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Integrating Digital Games into Project-Based Learning to Enhance Student Achievement in STEM Education

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ABSTRACT
Objective: This study aimed to address the gap in STEM education by developing and evaluating a digital game focused on energy concepts to enhance students' learning outcomes, engagement, and collaboration. **Method**: The research utilized a Research and Development (R&D) approach based on the Borg and Gall model, encompassing analysis, development, validation, and implementation phases. The experimental design involved high school students divided into two groups: the experimental group, which engaged with the digital game, and the control group, which participated in conventional Project-Based Learning (PjBL) activities. **Results**: The findings revealed that the experimental group demonstrated significantly more improvement in STEM learning outcomes than the control group. The experimental group also showed enhanced engagement and collaboration during learning activities. Statistical analyses confirmed that the digital game effectively created interactive and engaging learning environments that fostered active participation and teamwork. **Novelty**: This study contributes to the field by highlighting the transformative potential of digital game-based learning to address limitations in current PjBL practices. The digital game provides a more engaging and collaborative approach to STEM education, bridging the gap between theoretical concepts and practical problem-solving.

INTRODUCTION

STEM education, emphasizing Science, Technology, Engineering, and Mathematics, is a globally recognized framework for equipping students with critical thinking, problem-solving, and creativity as a key competency for addressing 21st-century challenges (Aifan, 2022). Project-Based Learning (PjBL), which emphasizes active, inquiry-based, and collaborative learning through meaningful projects, has emerged as a preferred pedagogy for STEM education worldwide (Culclasure et al., 2019; Aifan, 2022). However, in the Indonesian context, PjBL faces challenges in fully achieving its potential. A lack of advanced technological tools has restricted its ability to provide immersive and interactive learning experiences, limiting STEM education's exploratory and practical nature (Mudinillah et al., 2024; Irfana et al., 2022). This study contributes to the field by addressing this gap by developing and evaluating tailored digital games integrated with PjBL frameworks.

The manuscript explores how these games can enhance student engagement, critical thinking, and collaborative problem-solving, providing a novel approach to STEM education in Indonesia. By bridging the gap between traditional methods and modern technological integration, this research demonstrates the transformative potential of digital games in aligning STEM education with 21st-century demands. This limitation is particularly problematic in contexts where students need hands-on, real-world.

Simulations to fully grasp STEM concepts (Perets et al., 2020; Irfana et al., 2022). Overusing PjBL without adequate technological integration often results in learning experiences lacking the depth and real-world relevance necessary for meaningful STEM education (Sahito & Wassan, 2024; Bulu & Tanggur, 2021). These gaps highlight the urgent need for innovative tools that address technological limitations and enhance the accessibility and effectiveness of STEM and PjBL.

Moreover, the increasing reliance on PjBL without technological innovation has led to a saturation effect, where its effectiveness diminishes due to repetitive and non-interactive project designs (Mabrurah et al., 2023; Hastuti, 2024). This overuse risks reducing student engagement and motivation, particularly when projects fail to connect with students' lived experiences or practical applications. The lack of dynamic, technology-driven tools exacerbates this problem, making it difficult for educators to bridge the gap between theoretical STEM knowledge and its real-world applications (Sumarni & Kadarwati, 2020).

The core challenge in achieving the full potential of STEM and PjBL in Indonesia is the absence of educational tools that provide immersive and engaging learning environments. While PjBL is inherently designed to foster collaboration and inquiry, its implementation often falls short due to resource constraints and outdated methods (Untari et al., 2020; Wahyudiati et al., 2022). Without adequate technological support, the projects fail to create the deep, experiential learning environments central to PjBL's success (Roemintoyo & Budiarto, 2023; Dogara et al., 2020). Digital games offer a promising solution to these challenges by combining interactive, real-world simulations with engaging, gamified elements. Unlike traditional tools, digital games can create dynamic environments where students actively experiment with STEM principles and collaborate to solve problems (Lee et al., 2023). However, integrating digital games into PjBL frameworks in Indonesia remains underexplored, mainly leaving a significant gap in the tools available to enhance STEM education. Addressing this gap through developing and evaluating tailored digital games can create a transformative impact on the quality and relevance of STEM learning (Fernández-Gavira et al., 2021; Mabrurah et al., 2023).

Digital games present a promising solution to these challenges by offering interactive and immersive learning experiences that engage students while reinforcing STEM concepts (Irfana et al., 2022; Greipl et al., 2020). Research shows that digital games can simulate complex scenarios, enabling students to experiment with STEM principles in realistic contexts (Idris et al., 2020; Blegur et al., 2023). When integrated into PjBL settings, digital games can support collaborative problem-solving and critical thinking, aligning seamlessly with STEM education goals (Horne, 2024; Aranzabal et al., 2022). These characteristics make digital games a viable tool for addressing engagement and learning gaps in STEM classrooms.

