and attitudes toward learning. While these aspects are undeniably important, they do not fully capture the complexity of mathematics learning, which also requires the development of higher-order thinking skills. The limited focus on cognitive outcomes suggests a gap in the existing literature [25]. In addition, the overrepresentation of certain contexts may limit the generalizability of research findings. As educational needs evolve, it becomes increasingly important to explore the impact of gamification across diverse learning environments and student populations. Therefore, expanding research to include more varied contexts is essential for a comprehensive understanding of gamification's effectiveness [25].

Another critical limitation in current research is the lack of integration between gamification and other innovative instructional approaches. While gamification has proven effective in enhancing motivation, it is often implemented as a standalone strategy without being combined with pedagogical models that promote deeper learning. For instance, problem-based learning (PBL) or problem-based instruction (PBI) emphasizes the development of critical thinking and problem-solving skills through engagement with real-world problems ([24]. Integrating gamification with such approaches could create a more balanced learning experience that addresses both affective and cognitive domains. Similarly, the incorporation of artificial intelligence (AI) into gamified learning environments remains underexplored. AI has the potential to provide personalized feedback, adaptive learning pathways, and intelligent support systems [25]. When combined with gamification, AI could further enhance student engagement and learning efficiency. However, the lack of empirical studies examining these integrations represents a significant research gap. Addressing this gap could lead to the development of more comprehensive and effective instructional models in mathematics education [26].

Given these gaps, there is a clear need for further research that investigates the application of gamification in more advanced educational contexts, particularly at the senior high school level. Such research should not only examine the impact of gamification on motivation and attitudes but also explore its effectiveness in improving higher-order thinking skills and academic performance. Additionally, studies should focus on the integration of gamification with problem-based instruction and AI-based educational tools [27]. This integrated approach has the potential to create a more holistic learning environment that supports both engagement and deep understanding. By combining the strengths of these strategies, educators can better address the diverse needs of students in modern classrooms. Furthermore, exploring these integrations can provide valuable insights into how technology can be effectively leveraged in education. As the field of mathematics education continues to evolve, adopting innovative and evidence-based approaches will be essential. Therefore, future research in this area is not only relevant but also necessary for advancing the quality of mathematics learning [26].

2.2. Problem-Based Instruction (PBI) in Mathematics

Problem-based instruction is a student-centered pedagogy where students learn through solving complex, real-world problems [28]. PBI fosters critical thinking, collaboration, and self-directed learning. In mathematics, PBI helps students connect abstract concepts to practical applications. However, PBI can be challenging for students who lack sustained motivation. Gamification elements can address this by providing immediate rewards and progress tracking [29].

Problem-based instruction (PBI) is a student-centered pedagogical approach in which learning occurs through the exploration and resolution of complex, real-world problems. As emphasized by [28], PBI shifts the focus of instruction from teacher-led explanations to student-driven inquiry and investigation. In this approach, students are not merely passive recipients of information but active participants who construct their own understanding through problem-solving activities [27]. The problems presented in PBI are typically ill-structured, meaning they do not have a single correct answer and require deep reasoning. This characteristic encourages students to explore multiple strategies and perspectives when approaching mathematical tasks. Furthermore, PBI aligns well with constructivist learning theory, which emphasizes that knowledge is actively built by learners [30]. In mathematics education, this approach is particularly valuable because it allows students to engage with concepts in meaningful and contextualized ways. As a result, students develop a deeper and more flexible understanding of mathematical ideas. PBI also promotes inquiry-based learning, where questioning and exploration become central to the learning process. Therefore, it represents a significant shift toward more active and meaningful mathematics instruction [26].

One of the major strengths of PBI is its ability to foster critical thinking skills among students. When students are presented with complex problems, they are required to analyze information, identify relevant variables, and develop appropriate solution strategies. This process enhances their ability to think logically and systematically. In addition, PBI encourages collaboration, as students often work in groups to discuss ideas and share different perspectives [27]. Through collaborative learning, students can learn from one another and develop communication skills that are essential for academic and professional success. Moreover, PBI promotes self-directed learning by giving students greater responsibility for their own learning process. Students must identify what they need to know, seek out relevant information, and evaluate the effectiveness of their solutions. This autonomy helps build confidence and independence in learning [30]. In mathematics, these skills are particularly important because they enable students to approach unfamiliar problems with greater confidence. Consequently, PBI not only enhances cognitive development but also supports the development of essential soft skills. These outcomes make PBI a highly valuable approach in modern education [26].

In the context of mathematics education, PBI plays a crucial role in helping students connect abstract concepts to real-world applications. Mathematics is often perceived as a collection of abstract symbols and procedures, which can make it difficult for students to see its relevance. PBI addresses this issue by presenting problems that are grounded in real-life situations. For example, students might be asked to solve problems related to budgeting, engineering design, or data analysis. These contexts make mathematical concepts more meaningful and easier to understand [26]. By engaging with real-world problems, students can see how mathematics is used in everyday life and various professional fields. This relevance increases student interest and motivation to learn. Additionally, PBI encourages students to apply their knowledge in practical situations, which enhances retention and transfer of learning. Students are not only learning mathematical procedures but also understanding when and how to use them. As a result, their learning becomes more functional and applicable. Therefore, PBI serves as an effective bridge between theoretical knowledge and practical application in mathematics [31].

Despite its many benefits, the implementation of PBI in mathematics classrooms is not without challenges. One of the primary difficulties is that students may struggle to maintain sustained motivation throughout the problem-solving process. Complex problems often require significant time and effort, which can lead to frustration, especially for students who lack confidence in their abilities. Without adequate support, some students may become disengaged and lose interest in the task [31]. Additionally, PBI requires students to take a more active role in their learning, which can be challenging for those who are accustomed to traditional, teacher-centered instruction. Teachers also face challenges in designing appropriate problems and facilitating the learning process effectively [32]. The open-ended nature of PBI tasks can make assessment more complex as well. Furthermore, not all students have the same level of readiness for self-directed learning. These challenges highlight the need for additional strategies to support student engagement and persistence. Without such support, the potential benefits of PBI may not be fully realized. Therefore, it is important to complement PBI with approaches that can enhance motivation and provide structured guidance [33].

