Membrane Movers: A Game-Based Instructional Tool for Teaching Cell Membrane in Secondary Biology

Angelito M. Rivera, Ferdinand L. Osena

Graduate School, Nueva Ecija University of Science and Technology

DOI: https://dx.doi.org/10.47772/IJRISS.2026.100500629

Received: 14 May 2026; Accepted: 19 May 2026; Published: 09 June 2026

ABSTRACT

Membrane transport is often challenging for students to understand because it involves abstract biological processes that cannot be directly observed in the classroom, which may reduce student interest and engagement with the topic. This study examined the design, implementation, and classroom feasibility of an educational board game developed to teach Grade 10 Biology students about cell membrane transport. Using a design-based, descriptive mixed-methods approach, the study explored instructional alignment, student engagement and classroom feasibility through student questionnaires (n=20), open-ended responses, teacher observations adapted from the Playful Learning Observation Tool (PLOT), and alignment with North Dakota Science Standards. Quantitative data were analyzed descriptively while qualitative data were examined through thematic analysis and triangulation. Results indicated high levels of student enjoyment and engagement (M=4.28, SD=0.46) supported by teacher observations of active participation, collaboration and concept-driven decision-making. Triangulated findings showed strong convergence in engagement, rule clarity, collaboration and conceptual learning although some divergence was noted concerning time and pacing during implementation. These findings suggest that *Membrane Movers* is a feasible and standards-aligned instructional approach for teaching membrane transport. The study provides preliminary evidence supporting the use of analog educational board games in science education and offers a model for designing or adapting game-based learning interventions.

Keywords: Game-based learning, educational board games, Biology education, cell membrane transport, secondary science

INTRODUCTION

Background

Teaching abstract cellular processes such as cell membrane transport pose a challenge for secondary science educators, as students often lack hands-on opportunities to understand these invisible mechanisms. This challenge aligns with the goals of United Nations Sustainable Development Goal 4 (SDG 4), which promotes equitable and quality education through innovative pedagogies that build problem-solving and lifelong learning (United Nations, 2022). In North Dakota, where many rural schools face resource constraints, educational initiatives increasingly emphasize open educational resources (OER), game-based learning, and STEM integration to improve engagement and equity in rural education contexts.

Board games have emerged as powerful tools in Biology instruction, simulating dynamic processes while enhancing motivation, collaboration, and retention. For instance, Rahayu et al. (2023) reported that curriculum-aligned games improved interpretation of molecular processes like diffusion and osmosis. Similarly, Gonçalves et al. (2023) highlighted adaptability of board games for diverse learners, including games on cell division, echoing findings by Ching and Wang (2021) on the effectiveness of educational board games in molecular biology learning. Reviews of educational games in science education further suggest that well-designed games can support conceptual understanding, collaboration, and motivation in classroom learning environments (Gros & López, 2023).

Although game-based learning has been widely studied, most of the existing research focuses on digital games and large-scale urban contexts, with limited attention to the design and implementation of analog games in rural secondary science classrooms. Moreover, few studies integrate motivational theory with design-based research to examine both pedagogical alignment and classroom feasibility. Research examining students' perspectives on game-based approaches in science classrooms further suggests that interactive learning environments can enhance meaningful learning experiences and increase student engagement (Huang et al., 2023).

North Dakota's science education landscape reflects these global shifts amid local priorities. The North Dakota Department of Public Instruction and North Dakota University System (NDUS) promote OER repositories across institutions such as the University of North Dakota (UND) and North Dakota State University (NDSU) to reduce costs and expand access, particularly in under-resourced rural districts like Langdon (NDUS, 2025). Recent educational initiatives also emphasize experiential learning and outreach programs to strengthen K-12 STEM pathways, particularly in rural regions.

Despite this progress, gaps persist. Many students still struggle to visualize membrane transport or apply concepts in novel contexts. To address this gap, *Membrane Movers*, an educational board game, was developed by adopting established design practices that include iterative development, validation, and usability testing. The game targets learning experience, promoting inclusivity per SDG 4. In North Dakota's context, such tools may help bridge lab limitations, support equity for diverse, rural learners and contribute to statewide STEM modernization.

Research Questions

The following research questions guide this study:

RQ1. How was Membrane Movers board game designed and aligned with learning objectives using a structured board-game framework?

RQ2. How do the students describe their engagement levels and learning experiences during the implementation of Membrane Movers?

RQ3. How feasible is the classroom implementation of Membrane Movers in secondary biology instruction?

Conceptual Framework

This study is grounded in Self-Determination Theory (SDT), which explains student motivation through the fulfillment of three basic psychological needs: autonomy, competence, and relatedness (Ryan & Deci, 2020). In game-based learning contexts, SDT provides a framework for understanding how instructional games can enhance student engagement by offering meaningful choices, achievable challenges, and opportunities for social interaction (Sailer et al., 2021; Howard et al., 2021). The design of the *Membrane Movers* board game aligns with these SDT principles by linking specific game mechanics to students' motivational experiences in secondary biology learning.

The conceptual framework for *Membrane Movers* positions educational board game development as a two-phase, five-step process that links game design with classroom enactment. Phase 1 (Instructional Game Development) focuses on the design of the board game. In this phase, teacher-designers adopt familiar commercial mechanics to reduce cognitive load and entry barriers for students. These mechanics are then enhanced by adding strategic elements that promote player agency and meaningful decision-making. The cell membrane transport content (e.g., diffusion, osmosis, active transport) are embedded into cards, rules, and win conditions so that gameplay progression depends on demonstrating target understanding. This process follows the practical K–12 board game framework proposed by Nautiyal and colleagues, which emphasizes familiarity, balanced luck, strategy, and explicit curriculum alignment before classroom use. Similar frameworks emphasize the importance of integrating pedagogical objectives with game mechanics to ensure that learning outcomes are embedded within gameplay design (Cardinot et al., 2022).