Digital games hold significant potential as innovative educational tools by merging educational content with gamified elements that motivate and challenge students, thereby enhancing engagement and learning outcomes (Robinson et al., 2021; Rasti-Behbahani, 2021). Unlike traditional teaching methods, digital games provide unique advantages such as real-time feedback, adaptive learning paths, and collaborative features, essential for fostering critical thinking and problem-solving skills (Hartt et al., 2020). Research has shown that when digital games are designed to align with curricular goals and real-world applications, they can effectively improve STEM learning outcomes (McMahon et al., 2019; Salam, 2023). Furthermore, these games create immersive environments encouraging active participation and deep learning, bridging the gap between theoretical knowledge and practical application through challenges, rewards, and immediate feedback (Zainil et al., 2023; Blegur et al., 2023). This synergy aligns seamlessly with the principles of PjBL, which emphasizes collaboration, inquiry, and applying concepts in real-world contexts (Pengyue et al., 2020). Despite the growing evidence of their benefits, there remains a pressing need for systematic research into the development and effectiveness of digital games within PjBL frameworks. The application of digital games in STEM education has shown promising results, particularly in enhancing students' motivation and conceptual understanding. For example, studies have demonstrated that well-designed digital games can simulate real-world STEM problems, allowing students to experiment and collaborate in solving these challenges (Rizaldi et al., 2020). These games also encourage critical thinking and problem-solving skills, essential components of STEM competencies (Davidi et al., 2021; Tong et al., 2022). By creating a safe and engaging space for exploration, digital games can help students build confidence in applying STEM concepts, making them an ideal tool for PjBL.

STEM education, emphasizing the integration of Science, Technology, Engineering, and Mathematics, is globally acknowledged as a cornerstone for preparing students to face 21st-century challenges. Central to this framework is competencies such as critical thinking, problem-solving, creativity, and collaboration, which equip learners to navigate complex real-world issues (Aifan, 2022). In the Indonesian context, STEM education is increasingly delivered through PjBL, a pedagogy that promotes inquiry-based, collaborative, and experiential learning. While this approach has been shown to enhance student engagement and understanding (Sumarni & Kadarwati, 2020), its effectiveness is often constrained by limited access to advanced technological tools that provide immersive and interactive learning experiences. Existing methods frequently rely on static materials, such as printed texts or basic multimedia, which fail to support the exploratory and practical nature of PjBL (Faruque et al., 2024; Irfana et al., 2022). This gap underscores the need for innovative educational tools like digital games to enrich STEM education by offering dynamic, real-world simulations that foster critical thinking and collaboration (Lee et al., 2023; Fernández-Gavira et al., 2021). By situating the discussion within the broader educational landscape and emphasizing the challenges of resource limitations, this study explores how tailored digital games integrated into PjBL can bridge these gaps, enhance learning outcomes, and align STEM education with 21st-century demands.

The effectiveness of digital games as instructional tools is primarily attributed to their capacity to simulate complex scenarios and provide real-time feedback, enabling students to test hypotheses, analyze outcomes, and iteratively revise their strategies (Hartt et al., 2020). This experiential learning process not only fosters a deeper understanding and retention of STEM concepts but also aligns closely with the objectives of PjBL (Widarti et al., 2020). Furthermore, the gamified elements inherent in digital games, such as rewards and levels, play a crucial role in sustaining student motivation and ensuring consistent engagement throughout the learning experience (Bulu & Tanggur, 2021; Handayani, 2021). Another significant advantage of digital games is their ability to facilitate collaborative learning; many games are designed to promote teamwork, requiring students to communicate, negotiate, and coordinate their efforts to achieve common goals (Hastuti, 2024; Subiyantoro, 2023). This collaborative aspect mirrors the nature of PjBL and equips students with essential skills for real-world challenges that demand teamwork and problem-solving (Dogara et al., 2020). Additionally, digital games provide immediate and individualized feedback, allowing students to identify and address misconceptions in real-time (Fajri et al., 2021; An, 2020)—these features position digital games as a superior choice for enhancing STEM education through the PjBL framework.

Previous studies have highlighted the potential of digital games in enhancing STEM education. For instance, Fajri et al. (2021) investigated the role of digital games in improving students' conceptual understanding and found that interactive game-based learning environments significantly boosted learning outcomes. Similarly, Ngabekti et al. (2019) demonstrated that digital games could effectively engage students in STEM subjects, particularly when integrated into PjBL frameworks. These findings are supported by research from Purwaningsih et al. (2020), which revealed that digital games foster critical thinking and problem-solving skills in STEM education.

While existing studies highlight the benefits of digital games in education, they primarily focus on their general impact rather than their systematic development and alignment with the principles of PjBL. For instance, while Emerson et al. (2020) and Greipl et al. (2020) discuss the theoretical foundations of game-based learning, they offer limited insights into practical applications within classroom settings. This gap underscores the necessity for further research that delves into the iterative development and evaluation of digital games tailored explicitly for PjBL in STEM education. Unlike prior research that mainly examines the effects of pre-existing digital games, this study emphasizes the systematic development and evaluation of a digital game designed explicitly for PjBL in STEM contexts. By employing a Research and Development (R&D) methodology, this study ensures that the game aligns with both curricular goals and the principles of PjBL, thereby addressing the existing literature gap and providing a practical framework for integrating digital games into STEM classrooms. Furthermore, this research introduces a novel perspective by merging digital game-based learning with real-world problem-solving scenarios, enhancing the game's relevance and effectiveness in PjBL settings. This unique combination of innovation and practicality represents a significant contribution to the field of STEM education, moving beyond theoretical applications to incorporate real-world challenges into game design.

