Enhancing Students' Conceptual Understanding of Nucleic Acids through the "Nuclequest" Board Game

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ABSTRACT

Teaching abstract biochemistry concepts, particularly nucleic acids, remains a persistent challenge for educators. To address this, the study developed NucleQuest, a game-based instructional board game, and evaluated its effectiveness in improving students' conceptual understanding. Specifically, the study examined changes in learners' pretest and posttest scores and gathered their perceptions of the intervention. A one-group pretest–posttest design was employed with 31 second-year BS Biology students. Participants completed a pretest, engaged in several NucleQuest sessions, and subsequently took a posttest and perception survey. The board game integrated key concepts on nucleotides, DNA, RNA, and protein synthesis through interactive tasks designed to promote engagement and active learning. Findings showed a marked improvement in conceptual understanding, with pretest scores ($M = 13.74$, $SD = 3.23$; Very Low) increasing to posttest scores ($M = 26.65$, $SD = 2.72$; Very High). The Wilcoxon Signed-Rank Test confirmed a significant difference between the two sets of scores ($Z = -4.868$, $p < .000$). Students also reported positive perceptions, noting that the activity was enjoyable, helped them concentrate, and allowed them to feel more in control of their learning. The study concluded that NucleQuest was an effective supplementary tool for teaching nucleic acids. Its game-based format enhanced engagement, supported conceptual understanding, and offered an alternative instructional strategy for addressing complex biochemistry topics.

Keywords: Biochemistry, Board-game, Conceptual Understanding, NucleQuest, Nucleic Acid

INTRODUCTION

Teaching complex biochemical concepts such as nucleic acids poses a significant challenge for both educators and students. Nucleic acids—DNA and RNA—are abstract biomolecules whose structures and functions are difficult to visualize using traditional lecture-based methods. Students often struggle with replication, transcription, and translation because these processes require mental modeling and spatial reasoning, which are not adequately supported by conventional instruction. Motivation to learn science is strengthened when students experience interactive and meaningful learning environments (Sholahudin et al., 2024). Persistent visualization difficulties in molecular biology further contribute to students' misconceptions(Spencer et al., 2024). Offerdahl et al. (2017) state that high cognitive load also affects students' ability to integrate complex biochemical information. These challenges highlight the need for innovative, multimodal, and engaging instructional tools to support deeper conceptual understanding.

Contemporary science education research emphasizes the importance of visualization-based and hands-on approaches for teaching molecular concepts. Building representational competence is essential for understanding biochemical processes (Pokojná et al., 2023). Multimodal strategies significantly enhance molecular visualization skills, helping students grasp abstract structures (Kiernan et al., 2024). Drawing-based techniques support reasoning and conceptual clarity in biology learning (Quillin & Thomas, 2015). Active learning strategies improve comprehension of dynamic biochemical mechanisms(Kopecki-Fjetland & Steffenson, 2021). Structured learning environments further support long-term retention and conceptual integration in biochemistry education (Terrell et al., 2020). Together, these findings reinforce the value of instructional materials that externalize and simplify complex molecular ideas.

Game-based learning has increasingly been recognized as an effective pedagogical approach that enhances motivation, engagement, and conceptual understanding. Educational games help sustain learner immersion and promote persistence in challenging tasks(Huber et al., 2023). Game mechanics also support student attention and meaningful engagement in both digital and non-digital learning contexts (Chen, 2025). Science-themed board games have been shown to improve learning outcomes and reinforce conceptual understanding (Othman & Ching, 2024). Recent meta-analytic evidence confirms that game-based learning significantly enhances STEM achievement and engagement (Wang et al., 2022). These findings demonstrate the strong pedagogical potential of game-based tools in biochemistry instruction.

In response to these needs, the present study introduces NucleQuest, an educational board game designed to simplify nucleic acid concepts through interactive gameplay and visual representations. The game incorporates molecular tiles, challenge scenarios, and guided tasks that promote conceptual integration and critical thinking. Interactive learning environments must accommodate diverse engagement patterns to maximize student learning (King et al., 2023). By developing and validating NucleQuest, the study aims to determine its effectiveness in enhancing students' conceptual understanding, academic performance, and engagement, as well as their perceptions of game-based learning in biochemistry.