Phase 2 (Classroom Application) focuses on implementation and evaluation in authentic classroom settings. During facilitated gameplay sessions, teachers monitor student participation and gather feedback on students' learning experiences. This is followed by repurposing, in which the gained insights are used to revise the game or adapt it for other science topics. To operationalize implementation quality and feasibility, the framework pairs measures of student experience with structured classroom observation. Specifically, it draws on the PLOT to document interactions, engagement indicators, and the ways in which game mechanics shape student participation. Evidence from open-access research on game-based learning further supports the focus on engagement and classroom climate as key outcomes of structured gameplay in secondary settings.

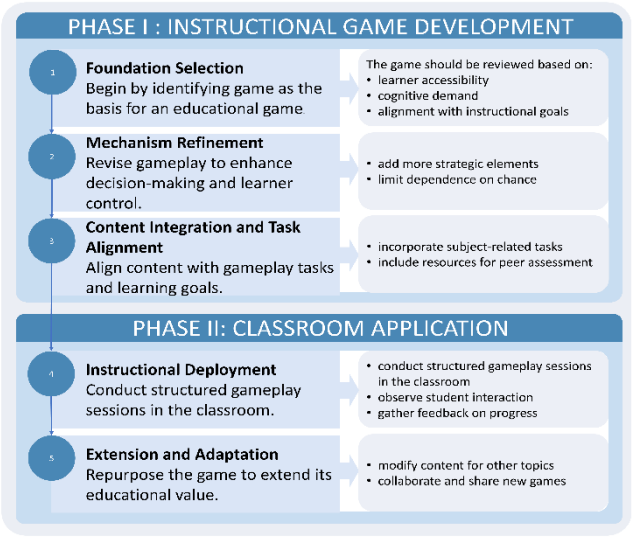


Fig. 1. The 5-Steps Educational Game Board Framework

MATERIALS AND METHODS

Research Design

This study employed a design-based research (DBR) approach using a descriptive mixed-methods design to develop, implement, and examine an educational board game in an authentic classroom context. DBR is particularly appropriate for educational game studies because it emphasizes the systematic design of learning artifacts, iterative refinement, and evaluation in real instructional settings, allowing researchers to connect theory, design, and practice (Anderson & Shattuck, 2012; McKenney & Reeves, 2020). Recent research in game-based learning highlights DBR as an effective methodology for investigating how educational games are conceptualized, aligned with curricular goals, and enacted in classrooms, particularly in K–12 settings, where contextual constraints and teacher facilitation play critical roles (Nautiyal et al., 2024; Hsu et al., 2022). Guided by a structured game design and implementation framework, this study focused on documenting the development process and examining how the game functioned during classroom use, rather than testing causal learning effects.

To address the research problems, the study integrated quantitative and qualitative methods to capture complementary dimensions of student engagement, learning experiences, and classroom feasibility. Quantitative data were collected through structured student feedback questionnaires to describe patterns of enjoyment, interaction, and perceived learning. Qualitative data were gathered through structured classroom observations and open-ended student responses to capture behavioral, cognitive, and emotional engagement during gameplay. This descriptive mixed-methods approach aligns with recent recommendations in educational game research, which emphasize combining numerical trends with contextualized qualitative evidence to understand how and why games function as learning tools (Creswell & Plano Clark, 2018; Algayres et al., 2022; Rodríguez-Ferrer et al., 2023). By triangulating multiple data sources within a DBR framework, the study supports a nuanced examination of both the educational artifact and its classroom implementation, enhancing the trustworthiness and practical relevance of the findings.

Participants and Context

The participants were 20 Grade 10 students from two small rural public schools in North Dakota during the 2025–2026 school year. These schools serve communities characterized by limited enrollment and small class sizes, which are typical of rural educational settings (National Center for Education Statistics, 2023). As a result, the sample (n=20) represents a bounded, intact classroom population rather than a convenience subset. Consistent with design-based research and feasibility-focused classroom studies, the purpose was not statistical generalization but to generate context-rich evidence on implementation, engagement, and instructional alignment within authentic classroom conditions (McKenney & Reeves, 2020). Contemporary methodological perspectives further emphasize that sample size should be justified based on the aims and design of the study rather than statistical power alone, particularly in exploratory and design-oriented research (Lakens, 2022).

Description of the Educational Board Game

This section presents the design and development of Membrane Movers as an educational board game which answer RQ1 of the study.

1) Game Objective

The primary objective of *Membrane Movers* is for players to be the first to transport molecules across the cell membrane while strategically managing energy resources and accumulating points. Players assume the roles of molecules attempting to enter or exit the cell, mirroring real biological transport processes. By requiring consideration of both molecule type and transport method, the game reinforces core concepts of membrane permeability and energy dependence in cellular transport. This structure promotes both competition and conceptual understanding, as success depends on biological accuracy rather than chance alone.

2) Game Components

Membrane Movers includes the game board, hero pieces for each player, molecule cards, transport cards, event cards, challenge cards, ATP energy tokens, and a six-sided die. Each component serves a distinct instructional purpose: molecules and transport cards introduce content constraints, challenge cards assess conceptual understanding, event cards add variability, and ATP tokens model cellular energy use. Together, these components provide a tangible representation of abstract biological processes, supporting multimodal learning and sustained engagement.

3) Game Mechanics

Gameplay follows a structured, turn-based system that integrates chance, strategy, and content mastery. On each turn, players draw a molecule card and a transport card, roll the die, and move their piece accordingly. Transport success depends on the alignment between molecule type and transport mechanism: passive transport requires no energy but depends on a successful roll, while active transport allows greater movement at the cost of ATP. Event and challenge spaces introduce real-time consequences and content-based decision points. These mechanics ensure that biological reasoning directly impacts player progress.

