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Exploring Mechanical Waves Through a Physics-Based Exploration Game for Secondary Education

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Abstract

Mechanical waves are an important part of high school physics, but they can be hard to understand because they are so abstract. The goal of this study was to create and test a physics-based digital exploration game that would help people understand wave phenomena. The game content included electromagnetic and mechanical waves, transverse and longitudinal waves, and the Doppler effect. This study employs a simplified instructional design model focusing on three key steps: analysis, design, and development. This model aims to enhance student engagement through the use of digital platforms and interactive learning resources such as educational games and mobile applications. Playzone was built on the CORE APPS platform. It had a shooting game set in a lab with tasks that required players to unlock objects, find clues, and get to areas that boost health. The expert reviewed the curriculum alignment, how the materials were presented, and how the evaluations worked. The assessment gave this game prototype a score of 89.33%, which means it is very feasible as learning media. These results show that the game could be very useful in the classroom because it makes learning about abstract physics concepts more fun and easier to understand by using stories and interactive activities.

Keywords: mechanical waves, digital educational games, exploration games, physics learning

INTRODUCTION

In high school physics, students learn the topic of mechanical waves, since it is the basis for other scientific principles, such as frequency, amplitude, and the Doppler effect. This topic explains how waves travel and interact by completing experiments with mechanical waves. Teachers faced a problem when students were unable to understand the workings and essential characteristics of mechanical waves, perhaps resulting in misconceptions (Tumanggor, 2020; Guerra-Reyes et al., 2024). If we as teachers or educators rectify these misunderstandings early on, students will be able to grasp both fundamental and advanced physics issues better (Korlat et al., 2024). Teachers in many classrooms still struggle to convey physics concepts to their students because they rely on oversimplified models and static representations that fail to account for the dynamic nature of physical phenomena. It is causing many students to misunderstand the material topic (Zouhri & Mallahi, 2025; Vidak et al., 2024). Abstract representations make it challenging for students to make personal connections (Aliu et al., 2025). This effect is particularly evident when discussing wave phenomena, a topic where capturing students' interest is crucial for their understanding. Simultaneously, a fully engaged student retains more information. The utilization of interactive tools like augmented reality, which are simulation-based technologies, has the potential to increase student engagement and help them draw stronger connections between theoretical concepts and their practical applications (Vidak et al., 2024; Liu & Liu, 2025).

Besides simulation-based interactive teaching methods, game-based learning (GBL) has come up as a possible way to attract students more interested in abstract physics topics. There are many evident benefits to adopting GBL in physics and science lectures, such as making students more interested, motivated, and understanding of the material. One benefit of GBL compared to more traditional types of education is that it encourages students to be more involved and engaged in the learning process. This increased engagement can help students see difficult subjects like physics in a new light (Rusevka et al., 2024; Zulhelmi, 2023). Being able to solve problems and think critically are important goals for science education, and GBL helps with both. Prior studies have shown that gamified learning environments help students deepen their understanding of scientific concepts by allowing them to explore multiple solutions within a safe and supportive context (Janiga & Haverlíková, 2024). The GBL has also been recognized for its adaptability to diverse learning styles and groups of learners (Lazarevic, 2024). Educational games considerably improve student motivation and facilitate conceptual learning in science and physics by establishing interactive, compelling environments that encourage active learning. Games frequently integrate rewards, challenges, and elements of competition, thereby enhancing the learning experience and motivating students (Zappalá, 2025).

Exploration games enable students to learn by exploring dynamic, immersive worlds in which they can learn organically. Its design encourages learning by capturing people's attention and engaging them in activities. This encourages critical thinking and expands their knowledge of the subject (Su & Zou, 2024). Narrative elements, such as a tale or a theme, make studying more fascinating and relatable, hence keeping pupils engaged in their studies. The game's missions and clue-finding tasks are designed to help pupils apply what they've learned in theory to real-world challenges. This closes the gap between theoretical principles and their practical applications (Rusevka et al., 2024). Simulation-based games have been found in studies to significantly improve physics students' learning outcomes. Exploration games have been particularly effective in helping students grasp complicated concepts such as energy transformation and sound waves by allowing them to view and manipulate variables in a dynamic environment (Zappalá, 2025; Santoso et al., 2022).