This research also aligns with the United Nations Sustainable Development Goal 4 (Quality Education), which emphasizes equitable and innovative learning opportunities for all. Transformative teaching approaches that foster scientific literacy and lifelong learning are essential for advancing global educational goals (Sayadi & Pangandaman, 2025). By integrating game-based learning into biochemistry instruction, NucleQuest contributes to SDG through learner-centered, engaging, and innovative pedagogical practices.

Research Objectives

This study aim to develop and validate a board game to enhance the conceptual understanding in biochemistry. specifically, this study sought to:

1. develop a board game to enhance the conceptual understanding of the students.

2. investigate the student's conceptual understanding after utilizing the NucleQuest board game.

3. assess the student's perception on the utilization of the NucleQuest board game.

METHODOLOGY

Research Design

This study employed a quasi-experimental one-group pretest–posttest design, supported by qualitative insights to strengthen the quantitative findings. The quantitative component aimed to determine the effectiveness of the NucleQuest board game in enhancing students' conceptual understanding, academic achievement, and engagement in biochemistry. In this design, the same group of respondents was assessed before and after the intervention using a researcher-made test to measure changes in performance and understanding. According to Knapp (2016), the one-group pretest–posttest design is appropriate for evaluating the effects of an educational intervention when random assignment or control groups are not feasible.

Participants

The respondents of this study were second-year BS Biology students from a state university in Iloilo City during the School Year 2025–2026. This group was purposively selected because their curriculum includes Biochemistry, a subject widely documented as challenging for undergraduate learners due to its abstract concepts, extensive content, and high cognitive demands. Recent studies indicate that students often perceive Biochemistry as difficult, citing the complexity of biochemical processes, time constraints, and limited access to effective learning supports (Terrell, et al., 2020). One section with 35 students was identified; however, only 31 students participated because four were absent during data collection. The participants completed pretest and

posttest assessments to measure their conceptual understanding and provided qualitative feedback to describe their engagement and perceptions of the NucleQuest board game.

Instruments

Development of Board Game

It served as the main intervention tool developed by the researcher to enhance students' conceptual understanding of nucleic acids. The material was a biochemistry-themed educational board game that integrated key concepts such as DNA and RNA structure, replication, transcription, and translation into interactive gameplay mechanics (see Figure 1). The game featured question cards, activity tiles, enzyme boosters, and challenge zones that required players to recall, apply, and explain biochemical concepts as they progressed through the board (see Figure 2). The board game underwent expert validation by specialists in biochemistry and educational design to ensure scientific accuracy, clarity of instructions, educational value, and visual appeal. Revisions were made based on expert feedback prior to its implementation.

Figure 1. NucleQuest Board Game: Cover Design and Game Board Layout

Figure 2. NucleQuest Instructions and Difficulty-Based Item Cards

Conceptual Understanding Questionnaire

A 30-item multiple-choice examination was used to assess students' comprehension of nucleic acid concepts, including structure, function, replication, transcription, and translation. It was administered as both a pretest and a posttest to measure improvements in understanding after the intervention. The test items underwent content validation by three experts in biochemistry and science education to ensure accuracy, relevance, and alignment with the course learning outcomes.

Perception Questionnaire

An adopted 25-item perception questionnaire was utilized in the study to gather students' feedback on the use of the NucleQuest board game as an instructional tool. The instrument assessed key dimensions such as interest

and enjoyment, value and usefulness, and perceived choice. The questionnaire was adapted from previously validated studies to ensure that the items were relevant to biochemistry instruction and appropriate for the target learners. It was administered after the intervention to capture students' overall experiences and insights regarding the board game.

Data Collection Procedure

The development of the NucleQuest board game was guided by the ADDIE Model (see Figure 3), a systematic instructional design framework that ensures educational materials are carefully planned, validated, and evaluated. This model supported the creation of an effective and engaging learning tool by following a structured sequence of phases.