4) Learning Alignment

Membrane Movers is intentionally aligned with biology learning objectives related to cell membrane structure and transport mechanisms. The differentiation between passive and active transport, the use of ATP as an energy currency, and the requirement to answer challenge questions all map directly onto standard high school biology outcomes. The assessment is embedded within gameplay, as correct responses to challenge cards allow advancement, while incorrect answers result in setbacks. This alignment transforms play into an active learning experience where conceptual understanding is continuously reinforced through application and feedback.

5) Player Interaction

Player interaction is a central feature of the game. It occurs through shared board spaces, competitive progression, and event-driven interactions such as energy loss or gain. Students engage in healthy competition while managing limited ATP resources, and they participate in discussions prompted by challenge questions and strategic decision-making during turns. These social dynamics encourage collaboration, communication, and peer-supported learning, enhancing engagement and motivation throughout gameplay.

6) Data Gathering Instruments and Procedure

Following the approach outlined in Nautiyal et al. (2024), the data gathering instruments included both quantitative and qualitative tools. The primary instrument was a student feedback form consisting of seven Likert-scale questions and three open-ended prompts designed to evaluate students' perceptions of engagement, enjoyment, and learning outcomes from the game sessions. Classroom observations were conducted using a validated tool such as the Playful Learning Observation Tool (PLOT) developed by Algayres et al. (2022), which systematically records student engagement, social interactions, and behavioral indicators during gameplay. Additionally, qualitative teacher feedback was collected through semi-structured interviews or reflective journals, capturing insights on the feasibility, instructional integration, and perceived effectiveness of the game-based learning sessions. This mixed methods data collection process ensured comprehensive understanding of the game's impact and areas for refinement, closely aligning with the procedures described in Nautiyal et al. (2024).

The internal consistency of the seven-item Likert questionnaire was evaluated using Cronbach's alpha. After reverse-coding negatively worded items, the scale demonstrated good reliability (α=0.889), indicating strong internal consistency among the survey items measuring student engagement and enjoyment.

7) Data Analysis

The data analysis for this study adopted a mixed methods approach centered on descriptive quantitative techniques and thematic qualitative analysis, consistent with Nautiyal et al. (2024). Quantitative data from the Likert-scale student feedback survey were analyzed using descriptive statistics such as mean and standard deviation to summarize students' engagement, enjoyment, and perceived learning outcomes without inferential statistical testing. Qualitative data from open-ended survey responses and classroom observations were analyzed using thematic analysis following Braun and Clarke's (2006) six-step procedure. Observational data collected through the Playful Learning Observation Tool (PLOT), together with alignment to the North Dakota Science Standards, were used for triangulation and qualitative coding in NVivo. The integration of qualitative findings with descriptive quantitative data enabled a richer understanding of the game's educational impact, user satisfaction, and areas for improvement, all aligned with the study's developmental and iterative research design (Algayres et al., 2022; Braun & Clarke, 2006; Nautiyal et al., 2024). To enhance qualitative rigor, thematic analysis was conducted through iterative coding and refinement of emerging categories. Themes were cross-validated across data sources to strengthen the credibility and consistency of interpretation.

Data triangulation was employed by integrating student questionnaire responses, open-ended student feedback, teacher observations adapted from the Playful Learning Observation Tool (PLOT), and curriculum standards alignment. The convergence and divergence of findings across these data sources were examined to enhance the credibility and interpretive depth of the results.

RESULTS

A. Design and Alignment Outcomes

To provide an overview of the design logic and instructional alignment of the Membrane Movers board game, a graphical representation of the development process is presented first. This visual framework summarizes the sequential design steps and conceptual relationships, serving as a guide for the detailed discussion that follows (see Fig. 2).

1) Step 1: Foundation Selection

Membrane Movers was designed as a turn-based educational board game that simulates molecular transport across a cell membrane. The foundational game structure was selected to represent biologically meaningful zones (outside the cell, the cell membrane, and inside the cell) allowing learners to engage with abstract cellular processes through spatial representation. Players assume the role of molecules attempting to cross the membrane using appropriate transport mechanisms, situating learning within a narrative that supports conceptual understanding while minimizing extraneous cognitive load. This design approach aligns with contemporary research indicating that instructional games are most effective when core mechanics are simple, accessible, and explicitly aligned with learning objectives (Mayer et al., 2020; Sailer et al., 2021).

2) Step 2: Mechanism Refinement

Game mechanics were refined to balance chance-based elements with concept-driven decision-making. Each turn requires players to draw a molecule card and a transport card, compelling them to evaluate the biological compatibility between molecule type and transport mechanism. Conditional movement rules rewarded correct conceptual matching, while energy constraints limit overreliance on random progression. Active transport requires ATP expenditure, whereas passive transport did not, reinforcing the energetic costs associated with cellular transport processes. These refinements align with evidence that learning outcomes improve when progression in educational games depends on informed decisions rather than chance alone (Sailer et al., 2021; Wouters & van Oostendorp, 2022).

3) Step 3: Content Integration and Task Alignment

Biology content was embedded directly into gameplay mechanics to align with Grade 10 learning objectives on cell membrane structure and transport. Molecule, transport, challenge, and event cards required students to apply concepts such as diffusion, osmosis, facilitated diffusion, and active transport during gameplay, with immediate feedback influencing movement outcomes. Tasks were explicitly aligned with North Dakota Science Standard HS-LS1-2, which emphasizes developing and using models to explain how cell membranes regulate internal conditions through transport processes. Gameplay required students to use conceptual models and construct explanations as they selected transport mechanisms and managed energy, reinforcing the LS1.A Structure and Function disciplinary core idea and associated science and engineering practices. Embedding disciplinary content within core game actions supports meaningful learning, consistent with recent evidence on effective game-based learning design (Vlachopoulos & Makri, 2023).