This study aims to explore the integration of digital games into PjBL as a means to enhance student achievement in STEM education. The primary research question asks: How does integrating digital games into PjBL impact students' learning outcomes, engagement, and collaboration in STEM education? Supporting this, the study investigates how digital game-based learning compares to conventional PjBL methods in improving STEM understanding, engagement, and collaboration skills. It also examines the usability and instructional effectiveness of the developed digital game, alongside how features such as real-time feedback and collaborative tasks shape learning experiences. Finally, it identifies the challenges and limitations of implementing digital games in STEM education, offering insights to optimize their impact. The research addresses critical gaps in current pedagogical practices by focusing on the development and effectiveness of a tailored digital game (Partovi & Razavi, 2019; Greipl et al., 2020). The study is particularly relevant given the increasing emphasis on equipping students with 21st-century skills through innovative educational approaches. This research examines the potential of digital games to transform STEM education, offering insights into their role in fostering engagement, critical thinking, and problem-solving (Menggo et al., 2019). The findings are expected to provide educators with practical tools and strategies for integrating technology into PjBL, ultimately improving the quality and impact of STEM education.

RESEARCH METHOD

Research Design

This research utilizes a Research and Development (R&D) methodology based on the Borg and Gall model, complemented by a quasi-experimental approach (Gall et al., 2003). The R&D model was chosen for its systematic steps in developing and validating educational products, ensuring their practicality and effectiveness in the learning environment (Gall et al., 2014). The experimental approach tests the effectiveness of the developed digital game, incorporating pre-test and post-test assessments to compare the experimental and control groups (Senjam et al., 2021).

The R&D process in this study follows the three primary stages adapted from Borg and Gall: analysis, development, and implementation (Idris et al., 2020). The analysis stage focused on identifying the needs of STEM teachers and students regarding tools that facilitate immersive and interactive learning in PjBL. The development stage involved designing the digital game prototype with features aligned with STEM learning objectives and PjBL principles. The implementation stage included field-testing the digital game in a classroom setting to evaluate its impact on student learning outcomes.

The quasi-experimental design employed a non-equivalent control group structure (Nurlaelah et al., 2021). The experimental group participated in STEM learning with the aid of the developed digital game, while the control group followed the conventional PjBL approach. Both groups underwent a pre-test to assess their initial STEM competencies, followed by a three-week intervention, and concluded with a post-test to evaluate improvements in their learning outcomes. The research stages are presented in Figure 1, illustrating the systematic procedure adopted in this study.

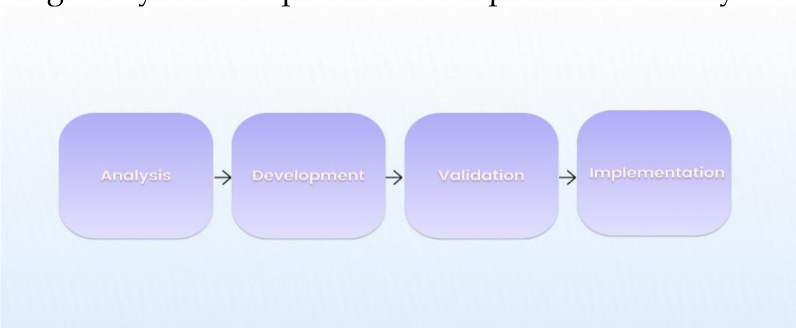

Figure 1. The research procedure is based on the Borg and Gall model.

At the analysis stage, needs were identified through interviews with STEM teachers and surveys with students. This stage aimed to uncover the gaps in existing teaching practices and the demand for innovative tools to enhance PjBL in STEM education. The development stage focused on designing the game prototype, integrating features such as interactive problem-solving tasks, simulations, and real-world scenarios aligned with STEM principles. This stage also included validation by media, material, and instructional design experts (Sayono et al., 2020). In the implementation stage, the developed game was applied in an actual classroom setting over three weeks. During this period, students in the experimental group engaged in STEM activities facilitated by the game, while the control group utilized conventional PjBL methods. Both groups' learning outcomes were compared using pre-test and post-test scores to measure the game's effectiveness. A detailed schedule of the program implementation is shown in Table 1.

Table 1. The schedule of the implementation program.

Date	Group	Types of Courses	Types of Activities	Place/Meeting
July 1–July 21, 2024	Control Group	STEM (Conventional)	Pre-test, PjBL without digital tools	Classroom
			Post-test	Classroom
July 1–July 21, 2024	Experimental Group	STEM (Digital Game)	Pre-test, PjBL with digital game integration	Classroom and online platforms
			Post-test	Classroom

Research Sample and Data Collection Techniques

The population in this study comprised 980 students from STEM-focused high schools across five districts in Central Java, Indonesia. The districts included Semarang, Surakarta, Banyumas, Pekalongan, and Kudus. The sample for this study consisted of 150 students selected through purposive sampling (Patel & Patel, 2019). This sampling method ensured that participants met the following criteria: enrolled in STEM-focused high schools, actively involved in PjBL activities, and willing to participate in the study. The selected sample was divided equally into experimental and control groups, with 75 students in each group. The distribution of the population and sample can be seen in Table 2.