One effective way to address these challenges is by integrating gamification elements into the PBI framework. Gamification can enhance motivation by introducing elements such as rewards, points, and progress tracking, which encourage students to remain engaged in the learning process. According to Hulse et al. (2019) [29], the use of immediate feedback and reward systems can significantly improve student persistence and participation. In a gamified PBI environment, students can earn points or badges for completing tasks, solving problems, or demonstrating progress [31]. These rewards provide a sense of achievement and motivate students to continue working on challenging problems. Additionally, progress tracking allows students to monitor their development and set personal learning goals. This can increase their sense of ownership and responsibility for their learning. Gamification also introduces an element of enjoyment, which can reduce the stress and anxiety often associated with complex problem-solving tasks [30]. When students perceive learning as both challenging and enjoyable, they are more likely to remain engaged [33]. Therefore, the integration of gamification with PBI creates a more balanced and effective instructional approach. It combines the cognitive benefits of problem-based learning with the motivational advantages of game-based elements.

2.3. AI Integration in Mathematics Learning

Artificial intelligence in education includes intelligent tutoring systems, adaptive learning platforms, and generative AI tools (e.g., ChatGPT, Google Gemini). AI can provide personalized scaffolding, generate step-by-step solutions, and offer instant feedback [34]. When combined with gamification and PBI, AI can act as a virtual coach, helping students navigate complex problems without diminishing their autonomy [35]. However, ethical considerations such as over-reliance and data privacy must be addressed.

Artificial intelligence (AI) in education encompasses a wide range of technologies, including intelligent tutoring systems, adaptive learning platforms, and generative AI tools such as ChatGPT and Google Gemini. These tools are designed to enhance teaching and learning processes by leveraging data, automation, and machine learning algorithms [33]. In the context of mathematics education, AI has become increasingly relevant due to its ability to handle complex problem-solving processes and provide tailored instructional support. Unlike traditional learning systems, AI-powered platforms can continuously analyze student performance and adjust learning pathways accordingly. This dynamic adaptability allows for more efficient and targeted instruction. According to Ng et al. (2024) [34], AI technologies have significantly improved the accessibility and quality of educational resources. Students can now engage with interactive systems that respond intelligently to their inputs. Furthermore, AI supports both synchronous and asynchronous learning environments. As digital transformation continues to accelerate, the role of AI in mathematics education is expected to expand further. Therefore, integrating AI into learning environments represents a critical advancement in modern education [36].

One of the most significant advantages of AI in mathematics learning is its ability to provide personalized scaffolding and adaptive support. AI systems can identify students' strengths and weaknesses by analyzing their responses in real time. Based on this analysis, the system can offer tailored hints, explanations, and additional practice problems [36]. This personalized scaffolding helps students overcome learning obstacles more effectively. Moreover, AI can generate step-by-step solutions that guide students through complex mathematical procedures. These detailed explanations are particularly beneficial for students who struggle with abstract concepts. Instant feedback is another key feature of AI, allowing students to immediately recognize and correct errors [36]. This rapid response helps prevent the reinforcement of misconceptions. Additionally, AI-driven visualizations can make difficult topics such as calculus or geometry more intuitive. By presenting concepts in interactive formats, students can better grasp underlying principles. Consequently, AI not only enhances procedural understanding but also supports conceptual learning. This makes AI an invaluable tool for improving mathematics education outcomes [37].

When combined with gamification and problem-based instruction (PBI), AI can function as a virtual coach that supports students throughout the learning process. In such an integrated framework, students engage with real-world problems while being motivated by gamified elements such as rewards and progress tracking. AI enhances this experience by providing timely guidance without directly giving away answers. According to Yim and Su (2025) [35], this balance is crucial in maintaining student autonomy while still offering necessary support. AI can break down complex problems into manageable steps, reducing cognitive load and making tasks more approachable. At the same time, it encourages students to think independently and explore different solution strategies. The role of AI as a virtual coach also includes monitoring student progress and suggesting appropriate interventions when needed. This creates a responsive and supportive learning environment. Furthermore, the integration of these approaches aligns with the goals of 21st-century education. It fosters not only knowledge acquisition but also critical thinking and problem-solving skills. Therefore, the synergy between AI, gamification, and PBI represents a powerful model for mathematics learning [37].

Another important contribution of AI in mathematics education is its ability to enhance learning efficiency and accessibility. AI-powered systems can be accessed anytime and anywhere, allowing students to learn beyond the boundaries of the classroom. This flexibility is particularly beneficial in supporting diverse learning needs and schedules. Students who require additional practice can access extra resources, while advanced learners can explore more challenging materials [37]. AI also reduces the burden on teachers by automating routine tasks such as grading and feedback. This allows educators to focus more on facilitating meaningful learning experiences. Additionally, AI can support inclusive education by providing accommodations for students with different learning abilities. For example, text-to-speech and adaptive interfaces can assist students with specific learning difficulties. The scalability of AI systems makes them suitable for large and diverse student populations [38]. As a result, AI contributes to more equitable access to quality education. These advantages highlight the transformative potential of AI in mathematics learning environments. However, effective implementation requires careful planning and integration with pedagogical strategies.

Despite its many benefits, the integration of AI in mathematics education also raises important ethical considerations that must be addressed. One major concern is the potential for over-reliance on AI tools, which may reduce students' ability to think independently. If students depend too heavily on AI-generated solutions, they may not fully develop critical problem-solving skills. Additionally, issues related to data privacy and security are increasingly significant [38]. AI systems often collect and analyze large amounts of student data, which must be handled responsibly to protect user confidentiality. There is also a need to ensure transparency in how AI algorithms function and make decisions. Without proper oversight, biases in AI systems could negatively impact learning outcomes. Educators must therefore strike a balance between leveraging AI's capabilities and maintaining pedagogical integrity [39]. Clear guidelines and ethical frameworks are essential for responsible AI use in education. Furthermore, students should be educated about the appropriate use of AI as a learning tool rather than a shortcut. Addressing these challenges is crucial for maximizing the benefits of AI while minimizing potential risks.

2.4. Theoretical Framework: ADDIE Model and SDT

This study is grounded in the ADDIE model (Analysis, Design, Development, Implementation, Evaluation) for systematic instrument and instructional design [28]. The Self-Determination Theory (SDT) posits that intrinsic motivation is enhanced when autonomy, competence, and relatedness are supported. Gamification addresses competence (through points/levels) and relatedness (through leaderboards/teams), while PBI supports autonomy (choice in problem-solving strategies). AI integration enhances competence by providing adaptive support [38].

This study is grounded in two complementary theoretical foundations, namely the ADDIE model and Self-Determination Theory (SDT), which together provide a comprehensive basis for instructional design and motivational support. The ADDIE models consisting of Analysis, Design, Development, Implementation, and Evaluationâ serves as a systematic framework for developing effective learning instruments and instructional interventions. As highlighted by Siregar and Rahmayanti [28], this model ensures that educational innovations are carefully planned, executed, and continuously improved. In the context of this study, the Analysis phase involves identifying students needs, learning challenges, and gaps in current mathematics instruction [39]. The Design phase focuses on structuring gamified problem-based learning activities integrated with AI tools. During the Development phase, instructional materials and digital components are created and refined. The Implementation phase involves applying these innovations in real classroom settings, particularly at the senior high school level. Finally, the Evaluation phase assesses the effectiveness of the intervention in terms of student motivation, engagement, and learning outcomes. Through this systematic process, the ADDIE model ensures that the developed learning approach is both practical and evidence-based. Therefore, it provides a strong methodological foundation for this research [40].