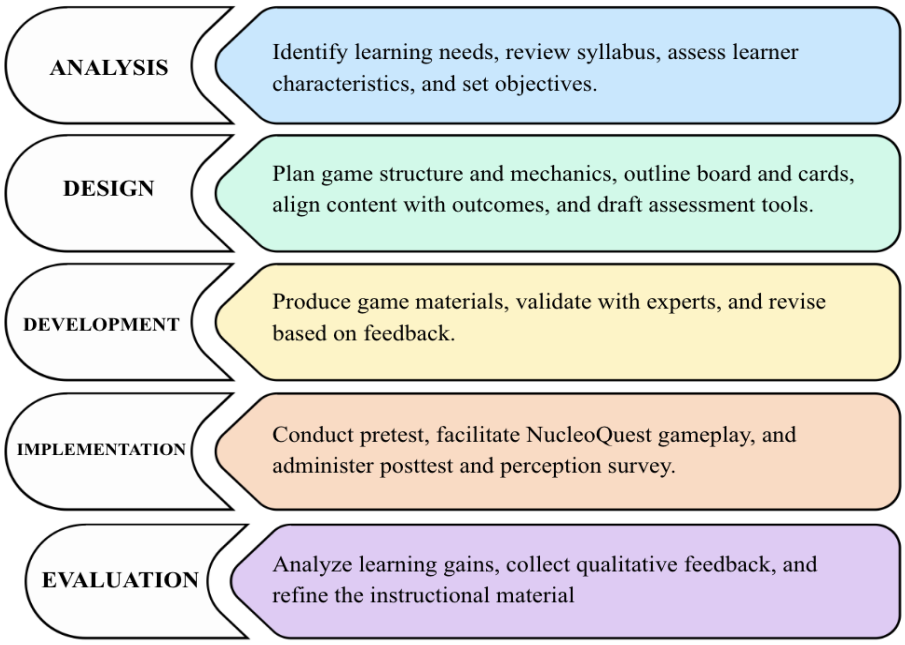

Figure 3. The Data Gathering Procedure of the Study

In the Analysis phase, learning needs, course objectives, and student difficulties related to nucleic acids were identified through syllabus review and instructor input. The Design phase focused on planning the game structure, mechanics, content, and assessment tools aligned with the Biochemistry curriculum. During the Development phase, the game board, cards, and manual were produced and refined based on expert validation to ensure scientific accuracy and instructional quality. In the Implementation phase, the validated game was administered to the selected class, accompanied by pretest and posttest assessments and a perception survey. Finally, the Evaluation phase involved analyzing quantitative results to measure learning gains and examining qualitative feedback to understand student experiences, which guided further improvement of the NucleQuest board game.

By applying the ADDIE model, the researcher ensured that the NucleQuest board game was systematically designed, validated, and implemented to enhance learning outcomes. This structured process made it possible to integrate instructional design principles into an engaging educational intervention aligned with Sustainable Development Goal 4 (Quality Education), thereby promoting innovative and inclusive learning experiences in higher education.

Data Analysis

Statistical analyses, including the weighted mean, standard deviation, the Shapiro–Wilk test, and the Wilcoxon Signed-Rank test, were used to evaluate the data. The weighted mean identified areas where learners experienced difficulty, while the standard deviation measured the variability of their scores. The Shapiro–Wilk test assessed the normality of the pretest and posttest distributions, and because the data were not normally distributed, the

Wilcoxon Signed-Rank test was employed to compare the paired scores and determine the effectiveness of the NucleQuest board game intervention.

Ethical Consideration

This study adhered to established ethical standards to protect the rights and welfare of all participants. Participation was voluntary, and informed consent was obtained after clearly explaining the study's purpose, procedures, benefits, and minimal risks. Students were assured that they could withdraw at any time without penalty. All data, including pretest, posttest, engagement scores, and feedback, were kept confidential, securely stored, and reported only in aggregate form to avoid identifying individuals. The study upheld the principles of beneficence, respect for persons, and justice in accordance with the National Ethical Guidelines for Health and Health-Related Research (2023) and the Data Privacy Act of 2012 (RA 10173), ensuring ethical and responsible conduct throughout the research process.

RESULTS AND DISCUSSION

Development a NucleQuest board game

Analysis Phase

The results of the needs assessment conducted among 100 students showed varying levels of difficulty across selected biochemistry topics. Students rated each topic using a Likert scale, and the mean scores were interpreted using descriptive categories.