Table 2. Population and sample distribution.

District	Population	Sample
Semarang	200	30
Surakarta	180	30
Banyumas	210	30
Pekalongan	190	30
Kudus	200	30
Total	980	150

The study also involved expert validation of the developed digital game. Six experts were selected using purposive sampling, ensuring they met the criteria of having at least five years of experience in their respective fields (Barbrook-Johnson & Carrick, 2021). The experts comprised two media experts, two material experts, and two instructional design experts. The details of the expert validators are presented in Table 3.

Table 3. Expert validators.

Validator	Position	Department	University
Media Expert A	Head of Department	Educational Technology	University A
Media Expert B	Senior Lecturer	Department of Basic Education	University B
Material Expert A	Professor	Non-Formal Education	University A
Material Expert B	Senior Lecturer	Department of Basic Education	University B
Instructional Design A	Lecturer	Educational Technology	University A
Instructional Design B	Senior Lecturer	Mathematics and Creative Multimedia	University B

Research Instrument

The instruments used in this research were carefully designed to measure the effectiveness of the developed digital game and students' engagement in STEM learning. These instruments consisted of multiple tools, including pre-test and post-test assessments, expert validation rubrics, questionnaires, and an observation checklist. Each instrument was tailored to align with the research objectives and ensured reliability through expert validation. Pre-test and Post-test Assessments were developed to evaluate the impact of the digital game on students' conceptual understanding and problem-solving skills in STEM education. The tests consisted of 30 multiple-choice questions derived from STEM curriculum standards. These items covered topics in mathematics, science, and technology, focusing on their application in real-world scenarios. The pre-test was administered to assess students' baseline knowledge, while the post-test measured their learning progress after the intervention.

Expert Validation Rubrics were used to evaluate the quality of the digital game. The validation process involved six media, content, and instructional design experts. Each expert assessed five dimensions: design and usability, interactivity, alignment with STEM objectives, language clarity, and instructional effectiveness (Kao & Luo, 2020). The evaluation was conducted using a 5-point Likert scale, where a higher score indicated better quality (Hartt et al., 2020). Engagement Questionnaires were distributed to students in the experimental group to measure their motivation and interaction with the digital game. The questionnaire consisted of 20 items rated on a 4-point Likert scale ranging from "strongly disagree" to "strongly agree." The items focused on three main aspects: the perceived usefulness of the game, ease of use, and overall engagement during learning activities.

Observation Checklists were employed during the classroom implementation phase to capture qualitative data on student behaviors and interactions. The checklist included 15 indicators, such as teamwork, critical thinking, and problem-solving, which were observed and recorded by the researchers (Yaniawati et al., 2021; Astuti et al., 2024). The data collected provided insights into how students responded to the digital game in an authentic learning environment. All instruments underwent a validation process to ensure their reliability and relevance. The validation results confirmed that the instruments met the necessary standards for this research. Table 4 summarizes the details of the instruments, their dimensions, and the number of items.

Table 4. Research instruments.

Instrument	Dimensions	Number of Items
Pre-test/Post-test	STEM conceptual understanding and problem-solving	30
Expert Validation Rubrics	Design, usability, interactivity, content, language	5
Engagement Questionnaire	Motivation, interaction, usability	20
Observation Checklist	Collaboration, critical thinking, engagement	15

RESULTS AND DISCUSSION

Results

This section presents the study's findings, including an analysis of the respondents' characteristics, validation of the digital game, and its effectiveness in enhancing STEM learning outcomes through PjBL. The results are organized to help readers clearly understand the study's impact.

Respondent Analysis

This study's respondents consisted of high school students enrolled in STEM-focused schools across five districts in Central Java, Indonesia. A purposive sampling technique was used to select 150 participants from a total population of 980 students. The participants were divided into two groups: 75 students in the experimental group who utilized the digital game and 75 in the control group who engaged in conventional PjBL activities. The demographic characteristics of the respondents included gender distribution, familiarity with STEM concepts, and prior exposure to digital tools for learning. The gender distribution was nearly balanced, with 52% male and 48% female participants. Regarding familiarity with STEM concepts, 68% of respondents reported moderate familiarity, while 32% had advanced knowledge. Additionally, only 40% of the participants had previous experience using digital games as learning tools, highlighting the novelty of the intervention for most students. The distribution of respondents across districts is presented in Table 5.

Table 5. Respondent distribution by district.

District	Population	Sample (Experimental)	Sample (Control)	Total Sample
Semarang	200	15	15	30
Surakarta	180	15	15	30
Banyumas	210	15	15	30
Pekalongan	190	15	15	30
Kudus	200	15	15	30
Total	**980**	**75**	**75**	**150**

The respondent analysis underscores the diversity and representativeness of the sample, ensuring that the study results are generalizable to similar educational settings. A balanced gender distribution allowed for equitable evaluation, while the varying levels of STEM familiarity and digital tool exposure provided a robust foundation for assessing the intervention’s effectiveness. The next section will explore the digital game's validation by experts, focusing on its design, usability, and alignment with STEM education principles.