In addition to the ADDIE model, this study is also informed by Self-Determination Theory (SDT), which emphasizes the importance of intrinsic motivation in the learning process. SDT posits that individuals are more motivated and engaged when three basic psychological needs are fulfilled: autonomy, competence, and relatedness. Autonomy refers to the sense of control over one's own learning activities, competence relates to the feeling of effectiveness and mastery, and relatedness involves meaningful connections with others [40]. These components are particularly relevant in mathematics education, where student motivation often plays a critical role in learning success. By incorporating SDT into the instructional design, this study aims to create a learning environment that not only enhances cognitive outcomes but also supports students psychological needs. When students feel autonomous, competent, and connected, they are more likely to engage deeply with learning tasks [41]. This intrinsic motivation leads to more meaningful and sustained learning experiences. Furthermore, SDT provides a theoretical explanation for why certain instructional strategies, such as gamification and problem-based learning, are effective. Thus, it complements the ADDIE model by addressing the motivational dimension of learning [42].

Gamification, as implemented in this study, primarily addresses the need for competence and relatedness within the SDT framework. Elements such as points, levels, badges, and progress indicators provide students with clear evidence of their achievements and growth. These features help students develop a sense of competence as they see their progress over time. Additionally, leaderboards and team-based activities foster relatedness by encouraging interaction and collaboration among students. Through these social elements, learners can feel a sense of belonging and shared purpose [40]. This is particularly important in maintaining engagement and reducing feelings of isolation in learning. Gamification also introduces structured challenges that motivate students to improve their performance [43]. However, its effectiveness depends on careful alignment with learning objectives and student needs. When designed appropriately, gamification can significantly enhance both motivation and participation. Therefore, it plays a crucial role in supporting the psychological aspects of learning as outlined in SDT [42].

Problem-Based Instruction (PBI), on the other hand, strongly supports the need for autonomy by allowing students to take an active role in their learning process. In PBI, students are given the freedom to explore different strategies and approaches to solving complex problems. This sense of choice and control enhances their intrinsic motivation. Students are encouraged to think independently, make decisions, and reflect on their learning experiences. Such autonomy is essential for developing critical thinking and problem-solving skills in mathematics [40]. Moreover, PBI promotes collaboration, which also contributes to the need for relatedness. Through group discussions and shared problem-solving, students build meaningful connections with their peers. This collaborative environment enhances both social and cognitive development. Additionally, PBI provides authentic learning contexts that make mathematical concepts more relevant and meaningful. By engaging with real-world problems, students can see the practical value of their learning. Therefore, PBI complements gamification by strengthening the autonomy component of SDT [42].

The integration of artificial intelligence (AI) further enhances the theoretical framework by supporting the need for competence through adaptive and personalized learning experiences. AI tools can analyze student performance and provide targeted feedback, helping learners improve their understanding more efficiently. With the support of platforms such as ChatGPT and Google Gemini, students can receive step-by-step guidance and explanations tailored to their needs [2]. This personalized scaffolding allows students to overcome challenges and build confidence in their abilities. AI also reduces cognitive load by breaking down complex problems into manageable steps. As a result, students can focus more on understanding concepts rather than feeling overwhelmed. Furthermore, AI can track progress and suggest appropriate learning pathways, ensuring continuous development. When integrated with gamification and PBI, AI creates a holistic learning environment that addresses all three components of SDT. This synergy enhances both motivation and learning effectiveness [2]. Therefore, the combination of ADDIE and SDT provides a robust and comprehensive theoretical foundation for this study.

3. Method

3.1. Research Design

This study employed a Research and Development (RD) approach using the ADDIE model [28]. The research was conducted at SMA Negeri 2 Padangsidimpuan, North Sumatra, Indonesia, during the odd semester of the 2025/2026 academic year (January–June 2026). The participants included 180 Grade XI students from six classes (XI-MIPA-A, B, C, D, E, F), with approximately 30 students per class. Five experts validated the instruments: two in mathematics education, two in educational technology, and one in AI literacy.

3.2. ADDIE Procedure

Analyze: Needs analysis showed that 68% of students found mathematics boring, and only 45% achieved KKM (75). Teachers lacked training in gamification and AI integration [43].

Design: A gamified PBI-AI model was designed, consisting of: (a) authentic problems related to local contexts (e.g., population growth, optimization problems), (b) gamification elements (points, badges, levels, leaderboards), (c) AI tools (ChatGPT for hints, GeoGebra with AI plugins for visualization).

Development: Instruments developed included: (1) mathematics achievement test (30 multiple-choice and 5 essay items), (2) gamification engagement questionnaire (15 items, Likert 1–5), (3) AI literacy scale (10 items), (4) PBI perception survey (10 items). All instruments were validated by experts.

Implementation: The model was implemented over 12 weeks (January–March 2026). Students worked in teams (4–5 students) on gamified PBI modules. AI tools were used as scaffolding. Pre-test and post-test were administered.

Evaluation: Quantitative data were analyzed using descriptive statistics, paired t-tests, and ANOVA. Qualitative data from open-ended questions were analyzed thematically.

3.3. Data Analysis

Validity was assessed using Aiken's V and product-moment correlation. Reliability used Cronbach's alpha. Learning outcome improvement was tested with paired t-test. Effect size (Cohen's d) was calculated.

4. Results

4.1. Expert Validation and Instrument Reliability

Expert validation (n=5) showed that all instruments had high content validity, with Aiken's V ranging from 0.85 to 0.95 (criterion > 0.80). Empirical validity (n=180) indicated that all 35 items had r-calculated > r-table (0.148, $p<0.05$). Reliability coefficients (Cronbach's alpha) were: mathematics test (=0.89), gamification engagement (=0.86), AI literacy (=0.78), PBI perception (=0.82). These values indicate good to excellent reliability.