Table 1. Difficulty Level of Basic Biochemistry Learning Concepts (N = 100)

Learning Concept	**Mean**	**Description**
Carbohydrates	2.74	Moderately Difficult
Lipids	2.93	Moderately Difficult
Proteins	2.83	Moderately Difficult
Nucleic Acids	**3.51**	**Difficult**
Water	2.43	Easy
Vitamins	2.40	Easy
Cell	2.65	Moderate

Note. Difficulty descriptions are based on the following mean range: 1.00–1.49 = Very Easy, 1.50–2.49 = Easy, 2.50–3.49 = Moderate/Moderately Difficult, 3.50–4.00 = Difficult, 4.00-5.00 Extremely Difficult

Nucleic acids received the highest difficulty rating (M = 3.51, Difficult), indicating significant challenges in understanding DNA and RNA structures, replication, transcription, and translation. This aligns with the findings of Jett & Labosfor (2023), who likewise reported that students commonly perceive nucleic acids as one of the most challenging biochemistry topics due to their abstract nature and multi-step molecular processes. Similarly, three topics—Lipids (M = 2.93), Proteins (M = 2.83), and Carbohydrates (M = 2.74)—were classified as Moderately Difficult, reflecting students' struggles with complex molecular structures, biochemical pathways, and metabolic processes. The Cell topic (M = 2.65) was rated Moderate, while Water (M = 2.43) and Vitamins (M = 2.40) were rated Easy, suggesting stronger familiarity with these foundational concepts.

The results clearly show that students experience greater difficulty with highly molecular, abstract, and mechanistic content, particularly nucleic acids and major biomolecules. This parallels the study by Jett & Labosfor (2023), which emphasizes the need for improved pedagogical strategies when teaching conceptually dense biochemistry topics. The present findings underscore the importance of incorporating targeted instructional support—such as visual aids, interactive modules, comics, and gamified tools—to scaffold learning, promote deeper conceptual understanding, and address identified learning gaps.

Design and Development Phase

The validation results showed that the developed board game demonstrated a high level of quality and acceptability based on expert evaluation. As presented in Table 2, the instructional material obtained an overall mean score of 8.80, which was interpreted as Excellent, indicating strong agreement among validators that the board game met or exceeded expectations in its design, content, and functionality.

Table 2. Validation Results of the Developed Board Game

Criteria	**M**	**Description**
Design and Creativity	10.00	Excellent
Questions	8.67	Excellent
Format and Purpose	8.00	Very Good
Directions	8.67	Excellent
Content and Difficulty	8.67	Excellent
Overall Mean	**8.80**	**Excellent**

Validators rated Design and Creativity the highest (M = 10.00), indicating that the game was visually engaging and thoughtfully designed. The criteria Questions, Directions, and Content and Difficulty also received Excellent ratings (M = 8.67), suggesting that the content was appropriate, the instructions were clear, and the difficulty level was suitable for learners. Only Format and Purpose was rated slightly lower at Very Good (M = 8.00), indicating minor areas for refinement. Overall, the consistently high ratings affirmed that the board game was well-constructed, pedagogically sound, and ready for classroom use.

Table 3. Validation Results of the Conceptual Understanding Questionnaire

Criteria	**Mean**	**Description**
Clarity and Organization	3.96	Exceeds Expectations
Wordiness	3.94	Exceeds Expectations
Consistency and Parallelism of Questions and Options	3.93	Exceeds Expectations
Appropriateness of Items to Learning Target	3.99	Exceeds Expectations
Overall Mean	**3.96**	**Exceeds Expectations**

Note. Description scale: 1.00–1.49 = Not Acceptable; 1.50–2.49 = Below Expectations; 2.50–3.49 = Meets Expectations; 3.50–4.00 = Exceeds Expectations.

To ensure the quality and appropriateness of the developed conceptual understanding questionnaire, expert validators evaluated the instrument based on clarity, structure, wording, alignment with learning targets, and overall item construction. Their assessments provided evidence of the questionnaire's validity and suitability for measuring students' conceptual understanding.

As shown in Table 3, the questionnaire achieved an overall mean of 3.96, interpreted as Exceeds Expectations, indicating a high level of acceptability among expert validators. All criteria received consistently excellent ratings (3.93–3.99), suggesting that the items were clearly written, well-organized, linguistically appropriate, and strongly aligned with the intended learning objectives. These results confirmed that the instrument was valid, coherent, and ready for implementation in the assessment process.