4) Step 4: Instructional Deployment

The Membrane Movers was implemented during regular classroom instruction using standardized setup procedures, consistent rules, and guided facilitation. All players began with equal energy resources and followed a structured turn sequence involving card draws, dice rolls, transport attempts, and energy adjustments. Special board spaces, including energy, challenge, and event zones, structured interaction and sustained engagement while preserving instructional focus. Student interactions, decision-making processes, and responses to challenge questions were observed to assess engagement, collaboration, and conceptual application. Prior research supports the use of structured educational board games in formal classroom settings as an effective strategy for integrating active learning without compromising instructional rigor (Nadolny et al., 2023).

5) Step 5: Extension and Adaptation

Membrane Movers was designed as a modular and adaptable instructional tool to support scalability and reuse. Core mechanics such as energy management, conditional movement, and challenge-based progression remained constant, while content elements including molecule types, challenge questions, and event scenarios could be modified to address additional biology topics or other areas of science at varying levels of difficulty. For instance, the game board could be repurposed for chemical reaction topics in Chemistry. This adaptability allows the game to be reused across instructional contexts while maintaining pedagogical coherence. Such

flexible design aligns with recent literature emphasizing the importance of reusable and scalable game-based learning interventions in formal education (Kangas et al., 2022).

Fig 2. Conceptual framework for the development and alignment of the Membrane Movers board game.

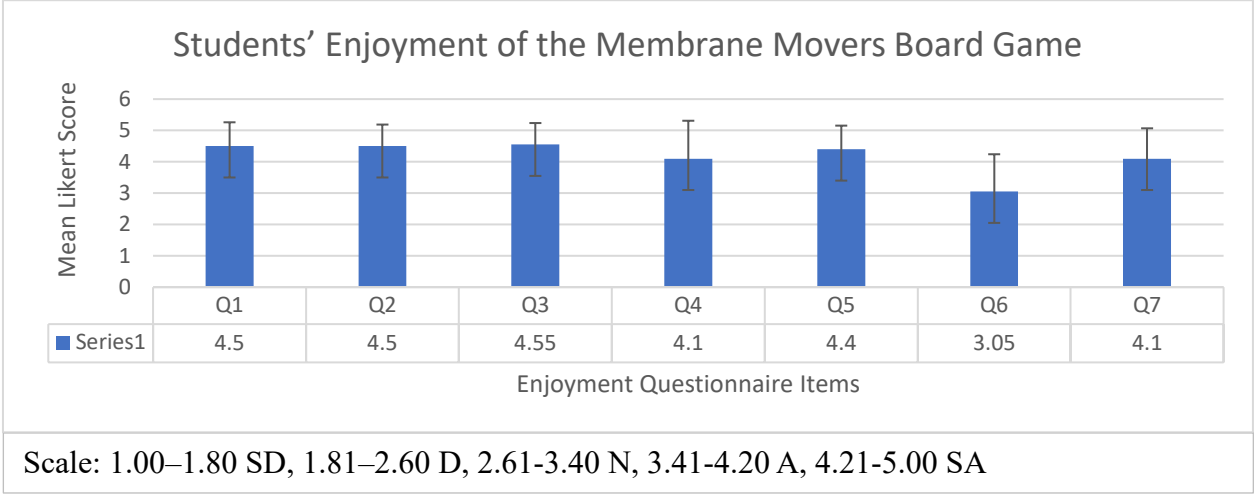
B. Student Engagement and Learning Experience

1) Likert-scale Responses

Fig. 3 summarizes students' responses to the enjoyment questionnaire using mean Likert-scale scores. Overall, mean ratings were above the scale midpoint for all items (M range=3.05–4.55), indicating generally positive perceptions of the Membrane Movers board game. Based on the interpretation scale shown in the figure, most items fall within the "agree" to "strongly agree" range.

The highest mean scores were observed for Q1, Q2, and Q3 (M=4.50, 4.50, and 4.55), reflecting strong enjoyment of the game. Items Q4, Q5, and Q7 also showed positive ratings (M=4.10–4.40). In contrast, Q6 had the lowest mean score (M=3.05), indicating more neutral perceptions. The error bars represent standard deviation, showing greater variability in responses for Q6 compared with the other items.

C. Thematic Analysis of Student-Perceived Game Design Features



Scale: 1.00–1.80 SD, 1.81–2.60 D, 2.61-3.40 N, 3.41-4.20 A, 4.21-5.00 SA

Fig. 3. Students' Mean Enjoyment Scores Across Questionnaire Items for the Membrane Movers Board Game.