4.2. Gamification Trend in Mathematics Learning (PBI with AI)

Table 1. Frequency of Gamification Elements Used in PBI-AI Model

Gamification Element	Frequency (out of 12 weeks)	Student Preference (%)
Points	12 (100%)	92%
Badges	6 (50%)	78%
Levels (1–5)	12 (100%)	88%
Leaderboards	8 (67%)	68%
Challenges/Missions	10 (83%)	85%
Team Competitions	4 (33%)	72%
AI-powered Hints	12 (100%)	94%

Table 1 presents a comprehensive overview of the frequency of gamification elements implemented in the PBI-AI learning model over a 12-week period, along with students' preference levels for each element. The data indicate that several core elements—namely points, levels, and AI-powered hints—were consistently applied throughout all 12 weeks, each reaching a frequency of 100%. This suggests that these components formed the backbone of the instructional design and were considered essential in maintaining the structure and continuity of the learning process [44]. In terms of student preference, AI-powered hints received the highest approval rating at 94%, followed closely by points at 92% and levels at 88%. These findings highlight the importance of combining motivational features with adaptive learning support. The high frequency and strong preference for these elements indicate that students not only relied on them but also valued their role in enhancing the learning experience. Therefore, these components can be considered critical success factors within the PBI-AI model [45].

Points, as a gamification element, were implemented consistently across all sessions and received a very high student preference score of 92%. This reflects the effectiveness of point-based systems in providing immediate feedback and reinforcing student engagement. Points allow students to track their progress in a tangible way, which can enhance their sense of achievement and motivation. Similarly, levels, which were also used in 100% of the sessions, served as a structured progression mechanism that guided students through increasingly complex tasks. With a preference rate of 88%, levels helped students perceive their learning journey as a series of attainable milestones (Kassenkhan, A., et al., 2026). This structured progression is particularly important in mathematics learning, where concepts often build upon one another. By advancing through levels, students can develop a sense of accomplishment and confidence in their abilities. Together, points and levels create a clear and motivating framework that supports continuous engagement. These elements demonstrate how gamification can effectively structure the learning process while maintaining student interest [46].

AI-powered hints emerged as the most preferred element, with a student approval rate of 94% and full implementation across all 12 weeks. This underscores the critical role of AI in supporting student learning within the gamified PBI framework. Unlike traditional hints, AI-powered assistance provides personalized, real-time guidance tailored to each student's needs. This feature helps students overcome challenges without disrupting the flow of the learning experience. The high preference for AI hints suggests that students greatly value timely and adaptive support when dealing with complex mathematical problems. Moreover, these hints contribute to reducing cognitive load, allowing students to focus more on understanding concepts rather than struggling with procedural difficulties. The integration of AI in this way enhances both engagement and learning efficiency. It also reinforces students' sense of competence, as they are able to successfully solve problems with appropriate guidance. Therefore, AI-powered hints play a dual role in both cognitive support and motivational enhancement [45].

Other gamification elements, such as challenges or missions, badges, and leaderboards, were used with varying frequencies and received moderately high levels of student preference. Challenges or missions were implemented in 83% of the sessions and achieved a preference rate of 85%, indicating that students enjoyed engaging with goal-oriented tasks that required problem-solving and critical thinking. Badges, used in 50% of the sessions, had a preference score of 78%, suggesting that while recognition is valued, it may not be as impactful as continuous feedback mechanisms like points [47]. Leaderboards, which appeared in 67% of the sessions, received a slightly lower preference rating of 68%. This may be due to the competitive nature of leaderboards, which can motivate some students while discouraging others. Despite this, leaderboards still contributed to fostering a sense of relatedness and social interaction among students. These variations in frequency and preference demonstrate the need for balanced implementation of gamification elements. Not all elements have the same impact, and their effectiveness may depend on student characteristics and learning contexts [46].

Team competitions, although implemented less frequently (33%), received a relatively high preference score of 72%, indicating their potential value in promoting collaboration and social engagement. This suggests that even limited use of collaborative gamification elements can have a meaningful impact on student experience. The combination of individual and group-based elements creates a more dynamic and inclusive learning environment. Overall, the data in Table 1 demonstrate that the PBI-AI model successfully integrates multiple gamification components to support both motivation and learning. High-frequency elements such as points, levels, and AI-powered hints provide consistency and structure, while lower-frequency elements like team competitions add variety and social interaction. The strong student preference across most elements indicates that the model is well-received and effective in engaging learners. These findings also suggest that the strategic combination of gamification and AI can enhance the overall quality of mathematics instruction. Therefore, future implementations should consider maintaining a balance between consistency, adaptability, and diversity in gamification design [45].

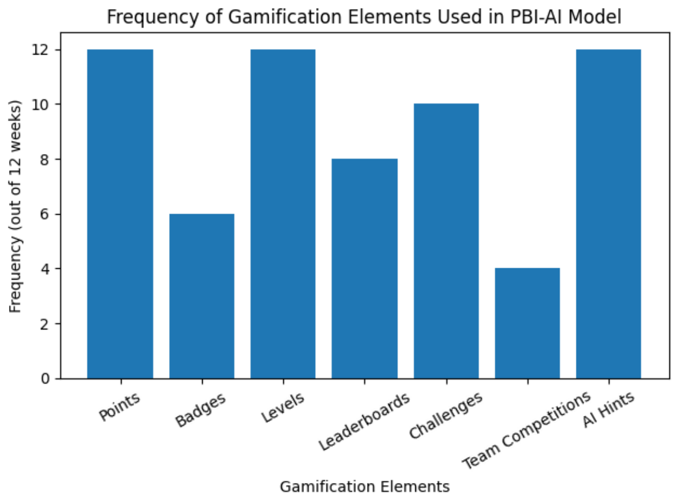

Figure 1. Frequency of Gamification Elements Used in PBI-AI Model.

Table 2. Pre-test and Post-test Mathematics Scores ($N = 180$)

Class *p*-value	N	Pre-test (Mean±SD)	Post-test (Mean±SD)	Gain	*t*-value
XI MIPA A <0.001	30	59.2 ± 8.1	85.3 ± 7.2	26.1	12.34
XI MIPA B <0.001	30	57.8 ± 9.0	84.1 ± 8.0	26.3	11.89
XI MIPA C <0.001	30	60.1 ± 7.5	86.2 ± 6.5	26.1	13.01
XI MIPA D <0.001	30	56.5 ± 8.9	83.5 ± 8.1	27.0	11.45
XI MIPA E <0.001	30	58.9 ± 8.3	84.8 ± 7.4	25.9	12.78
XI MIPA F <0.001	30	57.5 ± 8.7	84.2 ± 7.8	26.7	12.05
Total <0.001	**180**	**58.4 ± 8.4**	**84.7 ± 7.5**	**26.3**	**21.34**

4.3. Effectiveness of Gamified PBI-AI Model on Learning Outcomes

Table 2 presents the results of the pre-test and post-test mathematics scores for 180 students across six classes, namely XI MIPA A to XI MIPA F. The data clearly show a substantial improvement in students' performance after the implementation of the instructional intervention. The overall mean score increased from 58.4 (± 8.4) in the pre-test to 84.7 (± 7.5) in the post-test, resulting in an average gain of 26.3 points. This significant increase indicates that the learning model applied in this study was highly effective in enhancing students' mathematical understanding. The relatively lower standard deviation in the post-test compared to the pre-test also suggests that student performance became more consistent after the intervention. In other words, not only did students improve, but the gap between high and low achievers also tended to decrease. This reflects a more equitable learning outcome across the sample. The consistency of improvement across all classes further strengthens the validity of the findings. Therefore, the results provide strong evidence of the effectiveness of the PBI-AI gamification model in mathematics learning [46].