Implementation and Evaluation

The NucleQuest board game was implemented in a second-year BS Biology class at a state university in Iloilo City during a scheduled instructional session. Students first completed a pretest to determine their baseline understanding of nucleic acids. The researcher then facilitated the gameplay session, during which students interacted with the NucleQuest board game, answered concept-based questions, and applied nucleic acid concepts through collaborative problem-solving. After the session, a posttest was administered to measure changes in conceptual understanding. A brief perception survey was also conducted to gather feedback on students' learning experiences and engagement with the board game.

This interactive approach promoted active learning by allowing students to visualize molecular processes, reinforce key concepts, and construct their own understanding of nucleic acids. For data analysis, the mean and standard deviation were used to examine overall performance, while the comparison of pretest and posttest results determined improvements in students' conceptual understanding.

Conceptual Understanding of learners in Nucleic Acids

The students' conceptual understanding was assessed before and after the implementation of the instructional intervention using a 30-item conceptual test. Scores were categorized into five levels based on predetermined score ranges. Table 4 presents the distribution of learners across these levels for both the pretest and posttest.

Table 4. Pre-test and Post-test Conceptual Understanding Scores of Learners

Score Range	Rating	Pre-test (31)	Pre-test (%)	Post-test (31)	Post-test (%)	Description
24–30	90–100	0	0	25	81	Very High Conceptual Understanding
21–23	85–89	1	3	6	19	High Conceptual Understanding
18–20	80–84	2	6	0	0	Average
15–17	75–79	9	29	0	0	Low Conceptual Understanding
Below 15	Below 75	19	61	0	0	Very Low Conceptual Understanding

The results showed a substantial improvement in students' conceptual understanding following the intervention. In the pretest, most learners fell within the Very Low (61%) and Low (29%) conceptual understanding categories, with none reaching the Very High level. After the intervention, 81% of learners achieved Very High conceptual understanding, while the remaining 19% reached the High category. No students remained in the Low or Very

Low categories. These shifts indicate a marked increase in conceptual mastery, demonstrating the effectiveness of the instructional strategy in enhancing learners' understanding of the topic.

Table 5. Comparison of Conceptual Understanding Levels During Pretest and Posttest

Test	Mean	N	SD	Description
Pretest	13.74	31	3.23	Very Low Conceptual Understanding
Posttest	26.65	31	2.72	Very High Conceptual Understanding

The results presented in Table 5 showed a substantial improvement in students' conceptual understanding following the intervention. The pretest mean score of 13.74 (SD = 3.23) reflected Very Low conceptual understanding, indicating that students initially possessed minimal prior knowledge of the concepts. In contrast, the posttest mean score increased to 26.65 (SD = 2.72), corresponding to Very High conceptual understanding. The reduction in standard deviation from the pretest to the posttest suggests that learners' scores became more consistent after the instructional intervention. Overall, these findings indicate that the intervention was effective in significantly enhancing learners' conceptual understanding.

Table 1. Shapiro–Wilk Test of Normality for Difference Scores

Test	Statistic	df	Sig.
Shapiro–Wilk	0.921	31	0.026

Before selecting the appropriate inferential test, the normality of the difference scores between the pretest and posttest was examined using the Shapiro–Wilk test, as the sample size was fewer than 50 (n = 31), as presented in Table 1. The Shapiro–Wilk test yielded a significance value of p = .026, which is less than .05. This result indicates that the difference scores were not normally distributed, thereby violating the assumption of normality. Consequently, a nonparametric test, specifically the Wilcoxon Signed-Rank Test, was deemed appropriate for analyzing the pretest and posttest performance.

Table 2. Wilcoxon Signed-Rank Test for Pre-test and Post-test Scores

Test	Z-value	Sig. (2-tailed)
Wilcoxon Signed-Rank	–4.868	.000

To determine whether a significant change occurred after the intervention, the Wilcoxon Signed-Rank Test was conducted. This nonparametric test was appropriate for paired samples that did not meet the assumption of normality. As shown in Table 2, the Wilcoxon Signed-Rank Test yielded a Z-value of –4.868 with a p-value of .000, indicating a highly significant difference between the pretest and posttest scores. This result confirms that the intervention led to a substantial and statistically significant improvement in students' performance.