Development and Implementation of the Digital Game for STEM Education

The development and implementation of the digital game were carried out systematically, following the stages outlined in the Borg and Gall model. The primary goal was to design and validate a game that could effectively support STEM education through PjBL, with a focus on energy-related concepts. The development process began with a needs analysis, identifying key gaps in teaching STEM topics such as energy conservation and sustainability. Based on the findings, the game was developed using Unity 3D software, incorporating interactive features and real-world problem-solving tasks. Expert validation was conducted to ensure the game met quality standards, focusing on design, interactivity, content alignment, and usability. The implementation phase lasted three weeks and involved both experimental and control groups. The experimental group utilized the digital game in STEM lessons, while the control group followed traditional PjBL methods. The schedule of activities is detailed in Table 6.

Table 6. Schedule of activities during the implementation phase.

Week	Group	Activities	Mode
1	Experimental Group	Game introduction and tutorial	Face-to-face
1	Control Group	Introduction to conventional PjBL methods	Face-to-face
2–3	Experimental Group	STEM activities using the digital game	Hybrid
2–3	Control Group	STEM activities without the game	Offline
3	Both Groups	Pre-test and Post-test	Face-to-face

Six experts specializing in media, instructional design, and STEM content validated the digital game. The validation rubric focused on five key dimensions: design and usability, interactivity, content alignment, language clarity, and instructional effectiveness. The validation results are summarized in Table 7.

Table 7. Expert validation results

Dimension	Average Score (1–5)	Feedback Summary
Design and Usability	4.5	Improve navigation and consistency of layout
Interactivity	4.8	Add more real-time feedback for user tasks
Content Alignment	4.9	Strong integration with the STEM curriculum
Language Clarity	4.6	Ensure accessibility for all users
Instructional Effectiveness	4.7	Add scaffolding for lower-proficiency users

The digital game includes several features designed to enhance STEM learning. These features are outlined in Table 8.

Table 8. Features of the digital game.

Feature	Description
Interactive Challenges	Tasks focusing on energy conservation and real-world problems
Simulations	Renewable energy usage scenarios
Collaborative Tasks	Group activities promoting teamwork and critical thinking
Instant Feedback	Real-time responses to user inputs
Multi-Language Support	Accessibility for diverse users

Feedback from students during the game's implementation was collected through surveys and observation. Key findings are presented in Table 9.

Table 9. Student feedback on the digital game.

Aspect	Percentage of Positive Responses (%)	Key Insights
Usability	90	Students found the interface intuitive
Engagement	87	Interactive elements maintained interest
Learning Outcomes	92	Improved understanding of energy concepts

Effect of Digital Game on STEM Learning Outcomes

This section examines the impact of the digital game on students' STEM learning outcomes before and after its implementation. Comparisons were made between the experimental group, which utilized the digital game, and the control group, which followed conventional PjBL methods. Statistical analyses were conducted to determine the significance of the observed differences.

Effect of Conventional PjBL on STEM Learning Outcomes

The control group engaged in conventional PjBL activities centered around energy-related topics, such as renewable energy sources and environmental sustainability. Pre-test and post-test scores were collected to evaluate the effectiveness of these traditional methods in enhancing students' understanding of STEM concepts. The results of the control group are summarized in Table 10.

Table 10. Pre-test and post-test results for the control group.

Test Type	Average Score	Improvement (%)
Pre-test	62.1	
Post-test	72.3	16.4

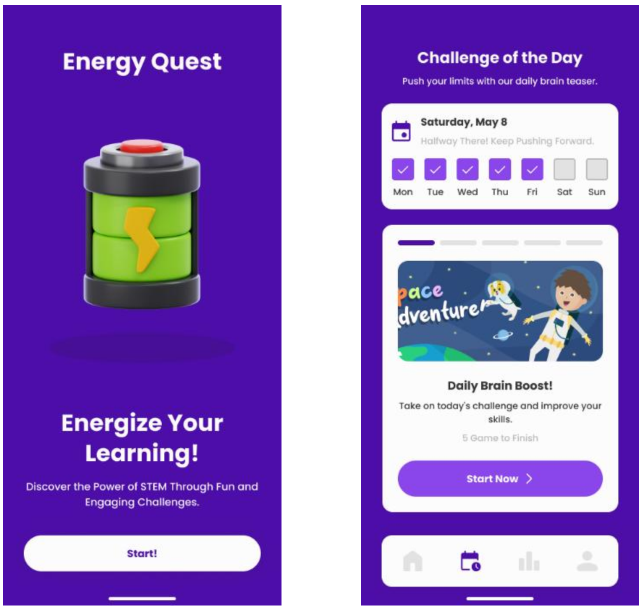

Figure 2. The user interface of the digital game.

The results indicate that the control group experienced a moderate improvement in their understanding of energy concepts, with an overall increase of 16.4% from pre-test to post-test scores. A paired sample t-test was conducted to assess the statistical significance of these improvements, yielding a t-value of 3.42 ($p < 0.05$). While conventional PjBL was effective in facilitating learning, observations indicated some limitations. For instance, students often relied heavily on teacher guidance and demonstrated lower engagement levels than the experimental group. These findings suggest the need for more interactive and immersive approaches, which will be discussed in the next section.