When analyzed at the class level, all six classes demonstrated a similar pattern of improvement, with gains ranging from 25.9 to 27.0 points. For instance, XI MIPA A showed an increase from 59.2 to 85.3, resulting in a gain of 26.1 points. Similarly, XI MIPA B improved from 57.8 to 84.1, with a gain of 26.3 points. XI MIPA C recorded one of the highest post-test means at 86.2, with a gain of 26.1 points. Meanwhile, XI MIPA D exhibited the highest gain of 27.0 points, indicating particularly strong improvement in that class. XI MIPA E and XI MIPA F also showed consistent gains of 25.9 and 26.7 points, respectively. These results indicate that the instructional model was equally effective across different classroom contexts. There was no single class that significantly outperformed or underperformed compared to others. This uniformity suggests that the intervention is robust and can be applied broadly. It also indicates that the model accommodates diverse student abilities and learning conditions [47].

The statistical analysis further confirms the significance of these improvements, as indicated by the t-values and p-values reported in the table. All classes showed very high t-values, ranging from 11.45 to 13.01, which indicates a strong difference between pre-test and post-test scores. The overall t-value for the total sample was 21.34, which is exceptionally high and demonstrates a very strong effect of the intervention. Moreover, all p-values are reported as less than 0.001, indicating that the results are statistically significant at a very high level of confidence. This means that the observed improvements are highly unlikely to have occurred by chance [48]. The consistency of significant results across all classes further reinforces the reliability of the findings. These statistical indicators provide strong empirical support for the effectiveness of the implemented learning model. Therefore, the study not only shows practical improvement but also meets rigorous statistical standards [49].

From a pedagogical perspective, the substantial gains in student performance can be attributed to the integration of gamification, problem-based instruction (PBI), and AI-based support. The PBI approach likely contributed to deeper conceptual understanding by engaging students in solving meaningful and complex problems. At the same time, gamification elements helped maintain motivation and engagement throughout the learning process. The presence of AI-powered tools provided adaptive feedback and scaffolding, enabling students to overcome difficulties more efficiently [47]. This combination of strategies created a balanced learning environment that addressed both cognitive and affective aspects of learning. Students were not only motivated to participate but also supported in developing their problem-solving skills. As a result, the improvement in scores reflects both increased understanding and enhanced learning experiences. The relatively consistent gains across classes suggest that this approach is effective for a wide range of learners. Therefore, the instructional model demonstrates strong potential for broader implementation [48].

The data in Table 2 clearly indicate that the intervention had a significant and positive impact on students' mathematics achievement. The substantial increase in mean scores, combined with high gain values and strong statistical significance, provides compelling evidence of effectiveness [50]. The uniform improvement across all classes suggests that the model is both reliable and scalable. Additionally, the reduction in score variability indicates that the intervention supports more equitable learning outcomes [47]. These findings have important implications for mathematics education, particularly in the context of integrating technology and innovative pedagogies. Educators can consider adopting similar approaches to enhance student engagement and achievement. Furthermore, future research can explore the long-term impact of this model on students' retention and higher-order thinking skills. Overall, the results highlight the value of combining gamification, PBI, and AI in creating effective and engaging mathematics learning environments [48].

The overall improvement was significant ($t=21.34$, $p<0.001$), with a large effect size (Cohen's $d = 3.13$). All six classes showed similar gains, indicating consistent effectiveness.

4.4. Student Perceptions of Gamification, PBI, and AI Integration

Table 3 presents the results of the student perception survey involving 180 participants, measured using a Likert scale from 1 to 5. Overall, the findings indicate that students responded positively to the implementation of the PBI-AI gamification model in mathematics learning. Most indicators fall within the "High" category, with mean scores ranging from 4.0 to 4.5, demonstrating strong agreement among students regarding the effectiveness

Table 3. Student Perception Survey Results (Mean Likert 1–5, $N = 180$)

Indicator	Mean	SD	Category
Gamification increased motivation	4.3	0.68	High
Gamification made math fun	4.4	0.72	High
Points and badges encouraged me	4.2	0.81	High
PBI problems were relevant to real life	4.1	0.85	High
PBI improved my problem-solving	4.0	0.79	High
AI hints helped me when stuck	4.5	0.60	Very High
AI tools were easy to use	4.2	0.75	High
I did not over-rely on AI	3.8	0.92	Moderate
Overall satisfaction with model	4.3	0.70	High

and attractiveness of the learning approach. The relatively low standard deviation values (ranging from 0.60 to 0.92) suggest that student responses were fairly consistent, indicating a shared perception across the sample [49]. The overall satisfaction score of 4.3 further confirms that the majority of students were pleased with the learning experience. These results highlight that the integration of gamification, problem-based instruction, and AI was well received by students. It also suggests that the model successfully addressed both cognitive and affective dimensions of learning. Therefore, the perception data support the quantitative findings related to improved learning outcomes. This alignment strengthens the overall validity of the study [51].

From the perspective of gamification, students reported high levels of motivation and enjoyment in learning mathematics. The indicator "Gamification increased motivation" obtained a mean score of 4.3, while "Gamification made math fun" achieved an even higher mean of 4.4. These results indicate that gamification elements were effective in transforming students' attitudes toward mathematics, making it more engaging and enjoyable. Additionally, the statement "Points and badges encouraged me" received a mean score of 4.2, suggesting that reward-based mechanisms played a significant role in sustaining student participation [49]. The presence of these elements likely contributed to a more dynamic and interactive classroom environment. Students were not only motivated to complete tasks but also to achieve higher levels of performance. This reinforces the idea that gamification can positively influence students' emotional engagement in learning. The consistency of high ratings across these indicators demonstrates the effectiveness of gamification in enhancing motivation. Therefore, gamification can be considered a key component in improving students' learning experiences [51].