Table 3. Descriptive Statistics of N-Gain Scores

Variable	N	Mean	Std. Deviation
N-Gain	31	0.7945	0.17023

The mean N-Gain of 0.7945 revealed that students achieved 79.45% of the maximum possible improvement. With a mean N-Gain of 0.79, the results fell under the High Gain category. This indicates that the intervention was highly effective in promoting substantial learning growth among the students. The high gain is consistent

with the observed increase in posttest performance and aligns with the significant results of the Wilcoxon Signed-Rank Test.

Perception of the learners on the utilization of the NucleQuest board game.

Table 6. Perception of the learners in using board game

Subscale	Mean	Description
Interest and Enjoyment	5.28	Somewhat True
Value/Usefulness	5.67	Very True
Perceived Choice	4.54	Somewhat True
Overall Mean	**5.16**	**Somewhat True**

Table 6 presents the computed means and descriptive interpretations for each subscale. The results showed that students generally responded positively to the activity. The highest mean score was obtained in the Value/Usefulness subscale (M = 5.67), interpreted as Very True, indicating that students perceived the activity as highly beneficial and relevant to their learning. Several students also expressed that they believed the activity was useful for improving their concentration, supporting the strong quantitative rating under this subscale.

The Interest and Enjoyment subscale likewise yielded a favorable mean score (M = 5.28), suggesting that learners found the activity enjoyable and engaging. Student comments, such as feeling that they were "truly enjoying the activity while doing it," reinforced the positive motivational impact reflected in the data.

Meanwhile, the Perceived Choice subscale recorded a mean of 4.54, interpreted as Somewhat True, indicating that students felt moderately autonomous during the activity. This aligns with student feedback noting that they believed they had some degree of choice in participating, although certain aspects of the activity remained structured.

Overall, the combined mean score of 5.16 reflects a generally positive perception, suggesting that the activity was meaningful, motivating, and supportive of student engagement.

CONCLUSION

The findings of the study demonstrated that the instructional intervention—specifically the use of the developed NucleQuest board game—significantly improved learners' conceptual understanding, particularly in the topic of nucleic acids, which students initially identified as one of the most difficult areas in Biochemistry. Pretest results showed that most learners fell within the Very Low and Low conceptual understanding categories, indicating limited prior knowledge of nucleic acids and related biochemical concepts. In contrast, posttest outcomes revealed a substantial shift, with the majority of students achieving Very High and High conceptual understanding. This improvement was reflected in increased mean scores and reduced variability, suggesting consistent learning gains across the group.

Expert validation rated the board game as Excellent, confirming its clarity, content alignment, organization, and suitability for teaching a complex topic such as nucleic acids. Student perception data further supported these findings: learners reported high levels of enjoyment, recognized the activity as useful for improving concentration, and expressed that they had some degree of choice while engaging with the material. These positive responses indicate that the board game was not only pedagogically effective but also engaging and motivating for learners.

Overall, the results confirmed that the NucleQuest board game was an effective instructional tool for enhancing conceptual understanding, particularly in challenging biochemistry topics such as nucleic acids.

RECOMMENDATION

The following recommendations were formulated based on the findings and conclusions of the study:

1. Integrate the NucleQuest board game into instruction on nucleic acids, particularly during lessons on DNA structure, replication, transcription, and translation, as the tool effectively supported students' comprehension of these abstract and complex biochemical processes.

2. Provide opportunities for student autonomy during gameplay to enhance learners' perceived choice and intrinsic motivation, thereby improving engagement and overall learning experiences.

3. Expand the content of NucleQuest by adding more scenarios, question cards, or pathway challenges that address advanced concepts such as genetic mutations, RNA processing, and protein synthesis to further enrich students' conceptual understanding.

4. Replicate the study with larger and more diverse samples to strengthen the generalizability of the findings, particularly in the context of teaching nucleic acids and other challenging biochemistry topics.