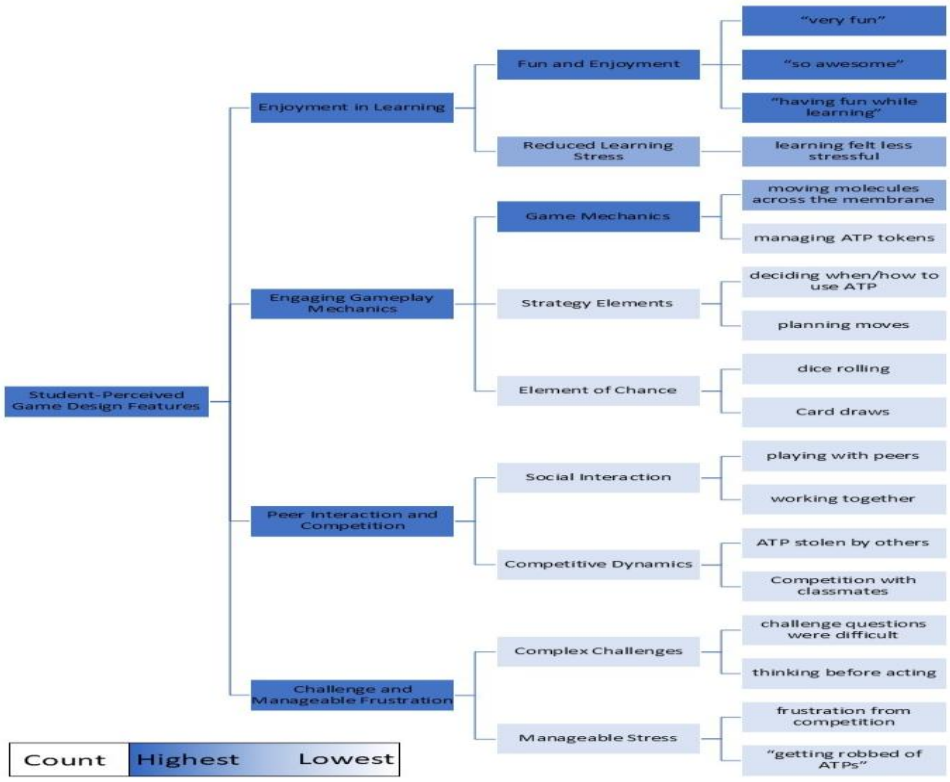


Fig. 4. Thematic Structure of Student-Perceived Game Design Features in the Membrane Movers Board Game.

1) Theme 1: Enjoyment in Learning. Students expressed a strong preference for learning games that seamlessly integrate enjoyment with academic content, emphasizing that learning becomes more engaging when it is fun and approachable. Responses highlighted the value of simple, familiar topics and clear alignment between the game mechanics and the learning objectives, which reduced anxiety and increased willingness to participate. The game was described as "very fun," "so awesome," and "having fun while learning," indicating that enjoyment was embedded within the learning process rather than separate from it. This theme suggests that when instructional games prioritize enjoyment alongside content, students perceive learning as less stressful and more intrinsically motivating.

*2) Theme 2: Engaging Gameplay Mechanics***.** Students valued gameplay mechanics that required active participation and strategic decision-making, particularly those that mirrored biological processes such as

moving molecules across the membrane and managing ATP tokens. These mechanics were perceived as interactive and cognitively stimulating, encouraging students to think ahead and plan their actions. Elements such as deciding when and how to use ATP, rolling dice, and drawing cards added layers of strategy and chance that sustained engagement throughout gameplay. Responses referencing "managing ATP" and "moving molecules" suggest that well-designed mechanics not only enhance enjoyment but also reinforce conceptual understanding through repeated application.

3) Theme 3: Peer Interaction and Competition. Peer interaction emerged as an important aspect of students' gaming experiences, with many students noting that playing with classmates and working together enhanced enjoyment and engagement. Social interaction fostered collaboration and communication, while competitive elements added excitement to the gameplay. However, competition also introduced moments of tension, particularly when students lost ATP or were affected by other players' actions. Responses referring to ATP being taken away illustrate how competition shaped students' emotional responses during play. Overall, this theme suggests that balanced social interaction combining cooperation and healthy competition can enhance engagement, while still requiring careful design to minimize negative experiences.

Table 1. Triangulation of Classroom Feasibility and Instructional Alignment of Membrane Movers

Theme	**Student Evidence**	**Teacher Evidence (PLOT)**	**Standards Alignment**	**Triangulated Finding**
Engagement	High enjoyment and active participation reported	Students appeared active and engaged; frequent discussions were observed (Items 30, 32)	Emphasis on active engagement through scientific practices	**Strong convergence**
Rule Clarity	Objectives and tasks were perceived as clear	Mechanics and objectives were easily understood; minimal frustration observed (Items 19, 23, 40)	Not explicitly specified	**Convergence**
Time & Pacing	Some pacing challenges were reported	Teacher intervention was required to manage pacing (Items 20, 22)	Not explicitly specified	**Partial divergence**
Collaboration	Peer interaction and teamwork were reported	Collaborative and competitive play were observed; peer support was evident (Items 37–38, 49)	Systems interaction emphasized	**Strong convergence**
Conceptual Learning	Perceived learning gains in biology concepts	Active use of knowledge observed; real-world task equivalence (Items 25, 27)	HS-LS1-1, HS-LS1-7 (structure–function; modeling)	**Strong convergence**

4) Theme 4: Challenge and Manageable Frustration. Students acknowledged that certain aspects of the game were challenging, particularly difficult questions and the potential loss of ATP, which sometimes led to frustration. However, this frustration was generally described as manageable and motivating rather than discouraging. Students viewed challenges as part of the game's appeal, prompting them to think carefully before acting and to persist despite setbacks. Statements about difficult questions and being "robbed of ATPs" illustrate how challenge contributed to emotional investment in gameplay. This theme indicates that when challenges are appropriately calibrated, frustration can function as a productive force that deepens engagement and supports learning.

Consistent with contemporary research on game-based learning, the four emergent themes from students' qualitative responses reflect key features identified in the educational games literature. Recent work in *Frontiers in Education* highlights the instructional value of educational board games and the importance of design principles that support student engagement and learning outcomes in authentic classroom contexts

(Nautiyal et al., 2024). Analog games, including board and tabletop formats, have been shown in systematic reviews to foster experiential learning and cognitive engagement, supporting learning processes across disciplines (Sousa et al., 2023). Broader research on gamification and game mechanics underscores that meaningful interaction, clear goals, and social engagement are critical determinants of motivation and sustained participation (Yaman et al., 2024).

Moreover, studies in digital game-based learning demonstrate that games can enhance student engagement and motivation when instructional design aligns with learners' preferences and supports immersive experiences (Nadeem et al., 2023; Li et al., 2024). The themes of *Enjoyment in Learning* and *Engaging Gameplay Mechanics* resonate with this evidence, as students valued fun and well-structured mechanics. *Peer Interaction and Competition* and *Challenge and Manageable Frustration* extend this scholarship by emphasizing the social and affective dimensions that students perceive as integral to their engagement, offering empirical, inductive support for features that many existing secondary or deductive studies mention but seldom foreground from learners' voices.