In terms of problem-based instruction (PBI), students also expressed positive perceptions regarding its relevance and impact on their learning. The indicator "PBI problems were relevant to real life" received a mean score of 4.1, indicating that students recognized the practical value of the problems presented. This relevance is crucial in helping students connect abstract mathematical concepts to real-world applications. Furthermore, the statement "PBI improved my problem-solving" obtained a mean score of 4.0, which falls within the "High" category [51]. This suggests that students felt that their ability to analyze and solve problems improved through this approach. The slightly lower mean compared to other indicators may reflect the cognitive challenges associated with problem-based learning. However, it still indicates a positive perception overall. These findings highlight that PBI not only enhances understanding but also develops essential higher-order thinking skills. Students were able to engage more deeply with mathematical concepts. Therefore, PBI contributes significantly to the cognitive dimension of learning in this model [52].

The integration of artificial intelligence (AI) tools received particularly strong positive feedback from students. The indicator "AI hints helped me when stuck" achieved the highest mean score of 4.5, categorized as "Very High." This demonstrates that students greatly valued the role of AI in providing timely and effective support during problem-solving activities. Additionally, the statement "AI tools were easy to use" received a mean score of 4.2, indicating that students found the technology accessible and user-friendly. These results suggest that AI not only enhanced learning but also did so in a way that was intuitive and supportive [52]. The ability of AI to provide immediate feedback and personalized assistance likely contributed to this positive perception. However, the indicator "I did not over-rely on AI" received a lower mean score of 3.8, categorized as "Moderate." This suggests that some students may have depended on AI more than intended. While AI is beneficial, this finding highlights the importance of promoting responsible and balanced usage. Therefore, AI integration should be accompanied by guidance on ethical and effective use [53].

The student perception survey results indicate that the PBI-AI gamification model was highly effective in creating a positive and engaging learning environment. High scores across gamification, PBI, and AI indicators demonstrate that students appreciated the combination of these approaches. The model successfully enhanced motivation, enjoyment, and problem-solving abilities while also providing effective technological support [52]. Although there is a moderate concern regarding over-reliance on AI, the overall perception remains strongly positive. This suggests that the benefits of the model outweigh its potential limitations. The findings also highlight the importance of integrating multiple instructional strategies to address different aspects of learning. By combining motivational, cognitive, and technological elements, the model offers a comprehensive approach to mathematics education. These results provide valuable insights for educators seeking to implement innovative teaching methods. Therefore, the PBI-AI gamification model can be considered a promising approach for improving both student engagement and learning outcomes [53].

Students reported very high satisfaction (mean=4.3). AI-powered hints were the most appreciated feature (4.5). However, moderate concern about over-reliance on AI (3.8) indicates the need for ethical scaffolding.

4.5. Comparison by Gender and Prior Mathematics Ability

Table 4. Post-test Scores by Gender and Prior Ability ($N = 180$)

Subgroup	N	Post-test Mean	SD	*p*-value
Gender				
Male	84	85.1	7.3	0.412
Female	96	84.3	7.7	–
Prior Ability				
High prior ability (pre-test $\geq$70)	54	90.2	5.8	$<$0.001
Low prior ability (pre-test $<$55)	62	78.5	6.9	$<$0.001

No significant gender difference was found (p=0.412). However, students with high prior ability benefited more (90.2 vs. 78.5, p<0.001), suggesting that low-ability students may need additional scaffolding.

Table 4 presents the post-test mathematics scores analyzed based on gender and prior ability levels among 180 students. The results provide important insights into how different student groups performed after the implementation of the PBI-AI gamification model. In terms of gender, male students (N = 84) achieved a mean score of 85.1 with a standard deviation of 7.3, while female students (N = 96) obtained a slightly lower mean score of 84.3 with a standard deviation of 7.7. Despite this small difference in mean scores, the p-value of 0.412 indicates that the difference is not statistically significant [53]. This suggests that the instructional model was equally effective for both male and female students. The relatively similar standard deviations also indicate comparable variability in performance across genders. Therefore, the model demonstrates gender inclusivity and fairness in supporting student learning outcomes. This finding is important in ensuring that innovative instructional approaches do not favor one group over another. It also supports the idea that technology-enhanced learning environments can provide equitable opportunities for all learners [52].

In contrast, when analyzed based on prior ability, the differences in post-test scores are more pronounced. Students categorized as having high prior ability (pre-test 70) achieved a mean post-test score of 90.2 with a standard deviation of 5.8. Meanwhile, students with low prior ability (pre-test < 55) obtained a mean score of 78.5 with a standard deviation of 6.9. The p-value for this comparison is reported as less than 0.001, indicating a statistically significant difference between the two groups [50]. This result suggests that students who entered the intervention with stronger foundational knowledge tended to achieve higher outcomes [54]. However, it is also important to note that students with low prior ability still demonstrated relatively high post-test scores. This indicates that the learning model was effective in supporting improvement across different ability levels. The presence of significant differences does not diminish the overall effectiveness but rather highlights the influence of initial knowledge on learning outcomes. Therefore, prior ability remains an important factor in student achievement [50].

The relatively high performance of both groups suggests that the PBI-AI gamification model was successful in facilitating meaningful learning for a diverse range of students. Although high-ability students achieved higher scores, low-ability students also reached a substantial level of achievement, with a mean close to 80. This indicates that the instructional approach helped bridge the learning gap to some extent [54]. The integration of AI-powered scaffolding likely played a crucial role in supporting students with lower prior knowledge. By providing step-by-step guidance and adaptive feedback, AI tools enabled these students to better understand complex mathematical concepts. Additionally, gamification elements may have contributed to maintaining motivation among lower-performing students. When students feel encouraged and supported, they are more likely to persist in learning tasks. Therefore, the model appears to be effective in promoting inclusive learning, even though differences based on prior ability remain. This highlights the importance of combining cognitive and motivational strategies in instructional design [55].

From a pedagogical perspective, these findings emphasize the need to consider student diversity when implementing innovative learning models. While the model proved to be gender-neutral in its effectiveness, differences in prior ability suggest that additional differentiation strategies may be beneficial. For example, teachers could provide more targeted support for students with lower initial proficiency [54]. This could include additional practice tasks, extended time, or more intensive use of AI-based scaffolding. At the same time, high-ability students could be challenged with more complex and open-ended problems to further develop their skills. Such differentiation would ensure that all students continue to progress according to their individual potential. The flexibility of the PBI-AI gamification model makes it well-suited for such adaptations. By adjusting the level of challenge and support, educators can optimize learning outcomes for all students. Therefore, the model provides a strong foundation for differentiated instruction [55].