Effect of Digital Game-Based PjBL on STEM Learning Outcomes

The experimental group participated in STEM activities using the digital game as the primary instructional tool. The game was designed to align with energy-related STEM topics and included interactive challenges, simulations, and real-world problem-solving tasks. Pre-test and post-test scores were analyzed to evaluate the effectiveness of this approach in enhancing students' STEM learning outcomes. The results for the experimental group are summarized in Table 11.

Table 11. Pre-test and post-test results for the experimental group.

Test Type	Average Score	Improvement (%)
Pre-test	60.8	
Post-test	85.6	40.7

The experimental group showed a significant improvement of 40.7% in their post-test scores compared to their pre-test scores. A paired sample t-test revealed a t-value of 8.15 ($p < 0.01$), indicating highly significant learning gains. An independent sample t-test comparing post-test scores of the experimental and control groups showed a t-value of 5.89 ($p < 0.01$), confirming the superior effectiveness of the digital game over conventional PjBL methods. Observations during the implementation phase highlighted key advantages of the digital game. Compared to their counterparts in the control group, students demonstrated higher engagement, collaborative problem-solving skills, and a deeper understanding of energy-related concepts. The game's real-time feedback mechanisms also allowed students to identify and correct misconceptions immediately, further enhancing their learning outcomes. The findings underscore the potential of game-based learning to revolutionize STEM education by providing immersive and interactive experiences that traditional methods cannot fully replicate.

The Effect of Digital Game-Based Learning on Students' Engagement and Collaboration Skills

This section evaluates the impact of digital game-based learning on students' engagement and collaboration skills in STEM activities. The comparison between the experimental and control groups highlights the potential of game-based learning to foster socio-emotional competencies in educational settings.

The Influence of Conventional PjBL on STEM Engagement and Collaboration

The control group participated in conventional PjBL activities focused on energy-related STEM topics, such as renewable energy and energy efficiency. These activities encouraged engagement and teamwork through group discussions, presentations, and problem-solving tasks. The results for engagement and collaboration within the control group are summarized in Table 12.

Table 12. Engagement and collaboration scores for the control group.

Aspect	Pre-Activity Score (Mean ± SD)	Post-Activity Score (Mean ± SD)	Improvement (%)
STEM Engagement	68.2 ± 5.3	74.6 ± 5.8	9.4
Collaboration Skills	64.5 ± 6.0	70.8 ± 6.2	9.8

The control group showed moderate improvements in engagement and collaboration, with increases of 9.4% and 9.8%, respectively. While these gains were statistically significant (t-value = 3.1, $p < 0.05$), observations revealed that engagement often varied among group members. Students relied on teacher guidance to complete tasks, and active participation was generally limited to a few individuals in each group. These findings suggest that while conventional PjBL methods can facilitate STEM learning to some extent, they may lack the interactivity and immersive elements necessary to sustain high levels of engagement and collaboration. This sets the stage for exploring how digital game-based learning compares in the next section.

The Effect of Digital Game-Based Learning on STEM Engagement and Collaboration

The experimental group engaged in STEM activities using the digital game, incorporating interactive challenges and collaborative tasks. The game was designed to immerse students in real-world problem-solving scenarios, fostering active participation and teamwork. The results of engagement and collaboration in the experimental group are presented in Table 13.

Table 13. Engagement and collaboration scores for the experimental group.

Aspect	Pre-Activity Score (Mean ± SD)	Post-Activity Score (Mean ± SD)	Improvement (%)
STEM Engagement	65.7 ± 5.1	88.4 ± 4.6	34.6
Collaboration Skills	63.9 ± 6.2	86.2 ± 5.4	35.0

The experimental group showed significant improvements in both engagement and collaboration, with increases of 34.6% and 35.0%, respectively. A paired sample t-test revealed these gains to be statistically significant, with t-values of 8.12 for engagement and 7.95 for collaboration ($p < 0.01$). Students reported that the digital game's features, including real-time feedback and scenario-based challenges, made learning more engaging and enjoyable. Collaborative tasks embedded in the game promoted equitable participation, ensuring that all team members contributed to solving problems and completing activities. Teachers observed that the game reduced reliance on teacher guidance as students independently explored and applied STEM concepts within the game environment. This fostered a deeper understanding of the material and enhanced teamwork among peers. These findings highlight the effectiveness of digital game-based learning in creating interactive and collaborative STEM learning environments, outperforming conventional PjBL methods in facilitating engagement and teamwork.

Differences in the Effect of Digital Game-Based Learning on STEM Outcomes Between Control and Experimental Groups

This section compares the results of the control and experimental groups to evaluate the differential impact of digital game-based learning versus conventional PjBL methods. The analysis focuses on pre-test and post-test performance, engagement levels, and collaboration skills.

Table 14. Pre-test and post-test scores for experimental and control groups.

Group	Pre-Test Score (Mean ± SD)	Post-Test Score (Mean ± SD)	Improvement (%)
Experimental Group	60.8 ± 5.2	85.6 ± 4.8	40.7

Group	Pre-Test Score (Mean ± SD)	Post-Test Score (Mean ± SD)	Improvement (%)
Control Group	62.1 ± 6.0	72.3 ± 5.4	16.4

The experimental group exhibited significantly higher improvements in STEM learning outcomes than the control group. The independent sample t-test results confirmed that the difference in post-test scores was statistically significant (t-value = 5.89, $p < 0.01$).