The purpose of this study is to create and verify a physics-based digital adventure game that will help secondary pupils comprehend mechanical waves. The game incorporates fundamental physics concepts, such as wave characteristics and the Doppler effect, into an interactive and narrative-driven world, encouraging students to actively engage with information through mission-based exploration and problem-solving challenges. The design is unique in that it employs multi-zone gaming, visual simulations, and embedded cues to aid contextual learning and conceptual reinforcement. To ensure instructional relevance and usability, the game was subjected to an expert evaluation for content feasibilty, as well as a preliminary classroom trial to evaluate user experience. By merging pedagogical tactics and game mechanics, this work adds to the increasing body of research on digital learning tools in physics education, providing a fresh approach to tackling abstract and difficult subjects through meaningful and engaging experiences.

METHODS

The framework used in this study adopts a structured instructional design approach focusing on three core steps: analysis, design, and development. This approach was chosen for its ability to provide a solid foundation for designing and developing digital-based learning. By integrating digital platforms and interactive learning resources, such as educational games and mobile applications, this study aims to effectively enhance student engagement and learning outcomes (Abuhassna et al., 2024).

Research Design

This study employed a Research and Development (R&D) framework, emphasizing the systematic creation and validation of an educational game prototype that integrates physics learning with interactive gameplay. The development process was organized into three major phases to ensure a coherent linkage between pedagogical objectives and game mechanics. During the Analyze phase, diagnostic observations revealed that several students experienced difficulties in understanding fundamental wave concepts, including amplitude, frequency, wavelength, and the differentiation between transverse and longitudinal waves. These learning challenges were subsequently formulated into specific instructional goals, which informed the development of narrative elements, game mechanics, and task designs during the Design phase. The storyline was constructed around real-world scenarios to enhance contextual relevance and cognitive engagement, allowing players to connect abstract concepts with observable phenomena.

In the Develop phase, the conceptual design was implemented into a functional game prototype using the CORE APPS platform. This platform facilitated the integration of multimedia resources, interactive clues, problem-solving challenges, and a zone-based progression system, thereby creating an immersive learning environment that encourages exploration, inquiry, and the application of physics principles in a simulated context. The combination of narrative-driven gameplay and conceptual visualization was designed to enhance students' motivation, promote active engagement, and support deeper understanding of wave-related physics concepts..

Game Development Process

Student confusion between transverse and longitudinal waves, as well as misunderstandings about the relationships between amplitude, frequency, wavelength, and energy transmission, has been shown in prior classroom observations and scholarly publications. The game's objective background is based on these observations. By using the CORE APPS platform, we create modular learning spaces, multimedia-based learning experiences, and interactive simulations and name it Playzone, the game of mechanical waves. Set in a shooting game with a physics lab aesthetic, this section describes many forms of waves and their characteristics. Inviting users to actively explore and learn more about concepts through sight and touch is the goal of this design.

Expert Assessment

The content feasibility of the game prototype was evaluated through an expert review process using a specifically designed assessment instrument. The review focused on three main aspects: curriculum alignment, content presentation, and evaluation components, each representing essential dimensions of pedagogical validity. The instructional content of the game was required to meet established standards of pedagogical coherence, conceptual accuracy, and cognitive appropriateness to ensure that the learning objectives were effectively represented within the gameplay. Accordingly, a structured instrument was developed to verify these criteria and to provide a systematic framework for expert judgment. The evaluation employed a Likert-scale questionnaire consisting of both closed-ended and open-ended items. The closed-ended questions were rated on a 5-point scale, ranging from very poor to very good, to quantify the level of validity for each indicator, while the open-ended questions captured qualitative feedback, allowing experts to suggest improvements in clarity, depth, and content relevance. This dual approach enabled a comprehensive assessment that combined quantitative rigor with qualitative insight, strengthening the reliability of the game's content validation process.

RESULTS AND DISCUSSION

Game Design Output

A physics-based adventure game featuring interconnected zones was developed, with each zone presenting its own narrative background, set of challenges, and specific learning objectives. Within this immersive environment, players take on the role of a young physics apprentice whose mission is to solve a series of scientific puzzles related to wave phenomena. Through exploration and interaction, players are required to engage in inquiry-based learning by collecting clues, analyzing situations, and applying relevant physics concepts to advance in the game. Conversations with in-game characters serve as a medium for information exchange, offering hints, challenges, and conceptual explanations that gradually deepen players' understanding. This design not only integrates storytelling and gameplay mechanics but also promotes problem-solving, critical thinking, and conceptual reinforcement, thereby transforming the learning process into an engaging and meaningful experience.