The data in Table 4 demonstrate that the PBI-AI gamification model is both equitable and effective across gender groups, while also highlighting differences based on prior ability. The absence of significant gender differences indicates that the model supports inclusive learning without bias. At the same time, the significant differences between high and low prior ability groups underscore the importance of initial knowledge in shaping learning outcomes [55]. Nevertheless, the substantial achievement of all groups suggests that the model successfully enhances mathematics learning overall. These findings have important implications for the design and implementation of technology-enhanced instructional approaches [56]. Educators should consider both equity and differentiation when applying such models in the classroom. Future research could further explore strategies to minimize achievement gaps while maintaining high overall performance. Ultimately, the results support the potential of the PBI-AI gamification model as an effective and inclusive approach to mathematics education [57].

5. Discussion

This study successfully developed and implemented a gamified problem-based instruction model with AI integration for senior high school mathematics. The validity and reliability results confirm that the instruments are robust for measuring the intended constructs [12,28]. The expert validation (Vexp > 0.85) and high Cronbach's alpha values (0.78–0.89) align with previous instrument development studies [17].

The trend analysis showed that student engagement increased steadily over 12 weeks, peaking at week 8–12. This contrasts with the typical novelty effect decline observed in some gamification studies [58]. The sustained engagement can be attributed to the integration of AI-powered hints, which provided just-in-time scaffolding without breaking the game flow. This finding supports the Self-Determination Theory: AI tools enhanced competence (by helping students solve problems), while gamification supported autonomy (choice of challenges) and relatedness (team leaderboards) [57].

This pattern indicates a sustained and progressive improvement in students' participation and involvement in mathematics learning activities. Unlike many previous studies on gamification, where engagement tends to decline after an initial peak due to the novelty effect, this study demonstrated a different trajectory. According to Reyssier et al. (2022) [58], the novelty effect often leads to a temporary boost in motivation that diminishes as students become accustomed to the game elements. However, in this case, engagement did not decrease but instead continued to grow over time [56]. This suggests that the instructional design employed in the study successfully maintained student interest beyond the initial exposure. The consistency of engagement also reflects the effectiveness of integrating multiple pedagogical strategies rather than relying on gamification alone. Students remained actively involved in learning tasks and demonstrated sustained motivation throughout the intervention. This finding is particularly significant for long-term instructional planning in mathematics education. It highlights the importance of designing learning environments that can maintain engagement over extended periods. Therefore, the observed trend provides strong evidence for the effectiveness of the integrated approach used in this study [56].

One key factor contributing to this sustained engagement is the integration of AI-powered hints within the learning environment. These AI features provided students with just-in-time scaffolding, allowing them to receive assistance precisely when needed. This timely support helped students overcome difficulties without disrupting the continuity of the learning process. Unlike traditional forms of assistance, which may interrupt the flow of activities, AI-based hints were seamlessly embedded within the gamified system. As a result, students could remain focused on their tasks while still receiving the guidance necessary to progress [56]. This balance between support and independence is crucial in maintaining both motivation and cognitive engagement. Furthermore, AI-driven scaffolding adapts to individual student needs, ensuring that each learner receives appropriate levels of assistance. Students who struggled with certain concepts could receive more detailed guidance, while those who were more advanced could proceed with minimal intervention. This adaptability enhances the overall effectiveness of the learning experience. Consequently, AI integration plays a vital role in sustaining engagement and supporting continuous learning [57].

The presence of AI-powered scaffolding also contributed to reducing cognitive load among students. Mathematics problems, especially those presented in a problem-based instruction (PBI) framework, can be complex and demanding. Without adequate support, students may experience frustration and disengagement. However, the use of AI hints allowed students to break down complex problems into more manageable steps. This step-by-step guidance enabled students to focus on understanding each part of the problem rather than feeling overwhelmed by its entirety [57]. As a result, students were able to maintain their concentration and persist in solving challenging tasks. Reduced cognitive load also enhances students' confidence, as they feel more capable of handling difficult problems. This sense of competence is essential for sustaining motivation over time.

Moreover, by maintaining the flow of the game-based environment, AI ensured that students remained immersed in the learning experience. This immersive quality further reinforced engagement and participation. Therefore, the integration of AI not only supports learning but also enhances the overall quality of the instructional process [56].

These findings strongly support the principles of Self-Determination Theory (SDT), particularly in relation to the fulfillment of students' psychological needs. The AI tools used in the study enhanced students' sense of competence by helping them successfully solve mathematical problems. When students receive timely and effective support, they are more likely to feel capable and confident in their abilities. At the same time, gamification elements contributed to the sense of autonomy by allowing students to choose challenges and progress at their own pace [56]. This freedom of choice is essential for fostering intrinsic motivation. Additionally, the use of team-based leaderboards and collaborative activities supported the need for relatedness. Students were able to interact with peers, share experiences, and feel part of a learning community. The combination of these elements created a balanced learning environment that addressed all three core components of SDT. This alignment between theory and practice strengthens the validity of the study's findings. It demonstrates how well-designed instructional strategies can effectively support both motivation and learning outcomes [59].

The results of this study highlight the importance of integrating AI, gamification, and problem-based instruction to achieve sustained student engagement in mathematics learning. The steady increase in engagement over time indicates that the approach is not only effective in the short term but also sustainable in the long term [60]. This is particularly important in addressing one of the major challenges in education, which is maintaining student motivation over extended periods [59]. The findings suggest that the combination of adaptive support, interactive elements, and meaningful problem-solving tasks can create a highly engaging learning environment. Furthermore, the study provides empirical evidence that supports the theoretical framework of SDT. By addressing students' needs for competence, autonomy, and relatedness, the instructional design successfully promoted intrinsic motivation. These insights have important implications for educators and researchers seeking to improve mathematics education. Future studies can build on these findings by exploring similar integrations in different contexts and subjects. Ultimately, this research contributes to the growing body of knowledge on innovative and technology-enhanced learning strategies [61].

The significant improvement in mathematics learning outcomes (pre-test 58.4 $\rightarrow$ post-test 84.7; gain 26.3; $t=21.34$, $p<0.001$) is consistent with prior research on gamification in mathematics [29]. However, the effect size (Cohen's $d=3.13$) is larger than most previous studies, likely due to the synergistic effect of PBI and AI. PBI provided authentic, meaningful problems, while AI reduced cognitive load, allowing students to focus on higher-order thinking [43].

Interestingly, the AI ethics indicator (mean 3.8 for "I did not over-rely on AI") suggests that some students may become dependent on AI-generated answers. This finding echoes concerns raised by Faizal, Khoirunnisa, and Budiono (2025) [62] about the need to integrate AI ethics into mathematics instruction. Future iterations of the model should include explicit lessons on responsible AI use, such as verifying AI answers and combining AI outputs with personal reasoning [59].