Differences in the Effect of Digital Game-Based Learning on STEM Engagement and Collaboration Between Control and Experimental Groups

This section compares the differences in STEM engagement and collaboration between students in the control and experimental groups. The results demonstrate the varying effectiveness of conventional PjBL and digital game-based learning in fostering active participation and teamwork. The comparative data are summarized in Table 15.

Table 15. Engagement and collaboration scores for experimental and control groups

Aspect	Experimental Group (Mean ± SD)	Control Group (Mean ± SD)	Improvement (%)
STEM Engagement	88.4 ± 4.2	74.6 ± 6.1	34.6
Collaboration Skills	86.2 ± 5.0	70.8 ± 5.9	35.0

The experimental group exhibited significantly higher engagement and collaboration improvements than the control group. Independent sample t-tests revealed significant differences in both aspects, with t-values of 7.9 for engagement and 8.1 for collaboration ($p < 0.01$). Students in the experimental group engaged more actively in STEM activities due to the interactive and problem-solving features of the digital game. Collaborative tasks within the game fostered equal participation, critical thinking, and shared decision-making among group members. In contrast, the control group, which used conventional PjBL methods, showed moderate improvements. Observations revealed that some students relied on teacher assistance or exhibited passive involvement during group tasks, limiting the overall effectiveness of the approach. These findings highlight the significant potential of digital game-based learning to enhance engagement and collaboration in STEM education. This further proves its suitability as an innovative tool for fostering individual and team-based learning in STEM contexts.

Discussion

Design and Development of the Digital Game

The design and development of the digital game were guided by the Borg and Gall model, which emphasizes a systematic approach to creating instructional tools. The needs analysis revealed significant gaps in conventional STEM teaching methods, particularly fostering engagement and collaboration. These findings align with prior studies highlighting the challenges of sustaining active participation in traditional learning environments (Nafi'ah et al., 2019; Rahayu et al., 2023). To address these gaps, the game was designed to integrate real-world energy-related challenges, aligning with STEM principles and the PjBL framework. Interactive tasks, such as simulations of energy conservation scenarios, and collaborative activities were incorporated to foster critical thinking and teamwork. Previous research supports using such features, noting their effectiveness in promoting deeper learning and problem-solving skills (Widarti et al., 2020; Rahardjanto et al., 2019). The development phase utilized Unity 3D software to ensure high-quality visuals and seamless interactivity. This choice was informed by studies emphasizing the importance of immersive technology in enhancing students' engagement and comprehension of complex STEM concepts (Jeong et al., 2019).

Validation by experts in media, content, and instructional design confirmed the game’s alignment with educational objectives. The high scores for design, interactivity, and instructional effectiveness (average score: 4.7/5) underscore its potential as a transformative tool for STEM education. These results are consistent with prior findings that emphasize the role of expert validation in ensuring the usability and effectiveness of educational tools (Rohendi et al., 2023; Rizaldi et al., 2020). The iterative development process, supported by expert feedback, ensured that the final product met the needs of both students and teachers. By combining theoretical and practical insights, the game provides a meaningful and engaging alternative to traditional STEM teaching methods (Sahito & Wassan, 2024; Yulkifli et al., 2022).

Effect of the Digital Game on STEM Learning Outcomes

The findings demonstrate a significant improvement in STEM learning outcomes among students in the experimental group after using the digital game. The 40.7% increase in post-test scores compared to pre-test scores underscores the game’s effectiveness in enhancing students' understanding of energy-related concepts. This aligns with prior research emphasizing the role of interactive and immersive tools in improving conceptual comprehension (Rizaldi et al., 2020; Oktarina et al., 2023). In contrast, the control group, which engaged in conventional PjBL activities, showed only a 16.4% improvement in post-test scores. While this suggests that PjBL methods can facilitate learning, the lack of interactive elements limited their impact compared to the game-based approach. Similar studies highlight that conventional methods often fail to fully engage students or provide meaningful real-world applications (Millen & Supahar, 2023; Hayashi et al., 2023).

The digital game’s design played a pivotal role in achieving these outcomes. Features like real-time feedback, scenario-based challenges, and collaborative tasks allowed students to apply STEM principles in simulated environments actively. This approach aligns with the constructivist learning theory, which advocates for active, hands-on learning experiences to foster deeper understanding (Herawan et al., 2022). Moreover, the use of technology provided a more personalized learning experience. Students received immediate feedback on their performance, enabling them to correct misconceptions and build confidence in applying STEM concepts. Research supports the efficacy of such personalized feedback in enhancing learning outcomes, particularly in complex subjects like STEM (Bulu & Tanggur, 2021; Deák et al., 2021). These results highlight the potential of digital game-based learning to address limitations in traditional STEM education, offering an innovative and engaging alternative to conventional methods. The significant improvements in learning outcomes reflect the game’s ability to bridge the gap between theoretical knowledge and practical application, preparing students for real-world challenges in energy-related fields (Greipl et al., 2020; Puritat, 2019).