The educational material is based on Fundamentals of Physics (Halliday et al., 2017) and focuses on two main types of waves: electromagnetic waves and mechanical waves. Electromagnetic waves can travel through a vacuum without needing a medium. Examples are visible light, ultraviolet light, radio and television waves, microwaves, X-rays, and radar waves. Mechanical waves, on the other hand, need a medium like water, air, or solids to move through. Water waves, sound waves, and seismic waves are all examples of this. The content of the Electromagnetic Waves and Mechanical Waves material is presented in FIGURE 1.

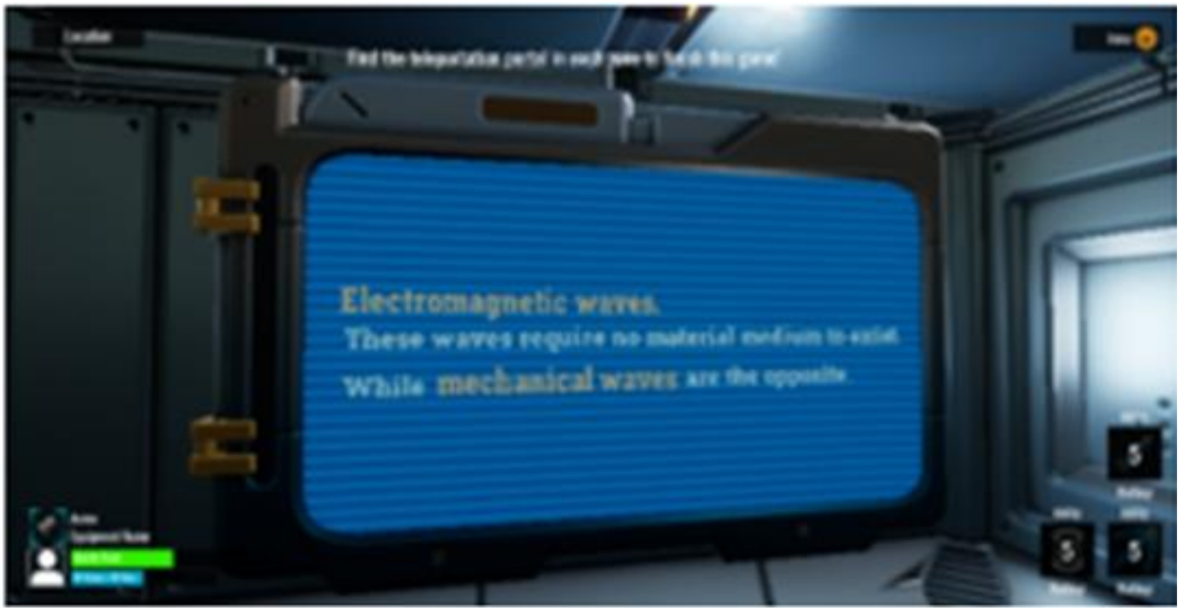


FIGURE 1. Learning content presented in the game on characteristics of electromagnetic and mechanical waves

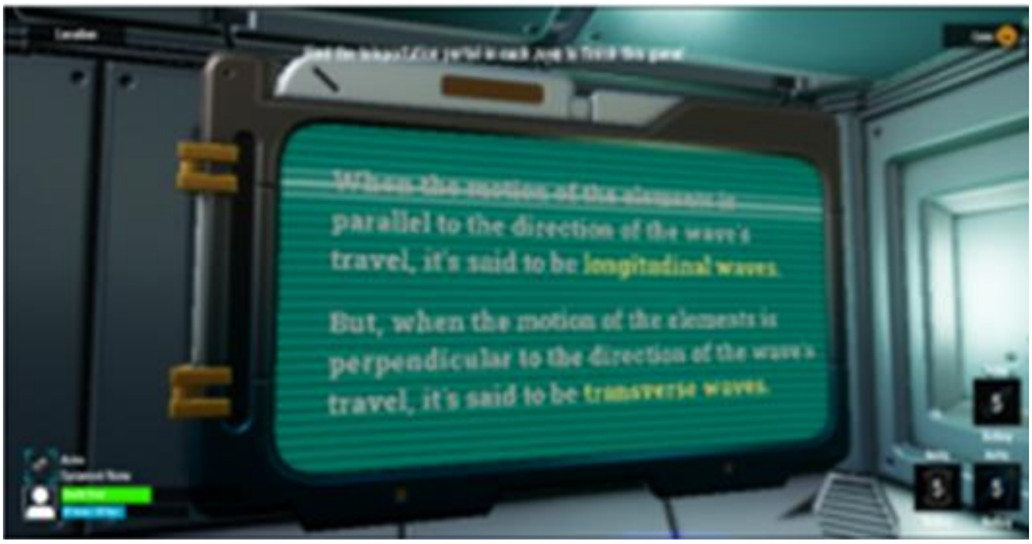


FIGURE 2. Learning content presented in the game on characteristics of transverse and longitudinal waves