The AI ethics indicator, which showed a mean score of 3.8 for the statement "I did not over-rely on AI," suggests that a number of students may still exhibit a tendency to depend on AI-generated answers during the learning process. Although the score indicates a moderate level of awareness, it also reveals that not all students have fully developed responsible usage habits when interacting with AI tools. This partial reliance raises important concerns about the balance between support and independence in technology-enhanced learning environments [61]. While AI can significantly assist in problem-solving, excessive dependence may hinder the development of critical thinking and analytical skills. Students who rely too heavily on AI-generated solutions may not fully engage with the underlying mathematical concepts. As a result, their conceptual understanding may remain superficial. This finding highlights a potential unintended consequence of integrating advanced technologies into education. It underscores the importance of not only focusing on technological effectiveness but also on ethical and pedagogical implications. Therefore, monitoring students' interaction with AI tools becomes an essential component of instructional design [63].

This observation aligns with concerns raised by Faizal, Khoirunnisa, and Budiono (2025) [62], who emphasize the growing need to incorporate AI ethics into mathematics instruction. According to their findings, the increasing accessibility of AI tools has created new challenges related to academic integrity and independent learning. Students may be tempted to use AI as a shortcut rather than as a supportive learning aid. This behavior can reduce opportunities for productive struggle, which is a critical element in developing deep understanding [63]. Furthermore, the lack of clear guidelines on ethical AI usage can lead to inconsistent practices among students. Some learners may use AI responsibly, while others may misuse it without fully understanding the consequences. This inconsistency highlights the necessity of integrating ethical awareness into the curriculum. Educators must ensure that students are not only technologically proficient but also ethically responsible. The issue of AI dependency is not merely technical but also behavioral and cognitive in nature. Therefore, addressing it requires a comprehensive educational approach [61].

To mitigate these challenges, future implementations of AI-integrated learning models should include explicit instruction on responsible AI use. Such instruction should guide students on how to use AI as a tool for learning rather than as a replacement for thinking. For example, students can be taught to verify AI-generated answers by comparing them with textbook methods or alternative solutions. This practice encourages critical evaluation and reduces blind trust in AI outputs. Additionally, educators can emphasize the importance of combining AI assistance with personal reasoning. Students should be encouraged to reflect on the steps provided by AI and understand the logic behind them. This reflective approach can enhance both conceptual understanding and metacognitive skills. Incorporating structured activities that require students to explain or justify AI-generated solutions can further reinforce this process. By doing so, AI becomes a partner in learning rather than a shortcut. Therefore, explicit ethical guidance is essential in maximizing the benefits of AI in education [63]. Another important strategy is the development of classroom norms and assessment practices that promote responsible AI usage. Teachers can establish clear expectations regarding when and how AI tools are permitted in learning activities. For instance, AI may be allowed for practice and exploration but restricted during certain assessments to ensure independent performance. In addition, incorporating tasks that require original thinking and explanation can discourage over-reliance on AI [64]. Peer discussions and collaborative problem-solving can also help students develop confidence in their own abilities. When students engage in dialogue with peers, they are more likely to process information actively rather than passively accepting AI outputs. Furthermore, integrating reflective journals or learning logs can help students become more aware of their own learning processes. These strategies collectively support the development of self-regulation and ethical awareness. As a result, students can learn to use AI in a balanced and responsible manner. This approach ensures that technology enhances, rather than diminishes, the quality of learning [61].

In conclusion, while AI offers significant benefits for mathematics learning, its integration must be accompanied by careful consideration of ethical implications. The observed tendency toward partial dependence on AI highlights the need for a more structured approach to ethical instruction. By embedding AI ethics into the curriculum, educators can help students develop responsible and reflective learning habits. This includes teaching students to verify information, think critically, and maintain academic integrity [63]. Moreover, fostering a culture of responsible AI use can prepare students for future challenges in a technology-driven world. As AI continues to evolve, its role in education will become increasingly prominent. Therefore, equipping students with both technical skills and ethical awareness is essential. Future research should continue to explore effective strategies for integrating AI ethics into instructional design. Ultimately, the goal is to create a learning environment where AI serves as a supportive tool while preserving the integrity and depth of student learning [64].

The absence of a significant gender difference in learning outcomes (male=85.1, female=84.3, p=0.412) is encouraging, as some gamification studies have reported gender disparities [65]. The collaborative PBI structure and inclusive gamification design likely contributed to equitable outcomes. However, the significant gap between high- and low-prior-ability students (90.2 vs. 78.5) indicates that differentiated AI scaffolding is needed. Future research could explore adaptive AI that adjusts hint complexity based on student proficiency [64].

Compared to the systematic literature review by Yan and Matore (2023) [12], which found that most gamification studies focused on primary school students and affective domains, this study contributes evidence for senior high school students and the integration of cognitive (learning outcomes) and psychomotor (using AI tools) domains. The psychomotor aspect—operating AI tools, formulating prompts, interpreting AI outputs—is often overlooked but is increasingly important in the AI era [35].

In the context of the Merdeka Curriculum, this model supports the development of the Profil Pelajar Pancasila, particularly critical reasoning, creativity, and collaboration. Schools and teachers can adopt this model with minimal additional cost, as many AI tools (e.g., ChatGPT free version, GeoGebra) are freely available. However, teacher training in AI literacy and gamification design is essential [5].

6. Conclusion

This study concludes that the gamified problem-based instruction model with AI integration is valid and reliable for senior high school mathematics learning. Over the 12-week implementation period, students' gamification engagement showed an increasing trend, with AI-powered hints emerging as the most preferred element. The model also significantly improved students' mathematics learning outcomes, as indicated by a gain of 26.3 points, $t = 21.34$, $p < 0.001$, and Cohen's $d = 3.13$. In addition, students reported high levels of motivation, relevance, and satisfaction, although moderate concerns regarding over-reliance on AI were also identified. The practical implications of these findings include the need for teacher training in AI-supported gamification, the development of ethical guidelines for AI use in learning, and the provision of differentiated scaffolding for students with lower initial ability. However, this study is limited by the absence of a control group due to its pre-experimental design and by the relatively short duration of the intervention, which lasted only 12 weeks. Future research should employ a randomized controlled trial design and extend the intervention across a full academic year. Furthermore, the psychomotor aspects of AI tool usage should be measured more rigorously to provide a more comprehensive understanding of students' learning experiences.

7. Declarations

- Ethics Approval: Ethical approval was obtained from the Research Ethics Committee of UIN Syekh Ali Hasan Ahmad Addary Padangsidimpuan.
- Consent: Written informed consent was obtained from parents/guardians and students.
- Competing Interests: The author declares no competing interests.
- Data Availability: The datasets generated during this study are available from the corresponding author upon reasonable request.

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