REFERENCES

1. Chen, C.-W. (2025). Low-tech serious games in higher education: bridging the digital divide and enhancing student thinking and performance. Humanities and Social Sciences Communications, 12(1). https://doi.org/10.1057/s41599-024-04341-2
2. Huber, S. E., Cortez, R., Kiili, K., Lindstedt, A., & Ninaus, M. (2023). Game elements enhance engagement and mitigate attrition in online learning tasks. Computers in Human Behavior, 149, 107948. https://doi.org/10.1016/j.chb.2023.107948
3. Kiernan, N., Manches, A., & Seery, M. K. (2024). Resources for Reasoning of Chemistry Concepts: Multimodal Molecular Geometry. Chemistry Education. Research and Practice. https://doi.org/10.1039/d3rp00186e
4. King, J., Marcus, T., & Markant, J. (2023). Individual differences in selective attention and engagement shape students' learning from visual cues and instructor presence during online lessons. Scientific Reports, 13(1). https://doi.org/10.1038/s41598-023-32069-7
5. Knapp, T. R. (2016). Why Is the One-Group Pretest–Posttest Design Still Used? Clinical Nursing Research, 25(5), 467–472. https://doi.org/10.1177/1054773816666280
6. Kopecki-Fjetland, M. A., & Steffenson, M. (2021). Design and implementation of active learning strategies to enhance student understanding of foundational concepts in biochemistry. Biochemistry and Molecular Biology Education, 49(3), 446–456. https://doi.org/10.1002/bmb.21498
7. Mohd Kamal Othman, & Sim Kah Ching. (2024). Gamifying science education: How board games enhances engagement, motivate and develop social interaction, and learning. Education and Information Technologies. https://doi.org/10.1007/s10639-024-12818-5
8. Offerdahl, E. G., Arneson, J. B., & Byrne, N. (2017). Lighten the Load: Scaffolding Visual Literacy in Biochemistry and Molecular Biology. CBE—Life Sciences Education, 16(1), es1. https://doi.org/10.1187/cbe.16-06-0193
9. Pokojná, H., Barbora Kozlíková, Berry, D., Kriglstein, S., & Katarína Furmanová. (2023). Seeing the unseen: Comparison study of representation approaches for biochemical processes in education. PloS One, 18(11), e0293592–e0293592. https://doi.org/10.1371/journal.pone.0293592
10. Quillin, K., & Thomas, S. (2015). Drawing-to-Learn: A Framework for Using Drawings to Promote Model-Based Reasoning in Biology. CBE—Life Sciences Education, 14(1), es2. https://doi.org/10.1187/cbe.14-08-0128
11. Sayadi, D., & Pangandaman, H. (2025). Technology-Enhanced Science Teaching for 21st-Century Learning: A Systematic Review of Evidence-Based Strategies and Their Alignment with SDG 4. Jurnal Pendidikan IPA Indonesia, 14(3). https://doi.org/10.15294/jpii.v14i3.29379
12. Sholahudin, N. P., Shofa Nabilah, Nimas Ayu Lestari, Adi Rahmat, Nanang Winarno, & Yanti Hamdiyati. (2024). Exploring the Correlation between Motivation and Self-Regulation in Science Learning among

Junior High School Students: A Case Study. Unnes Science Education Journal, 13(1), 20–32. https://doi.org/10.15294/usej.v13i1.593

13. Spencer, D., McKeown, C., Tredwell, D., Huckaby, B., Wiedner, A., Dums, J. T., Cartwright, E. L., Potts, C. M., Sudduth, N., Brown, E., Albright, P., Arnav Jhala, & Srougi, M. C. (2024). Student experiences with a molecular biotechnology course containing an interactive 3D immersive simulation and its impact on motivational beliefs. PLoS ONE, 19(7), e0306224–e0306224. https://doi.org/10.1371/journal.pone.0306224
14. Terrell, C. R., Nickodem, K., Bates, A., Kersten, C., & Mernitz, H. (2020). Game-based activities targeting visual literacy skills to increase understanding of biomolecule structure and function concepts in undergraduate biochemistry. Biochemistry and Molecular Biology Education, 49(1), 94–107. https://doi.org/10.1002/bmb.21398
15. View of Difficulties in learning biochemistry: Case of 1st year medical students, Tangier. (2025). Labosfor.com. https://jett.labosfor.com/index.php/jett/article/view/1122/866
16. Wang, L.-H., Chen, B., Hwang, G.-J., Guan, J.-Q., & Wang, Y.-Q. (2022). Effects of digital game-based STEM education on students' learning achievement: a meta-analysis. International Journal of STEM Education, 9(1). https://doi.org/10.1186/s40594-022-00344-0