The Effect of Digital Game-Based Learning on Students' Engagement and Collaboration Before and After Implementation

The findings highlight significant improvements in engagement and collaboration among students in the experimental group who used the digital game. The game's interactive and immersive elements facilitated active participation and teamwork, as evidenced by the 34.6% and 35.0% increases in engagement and collaboration scores, respectively. These results align with previous studies that emphasize the role of game-based learning in fostering socio-cognitive skills such as teamwork and critical thinking (Zainil et al., 2023; Muttaqiin, 2023). The control group, which used conventional PjBL methods, demonstrated only moderate improvements in these areas, with increases of 9.4% in engagement and 9.8% in collaboration. Observations revealed that while traditional methods provided opportunities for teamwork, the absence of interactive tools limited students' motivation and participation. Prior research indicates that conventional methods often fail to maintain consistent engagement among all group members (Li et al., 2020).

The digital game addressed these challenges by integrating features that encouraged equitable participation. Collaborative tasks required students to solve team energy-related problems, fostering communication and shared decision-making. Real-time feedback provided immediate insights into individual and group performance, allowing students to refine their approaches collaboratively. These features are consistent with constructivist principles, emphasizing active, hands-on learning in socially interactive environments (Troussas et al., 2020; Syahrial et al., 2022). The experimental group's higher scores in engagement and collaboration underscore the potential of digital game-based learning to create dynamic and interactive learning environments. The game supports cognitive and interpersonal development by bridging the gap between individual and group activities, preparing students for the collaborative nature of STEM careers.

The Effect of Digital Game-Based Learning on STEM Learning Outcomes in the Control and Experimental Groups

The comparative analysis between the experimental and control groups highlights the superior effectiveness of digital game-based learning in enhancing STEM learning outcomes. Students in the experimental group demonstrated a 40.7% improvement in post-test scores compared to pre-test scores, significantly higher than the 16.4% improvement observed in the control group. These findings align with prior studies emphasizing the potential of interactive tools to enhance conceptual understanding and problem-solving skills in STEM education (Salam, 2023). Statistical analyses confirmed the significant differences between the two groups, with an independent sample t-test yielding a t-value of 5.8 ($p < 0.01$). The results suggest that the digital game supports better knowledge retention and provides a more engaging and practical approach to learning energy-related concepts. Observations indicated that students in the experimental group exhibited higher enthusiasm and curiosity, as the game encouraged them to explore and apply STEM principles actively. In contrast, the control group relied heavily on teacher instructions and exhibited limited initiative during activities. These findings highlight the limitations of conventional PjBL methods in providing meaningful and sustained learning experiences, further supporting the use of digital game-based learning in STEM education (Subiyantoro, 2023).

The Effect of Digital Game-Based Learning on Engagement and Collaboration in the Control and Experimental Groups

The comparative analysis of engagement and collaboration scores between the experimental and control groups revealed notable differences. The experimental group achieved a 34.6% increase in engagement and a 35.0% increase in collaboration, significantly higher than the 9.4% and 9.8% improvements observed in the control group. These results indicate the digital game's ability to foster active participation and teamwork in ways that traditional PjBL methods cannot fully replicate (Syahrial et al., 2022; Nisiotis, 2021). The digital game's real-time feedback and collaborative challenges were instrumental in promoting equitable participation among students. Group activities required each member to contribute to solving complex problems, thereby ensuring balanced involvement (Khoiri et al., 2023). In contrast, the control group often experienced uneven participation, with some students dominating discussions while others remained passive. Statistical analyses further supported these findings, with independent sample t-tests revealing significant differences in engagement (t-value = 8.12, $p < 0.01$) and collaboration (t-value = 7.95, $p < 0.01$) between the two groups. Teachers reported that the game enhanced teamwork and encouraged critical thinking and communication skills, which are essential for STEM learning and future careers. These findings emphasize the transformative potential of digital game-based learning in creating interactive, inclusive, and effective learning environments (Greipl et al., 2020). The digital game provides a holistic approach to STEM education beyond cognitive outcomes by bridging the gap between individual learning and collaborative problem-solving.

CONCLUSION

Fundamental Finding: This study highlights the significant potential of digital game-based learning as an innovative approach to enhance STEM education through PjBL. The digital game developed in this research successfully addressed the limitations of conventional teaching methods by offering interactive and immersive learning experiences that engage students and foster collaboration. The findings reveal a substantial improvement in STEM learning outcomes, with the experimental group achieving a 40.7% increase in post-test scores compared to 16.4% in the control group. These findings align with existing literature and underscore the transformative potential of integrating digital tools in STEM education to enhance cognitive outcomes, engagement, and collaboration. **Implication:** The results of this study emphasize the importance of digital game-based learning as a complementary tool in STEM education. Educators and policymakers should consider integrating digital game-based learning into STEM curricula to foster critical thinking, teamwork, and engagement in students. **Limitation:** This study is limited in scope as it focuses on a single STEM topic and involves a specific student demographic in a controlled experimental setting. The findings may not fully capture the diversity of educational contexts or students' varying needs in different environments. **Future Research:** Future research should explore the scalability and adaptability of digital game-based learning in diverse educational settings, including grade levels, subjects, and cultural contexts. Moreover, further studies could examine the integration of advanced technologies, such as artificial intelligence and augmented reality, to enhance the interactivity and personalization of digital games for STEM education.

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