In FIGURE 2 discusses longitudinal and transverse waves. Longitudinal waves are a type of mechanical wave in which particles move back and forth in the same direction as the wave. Transverse waves are a type of mechanical wave in which particles move back and forth in the opposite direction. The game also discusses the Doppler effect, which shows how the wavelength and frequency change when a source or detector moves. It does this by giving real-world examples. FIGURE 3 shows the Doppler effect.

FIGURE 3. Learning content presented in the game on application of the Doppler effect

Playzone serves as the central area where the interactive component of the game begins, emphasizing the exploration of mechanical wave properties through engaging gameplay. Designed to resemble a physics laboratory, this zone adopts a shooting game format that combines entertainment with conceptual learning. Players are encouraged to navigate the virtual environment, interact with laboratory objects, and uncover hidden clues that progressively guide them toward completing each mission and advancing to the next zone. The learning content within Playzone focuses on the fundamental characteristics of mechanical waves, including demonstrations of the differences between longitudinal and transverse waves and an overview of the Doppler effect and its implications.

To continue playing, players can unlock locked chests by pressing the "F" key on their keyboard and traveling to places that restore health. This layout encourages users to study, perform tasks, and explore more. Illustrates various components of the Playzone user interface, which are divided into three main sections. The overall interface design, game format, on-screen instructions, and laboratory room layout are shown in FIGURE 4, FIGURE 5, FIGURE 6, and FIGURE 7. These visual elements provide a comprehensive overview of how students interact with the learning environment. The intuitive design allows users to easily navigate between sections, understand gameplay objectives, and access learning materials efficiently. The combination of instructional guidance and game-based interaction enhances students' motivation, concentration, and self-directed learning. By integrating entertainment and education, the Playzone interface not only presents physics content effectively but also cultivates an interactive and exploratory learning atmosphere.