D. Classroom Implementation and Feasibility

To address RQ3, data source triangulation was conducted using student questionnaire responses, teacher classroom observations adapted from the Playful Learning Observation Tool (PLOT), and relevant North Dakota Science Standards. Evidence from these sources was examined to evaluate the classroom feasibility of the Membrane Movers board game and to identify insights for its potential reuse or adaptation in Biology instruction. The triangulated findings highlight patterns of convergence and divergence related to student engagement, instructional clarity, classroom implementation, and curricular alignment, as summarized in Table 1.

As shown in Table 1, triangulated evidence from student responses, teacher observations, and curriculum standards indicates convergence across engagement, rule clarity, collaboration, and conceptual learning, with partial divergence observed in time and pacing.

DISCUSSIONS

This study examined the design, classroom implementation, and feasibility of Membrane Movers, an educational board game developed to support Grade 10 biology instruction on cell membrane transport. Drawing on triangulated evidence from student questionnaire responses, teacher observations, and North Dakota Science Standards, this discussion interprets the findings in relation to classroom feasibility, prior research on game-based learning, the contribution of the design framework, and the instructional affordances and limitations of board games in formal classroom settings.

Although this study did not measure objective learning gains, students' concept-driven decision-making and teacher observations reflect engagement with disciplinary concepts during gameplay. This study contributes to science education research by (1) proposing an SDT-informed analog board game design framework, (2) demonstrating the feasibility of game-based learning in small rural classrooms, and (3) providing triangulated evidence linking game mechanics to student engagement and collaborative learning. Unlike many studies that focus on digital games, this research highlights the pedagogical potential of low-cost analog games in resource-limited educational contexts.

A. Classroom Feasibility and Convergent Evidence

Triangulated results demonstrated strong convergence across student engagement, rule clarity, collaboration, and conceptual learning, indicating that Membrane Movers functioned as a feasible instructional tool in a secondary biology classroom. Students' positive perceptions of enjoyment and engagement were corroborated by teacher observations of sustained participation, peer interaction, and on-task behavior, strengthening the credibility of the findings beyond self-reports alone. This convergence aligns with prior research showing that well-designed educational games can support both affective and behavioral engagement when gameplay mechanics are clearly aligned with learning objectives (Sailer et al., 2021; Kangas et al., 2022).

Partial divergence emerged in relation to time and pacing, as teacher observations indicated the need for occasional facilitation to maintain instructional flow. Similar implementation challenges have been reported in prior studies of classroom-based board games, particularly in formal instructional settings with fixed time constraints (Nadolny et al., 2023). Rather than undermining feasibility, this divergence highlights a common and manageable consideration in game-based learning implementation.

B. Alignment with Prior Game-Based Learning Research

The findings of this study are consistent with a growing body of literature demonstrating that educational board games can enhance engagement, collaboration, and conceptual understanding when learners actively apply disciplinary knowledge during gameplay. Students' positive responses to strategic decision-making, turn-based play, and social interaction align with evidence suggesting that meaningful interaction and informed choices are central drivers of motivation and learning in game-based environments (Mayer et al., 2020; Sailer et al., 2021). Meta-analytic research further shows that board games can improve both cognitive and social learning outcomes in educational settings (Estrada-Plana et al., 2024).

The emergence of challenge and manageable frustration as a positive aspect of gameplay further supports prior meta-analytic findings indicating that productive struggle can enhance persistence and engagement when appropriately scaffolded (Wouters & van Oostendorp, 2022; Vlachopoulos & Makri, 2023). While much of the existing literature emphasizes digital games, the present findings contribute empirical support for the instructional value of analog board games in secondary science classrooms (Kangas et al., 2022; Nadolny et al., 2023). Classroom studies also show that elements such as turn-taking, uncertainty, and strategic decision-making can increase student engagement during educational gameplay (Nurnberger-Haag et al., 2023).

C. Contribution of the Game Design and Implementation Framework

A key contribution of this study lies in demonstrating how a structured game design and implementation framework supported instructional alignment and classroom feasibility. The five-step process (foundation selection, mechanism refinement, content integration, instructional deployment, and extension) ensured that engagement was not incidental but directly linked to biological concepts and practices. Simple, accessible mechanics reduced extraneous cognitive load, consistent with instructional design principles for effective educational games (Mayer et al., 2020).

Embedding disciplinary core ideas and science practices directly into gameplay actions supported alignment with North Dakota Science Standards and reinforced structure–function reasoning and modeling practices. The modular design of Membrane Movers further supports reuse and adaptation, echoing recent calls for scalable and flexible game-based learning interventions in formal education (Kangas et al., 2022; Nadolny et al., 2023).

D. Why Board Games Worked and Where They Struggled

Membrane Movers was effective largely because its physical, social, and strategic features supported active participation and peer interaction. Tangible representations of abstract biological processes, such as ATP expenditure and molecule movement, enabled repeated application of concepts and facilitated collaborative discussion. These findings align with research suggesting that analog games can foster experiential and social learning, particularly when designed for classroom integration rather than standalone play (Kangas et al., 2022; Nadolny et al., 2023).

Challenges were primarily logistical rather than conceptual. Time and pacing constraints reflected the realities of formal classroom schedules and underscore the importance of iterative refinement in design-based research. These limitations do not diminish the instructional value of the game but instead provide clear guidance for future implementations, such as adjusting session length or structuring gameplay in phases, consistent with prior recommendations in the educational board game literature (Nadolny et al., 2023).

CONCLUSIONS

This study demonstrates that Membrane Movers, a framework-guided educational board game, can be feasibly implemented in a secondary biology classroom while maintaining alignment with curriculum standards and supporting student engagement. Through triangulated analysis of student responses, teacher observations, and instructional standards, the study provides empirical evidence that well-designed analog games can function as meaningful instructional tools rather than supplemental activities.