FIGURE 4. Playzone user interface

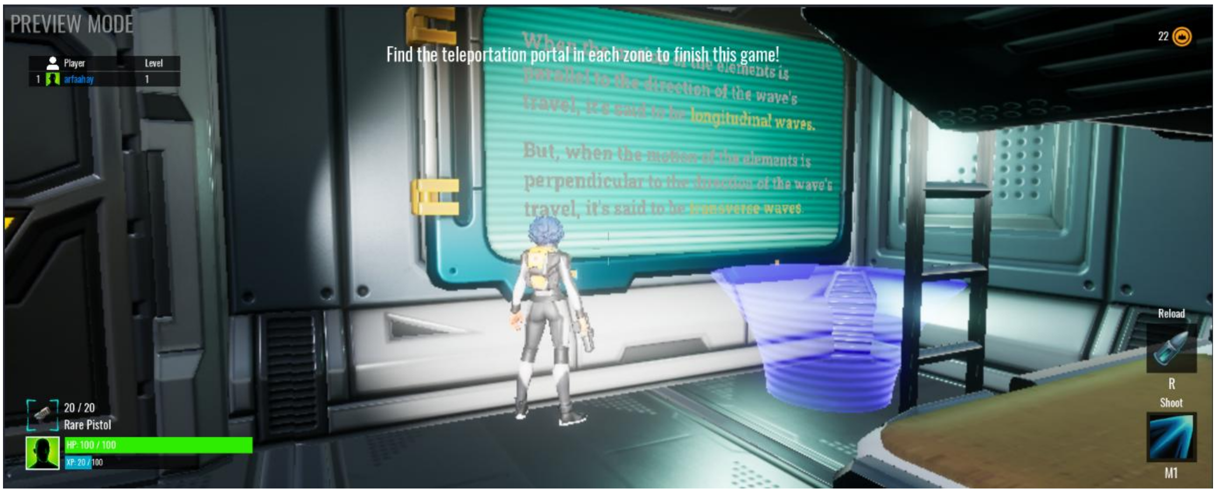
FIGURE 5. Shooting Game Format

FIGURE 6. On-Screen Instructions in Playzone

FIGURE 7. Laboratory room layout in Playzone

FIGURE 8 presents the learning content materials, namely Material 1, Material 2, and Material 3, which are systematically organized to guide students in exploring fundamental concepts of wave phenomena. The first material focuses on electromagnetic and mechanical waves, introducing their distinctive characteristics and propagation mechanisms. The second material discusses transverse and longitudinal waves, emphasizing differences in particle motion and energy transfer direction. The third material explains the Doppler effect, illustrating how frequency and wavelength change due to relative motion between the source and the observer. Collectively, these materials are designed to build conceptual understanding through sequential learning, enabling students to connect theoretical principles with real-world applications of wave behavior.

(a)



(b)

(c)

FIGURE 8. Learning content materials presented in Playzone, covering (a) Material 1, (b) Material 2, and (c) Material 3

FIGURE 9 highlights the interactive elements that promote user engagement and active participation through decision-making and problem-solving tasks. These interactive components are designed to encourage students to actively apply the concepts they have learned within the game environment. By responding to challenges, selecting appropriate answers, or manipulating virtual objects, students can directly experience the relationship between theoretical principles and observable outcomes. Such interactivity transforms the learning process from passive knowledge reception into active exploration and experimentation. Together, these components create an immersive learning experience that integrates gameplay, content delivery, and interactivity to foster deeper conceptual understanding, critical thinking, and sustained interest in physics learning.

FIGURE 9. Interactive elements featured in Playzone, consisting of the first and second interactive elements

Expert Assessment Result

The content feasibility test was carried out to determine the suitability of the material created for the game. The assessment stage was carried out offline using a Content Feasibility Assessment Sheet completed by a physics lecturer. The instrument consisted of a closed-ended questionnaire with three main assessment aspects: curriculum, material presentation, and evaluation. The results of the assessment are presented in TABLE 1. The curricular part received a rating of 22 out of 25 (88%), indicating a "very feasible" interpretation. The content presentation component received a perfect score of 10 out of 10 (100%), which is also characterized as "very feasible." The evaluation facet received 12 out of 15 (80%), which is also read as "very feasible." The aggregate average percentage score across all elements was 89.33%, which puts it in the "very feasible" category. Table 1 also shows that all assessed aspects met the feasibility criteria for use in physics learning.

In addition to the quantitative assessment, the experts provided qualitative feedback aimed at improving the instructional effectiveness and usability of the game. Several key recommendations were proposed, including the need to enhance the clarity of instructional prompts to ensure players fully understand task objectives and learning goals. Experts also suggested the inclusion of additional contextual examples to better illustrate abstract wave concepts, thereby strengthening the connection between theoretical content and practical understanding. Furthermore, the evaluation components were recommended for refinement, particularly in revising question items to more effectively measure higher-order thinking skills such as analysis, synthesis, and problem-solving. Minor revisions to the visual layout and interface design were also advised to improve navigation flow and maintain learner engagement throughout gameplay. All of this qualitative feedback was carefully considered and integrated into the revised version of the game prototype, ensuring that it would be more pedagogically robust and suitable for future classroom implementation and testing.

TABLE 1. Results of expert assessment for content feasibility.

Aspect	Score	Total Score	Percentage (%)	Interpretation
Curriculum	22	25	88	Very feasible
Material presentation	10	10	100	Very feasible
Evaluation	12	15	80	Very feasible
Average			**89.33**	**Very feasible**

Discussion

The assessment results indicate that the developed game achieved a “very feasible” category with an overall validity score of 89.33%. This result demonstrates that the game successfully fulfills the essential criteria of content accuracy, curriculum alignment, and appropriate cognitive level for the intended learners. The perfect score in the material presentation aspect (100%) further highlights the effectiveness of the game’s design in delivering abstract physics concepts through engaging visual and interactive formats. The integration of interactive narratives, visual representations, and problem-based game mechanics was found to significantly enhance students’ comprehension of complex topics, particularly those that are difficult to visualize, such as wave classifications and the Doppler effect. These findings suggest that embedding physics learning within a narrative-driven, exploratory game environment not only supports conceptual understanding but also fosters learner motivation and active participation. Overall, the high feasibility score underscores the potential of game-based learning as an innovative instructional medium for improving the teaching and learning of abstract scientific phenomena.

As summarized in TABLE 2, the present study targets secondary-level mechanical waves, was developed via a simplified Analyze-Design-Develop process, and runs on CORE APPS. In contrast, the fluid-mechanics study used full ADDIE on Genially and Moodle LMS and reported assessment scores of 92.06% (material), 96.88% (media), and 97.2% (software), alongside a 23% post-test gain (Zalika, 2025).. The hydroelectric-power game, built with a 4D model in Unity 3D using the Obi Fluid plugin, did not report numerical scores but provided qualitative evidence of improved understanding and motivation (Muliyati & Firdaus, 2024). TABLE 2 further shows that user testing has not yet been conducted for the present study, whereas both comparison projects include classroom evaluation. Feature-wise, our design emphasizes zone-based exploration, clue collection, and light shooting mechanics; the others employ case-based missions, puzzles/quizzes, level progression, and water-flow simulation.

TABLE 2. Comparison of the present study with similar educational game developments.

Aspect	Present Study	Fluid Mission (Zalika, 2025)	Hydro-Electric Game (Muliyati, 2024)
Topic	Mechanical waves (characteristics, longitudinal/transversal, Doppler effect)	Fluid mechanics (hydrostatics, Bernoulli’s principle, fluid dynamics)	Hydroelectric power stations (components, operation, energy conversion, transformers)

Aspect	Present Study	Fluid Mission (Zalika, 2025)	Hydro-Electric Game (Muliyati, 2024)
Development Model	R&D with simplified ADDIE (Analyze, Design, Develop)	R&D with full ADDIE (Analyze, Design, Develop, Implement, Evaluate)	R&D with 4D Thiagarajan model
Platform	CORE APPS	Genially + Moodle LMS	Unity 3D + Obi Fluid plugin
Assessment Aspects	Curriculum, material presentation, evaluation	Material, media, software, expert & user testing	Not specified in detail, focus on gameplay testing
Assessment Results	89.33% (very feasible)	Material 92.06%, media 96.88%, software 97.2% (very feasible)	No numerical score, qualitative positive feedback
User Testing	Not yet conducted	Post-test scores increased by 23%	Reported improved understanding and motivation
Game Features	Zone-based exploration, shooting game, clue collection	Case-based missions, puzzles, integrated quizzes	Level progression, interactive characters, water flow simulation
Potential Impact	Suitable for secondary physics, conceptually challenging topics	Effective for linking abstract concepts to real-world applications	Effective for introducing renewable energy at elementary level

These contrasts indicate that variations in content complexity and learner characteristics strongly influence the selection of game mechanics, scaffolding strategies, and visual representations. In the context of secondary-level physics learning, translating abstract wave phenomena into navigable zones and narrative clues has proven particularly effective, as reflected in the 100% score for material presentation. This approach enables students to visualize invisible processes and engage with concepts that are typically challenging to grasp through traditional instruction. Nevertheless, further classroom implementation trials are essential to evaluate the game's actual impact on learning outcomes, motivation, and engagement. Future development should focus on aligning in-game tasks more closely with curriculum standards, incorporating authentic and context-rich scenarios, and integrating adaptive feedback systems that respond dynamically to learners' actions. Such refinements will help ensure that the game not only supports conceptual understanding but also cultivates higher-order thinking skills and sustained interest in physics learning.

CONCLUSION

This study created and tested a digital physics-based exploration game to help high school students learn about mechanical waves, such as how to classify them and the Doppler effect. The game employed a research and development method using a simplified instructional design model to integrate curriculum-aligned content with interactive gameplay features, such as zone-based exploration, shooting mechanics, and clue collection. The expert assessment gave the game an overall feasibility score of 89.33%, which means it is "very feasible" in terms of curriculum alignment, material presentation, and evaluation components. Comparative analyses with analogous studies in fluid mechanics and renewable energy education reveal that the incorporation of narrative-driven tasks, authentic contexts, and interactive elements is essential for enhancing engagement and conceptual comprehension. This study primarily concentrated on expert evaluation; however, the results indicate significant potential for classroom application. Subsequent research ought to incorporate empirical testing with students to evaluate learning outcomes, motivation, and engagement, in addition to investigating the game's scalability for other physics subjects. This method shows that well-made educational games can be useful for connecting abstract physics ideas with real-world learning experiences.

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