Beyond evaluating a single game, this work contributes a replicable design and implementation approach for educational board games in science instruction. By illustrating how gameplay mechanics, content integration, and classroom facilitation interact to support learning, the study offers a foundation for future research and practice aimed at developing scalable, standard-aligned game-based learning interventions in formal educational settings.

Overall, the study demonstrates that theory-informed analog educational games can support student engagement and collaborative learning in secondary biology classrooms, particularly in rural contexts. By integrating motivational theory with design-based research, the Membrane Movers intervention offers a replicable model for developing low-cost, curriculum-aligned instructional games. Future research should build on these findings by examining learning outcomes and scaling the intervention across diverse educational settings.

B. Implications

1) Instructional Implications

Findings indicate that educational board games such as *Membrane Movers* can function as feasible, standards-aligned instructional tools in secondary biology classrooms. Convergent evidence across student and teacher data suggests that analog game-based activities can support engagement and collaborative learning without compromising instructional rigor. To maximize effectiveness, teachers should allocate sufficient time for gameplay and debriefing or distribute implementation across multiple sessions, as time and pacing emerged as key considerations.

2) Design Implications

The effectiveness of Membrane Movers highlights the importance of aligning game mechanics directly with disciplinary content. Conditional movement, energy constraints, and challenge-based progression required students to apply biological knowledge rather than rely on chance. The game's modular structure further supports reuse and adaptation, allowing content elements to be modified while preserving core mechanics. Such flexibility enhances scalability and sustainability in classroom-based game design.

3) Implications for Future Research

Future research should examine learning outcomes associated with repeated or longitudinal use of educational board games and compare their effectiveness with traditional instructional approaches. Additional studies may explore how facilitation strategies, group configurations, and instructional timing influence learning outcomes. Research conducted across diverse contexts and content areas, as well as comparisons between analog and digital formats, would further clarify the instructional affordances of board game–based learning.

The study has several implications for educational practice and research. Pedagogically, the findings suggest that analog board games can serve as low-cost instructional tools for teaching abstract biological concepts in resource-constrained classrooms. From a design perspective, the results highlight the importance of aligning game mechanics with motivational principles to enhance student engagement. For future research, the study underscores the need for larger-scale investigations and the inclusion of objective learning measures to further validate the effectiveness of theory-informed game-based learning interventions.

Limitations

This study has several limitations. First, the small sample size and rural context limit the generalizability of the findings to other educational settings. The study also relied primarily on descriptive data and student perceptions and did not include objective measures of learning outcomes. Nevertheless, the findings provide context-specific insights into the feasibility and motivational impact of an analog game-based intervention. Future studies should therefore incorporate larger samples and experimental designs to validate and extend these results.

Second, the study was conducted within a specific instructional setting, a secondary biology classroom implementing *Membrane Movers* during regular instruction. Contextual factors such as class size, instructional time, teacher facilitation style, and school culture may have influenced student engagement and observed outcomes. As a result, the feasibility and effectiveness observed in this study may differ in other curricular, institutional, or cultural contexts.

Finally, the study was primarily descriptive in nature and did not employ experimental or quasi-experimental design. While the findings provide insight into classroom feasibility, student experiences, and instructional alignment, causal claims regarding learning outcomes cannot be made. Future research incorporating comparative or longitudinal designs would be necessary to establish the impact of educational board games on student learning and retention.

Ethical statement

The study involving human participants was reviewed and approved by the school administration, including the Superintendent and Principal of the participating schools. The study was conducted in accordance with institutional policies and local educational regulations governing research involving minors. Written informed consent was obtained from the students' legal guardians or next of kin prior to data collection, and assent was obtained from the student participants. No personally identifiable information was collected, and all data were anonymized prior to analysis.

AI transparency statement

AI-based tools were used to assist with language editing and clarity, as well as to generate some illustrative images for visualization of the board game components. All aspects of the study design, data collection, analysis, interpretation, and conclusions remain the responsibility of the authors. AI-generated images were used for illustrative purposes only and do not represent empirical data.

Conflict of Interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated organizations, the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

REFERENCES

1. Algayres, R., Goldenberg, E., High, J., Li, V., & Hirsh-Pasek, K. (2022). Playful Learning Observation Tool (PLOT): Development and validation. Frontiers in Psychology, 13, Article 919168. https://doi.org/10.3389/fpsyg.2022.919168
2. Anderson, T., & Shattuck, J. (2012). Design-based research: A decade of progress in education research. Educational Researcher, 41(1), 16–25. https://doi.org/10.3102/0013189X11428813

3. Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), 77–101. https://doi.org/10.1191/1478088706qp063oa
4. Cardinot, A., Fairfield, J., & O'Riordan, C. (2022). Frameworks for game-based learning: Integrating educational and game design principles to create fun and effective learning experiences. Simulation & Gaming, 53(5), 486–503. https://doi.org/10.1177/10468781221110640
5. Ching, Y. H., & Wang, Y. (2021). Design and implementation of educational board games to enhance learning outcomes in molecular biology. Journal of Biological Education, 55(4), 456–464. https://doi.org/10.1080/00219266.2020.1740248
6. Creswell, J. W., & Plano Clark, V. L. (2018). Designing and conducting mixed methods research (3rd ed.). SAGE.
7. Estrada-Plana, V., Llorens, M., Hernández-Lara, A. B., & Sanz, M. M. (2024). Effects of board games on learners' cognitive and social outcomes: A meta-analytic review. Computers & Education, 209, 104848. https://doi.org/10.1016/j.compedu.2024.104848
8. Gonçalves, S., Oliveira, P., & Magalhães, V. (2023). Gamification in science education: Engagement, outcomes, and inclusiveness in classroom environments. Education Sciences, 13(3), 248. https://doi.org/10.3390/educsci13030248
9. Gros, B., & López, M. (2023). Impact of educational games on science teaching: A review and synthesis. Frontiers in Education, 8, 1165372. https://doi.org/10.3389/feduc.2023.1165372
10. Howard, J. L., Bureau, J., Guay, F., Chong, J. X. Y., & Ryan, R. M. (2021). Student motivation and associated outcomes: A meta-analysis from self-determination theory. Perspectives on Psychological Science, 16(6), 1300–1323. https://doi.org/10.1177/1745691620966789
11. Hsu, C.-Y., Tsai, M.-J., & Wang, C.-Y. (2022). Game-based learning in science education: A systematic review of design and learning outcomes. Education Sciences, 12(7), 457. https://doi.org/10.3390/educsci12070457
12. Huang, H.-H., Lai, Y.-C., & Lin, M.-J. (2023). Game-based approaches and meaningful learning in science classrooms: Perspectives from secondary school students. Journal of Science Education and Technology, 32(5), 893–905. https://doi.org/10.1007/s10956-023-10088-5
13. Kangas, M., Siklander, P., Randolph, J., & Ruokamo, H. (2022). Teachers' engagement and students' learning in game-based learning environments. Teaching and Teacher Education, 109, 103551. https://doi.org/10.1016/j.tate.2021.103551
14. Lakens, D. (2022). Sample size justification. Collabra: Psychology, 8(1), 33267. https://doi.org/10.1525/collabra.33267
15. Li, Y., Chen, D., & Deng, X. (2024). The impact of digital educational games on students' motivation for learning: The mediating effect of learning engagement and the moderating effect of the digital environment. PLoS ONE, 19(1), e0294350. https://doi.org/10.1371/journal.pone.0294350
16. Mayer, R. E., Fiorella, L., & Stull, A. (2020). Five ways to increase the effectiveness of instructional games. Educational Psychology Review, 32, 877–895. https://doi.org/10.1007/s10648-020-09515-4
17. McKenney, S., & Reeves, T. C. (2020). Conducting educational design research (2nd ed.). Routledge.
18. Nadeem, M., Oroszlanyova, M., & Farag, W. (2023). Effect of Digital Game-Based Learning on Student Engagement and Motivation. Computers, 12(9), 177. https://doi.org/10.3390/computers12090177
19. Nadolny, L., Valai, A., Easton, J., & Ganesh, G. (2023). Designing and implementing educational board games in formal learning environments: A systematic review. Simulation & Gaming, 54(2), 230–255. https://doi.org/10.1177/10468781221138564
20. National Center for Education Statistics. (2023). Educational attainment in rural areas. Condition of Education. https://nces.ed.gov/programs/coe/indicator/lbc
21. Nautiyal, V. V., Silverio, S. A., & Salvador, E. E. P. (2024). Let's get on-board: a practical framework for designing and implementing educational board games in K-12 classrooms. Frontiers in Education, 9, Article 1420515. https://doi.org/10.3389/feduc.2024.1420515
22. North Dakota University System. (2025). Open educational resources initiatives in North Dakota. https://www.ndus.edu
23. Nurnberger-Haag, J., Allred, S., & Karamanlidis, G. (2023). Turn-taking and chance in educational games increase engagement: Evidence from classroom data. Journal of Educational Research, 116(1), 104–120. https://doi.org/10.1080/00220671.2022.2102137

24. Rahayu, S., Suryana, A., & Pertiwi, K. (2023). The effectiveness of biology game-based learning in improving students' cognitive achievement and attitudes. Journal of Educational Research and Practice, 13(1), 158–166. https://doi.org/10.5590/JERAP.2023.13.1.11
25. Rodríguez-Ferrer, J. M., Manzano-León, A., Fernández-Jiménez, C., Luque de la Rosa, A., Fernández-Campoy, J. M., & Aguilar-Parra, J. M. (2023). Shall we play together? Game-based learning for engagement and classroom climate in Spanish socially deprived communities. Frontiers in Psychology, 14, Article 1163441. https://doi.org/10.3389/fpsyg.2023.1163441
26. Ryan, R. M., & Deci, E. L. (2020). Intrinsic and extrinsic motivation from a self-determination theory perspective: Definitions, theory, practices, and future directions. Contemporary Educational Psychology, 61, 101860. https://doi.org/10.1016/j.cedpsych.2020.101860
27. Sailer, M., Hense, J. U., Mayr, S. K., & Mandl, H. (2021). How gamification motivates: An experimental study of the effects of specific game design elements on psychological need satisfaction. Educational Psychology Review, 33, 371–402. https://doi.org/10.1007/s10648-021-09614-6
28. Sousa, C., Rye, S., Sousa, M., Torres, P. J., Perim, C., Mansuklal, S. A., & Ennami, F. (2023). Playing at the school table: Systematic literature review of board, tabletop, and other analog game-based learning approaches. Frontiers in Psychology, 14, Article 1160591. https://doi.org/10.3389/fpsyg.2023.1160591
29. United Nations. (2022). Goal 4: Quality education. The Sustainable Development Goals Report 2022. https://unstats.un.org/sdgs/report/2022/goal-04/
30. Vlachopoulos, D., & Makri, A. (2023). The effect of games and simulations on learning outcomes: A meta-analysis. Computers & Education, 184, 104648. https://doi.org/10.1016/j.compedu.2022.104648
31. Wouters, P., & van Oostendorp, H. (2022). A meta-analytic review of the role of instructional support in game-based learning. Computers & Education, 179, 104399. https://doi.org/10.1016/j.compedu.2021.104399
32. Yaman, H., Sousa, C., Neves, P. P., & Luz, F. (2024). Implementation of game-based learning in educational contexts: Challenges and intervention strategies. Electronic Journal of e-Learning, 22(10), 19–36. https://doi.org/10.34190/ejel.22.10.3480