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Transforming molecular diagnostics learning: the power of gamification in higher medical education

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Introduction: Traditional teaching models in molecular diagnostics often fail to engage students effectively, leading to superficial learning and limited development of core competencies.

Methods: This study evaluated the integration of gamified learning with collaborative inquiry learning to enhance student motivation and competencies improvement among 47 biotechnology undergraduates at Guilin Medical University. Participants engaged in a four-unit "Gene Detective" game, solving clinical cases through molecular techniques, earning skill points, and collaborative inquiry learning in group discussions.

Results: Data from skill assessments, self-reported competency scales, final exam scores from the concurrent course, and post-course questionnaires revealed significant improvements in core competencies especially in critical thinking, curiosity, creativity and communication skill, with a positive correlation between game-based skill values and academic performance. Over 88% of students reported high engagement, and 79.6% reported increased learning interest.

Discussion: While the hybrid model successfully promoted motivation and competencies development, challenges in enhancing collaborative skill and providing individualized support were identified. The findings underscore the potential of gamification in medical education and highlight future directions, including AI-driven personalization and refined collaborative tasks, to optimize learning outcomes.

KEYWORDS

gamification, molecular diagnostics, learning motivation, core competencies, medical education

1 Introduction

Molecular diagnostics is a field that involves cutting-edge technologies and their applications, aiming to diagnose and monitor diseases using modern molecular biology techniques (Schmitz et al., 2022; Udager et al., 2014; Buettner and Gültekin, 2022). It is both highly practical and specialized. The learning objectives of this course are not only to help students understand and apply the principles and techniques of molecular biology to address clinical problems, but, more importantly, to develop transferable core competencies such as self-directed learning, critical thinking, and teamwork. The cultivation of these competencies will enable students to adapt to various clinical situations, make informed decisions, and continually advance their professional development (Shiau and Chen, 2008; Taylor et al., 2023; Aulakh et al., 2024; Lerner et al., 2009).

The traditional teacher-centered teaching model primarily focuses on knowledge delivery and information transmission, placing students in a passive receiving role and limiting their opportunities to actively engage in the learning process. This model often results in low student motivation, insufficient classroom participation, and a learning process that remains superficial, all of which hinders the achievement of in-depth understanding and practical application of knowledge (Kusurkar et al., 2023). Furthermore, the lack of real-world simulations and interactive elements in traditional teaching limits the development of students' critical thinking and teamwork skills, failing to meet the demand for the cultivation of students' comprehensive abilities. Some student-centered Collaborative Inquiry Learning model, such as Problem-Based Learning (PBL) and Case-Based Learning (CBL), offer significant advantages in providing contextual simulations, helping students apply theoretical knowledge to solve clinical problems, and fostering deep learning, critical thinking, and teamwork skills (Trullàs et al., 2022). However, challenges remain in effectively stimulating students' interest in learning and their intrinsic motivation for active learning (Dolmans and Schmidt, 2006). This gap underscores the need for innovative approaches that can better engage students' intrinsic motivation and sustain their involvement throughout the learning process.

One promising solution is the introduction of gamified learning. The essence of gamification lies in applying game design elements in non-game contexts (Deterding et al., 2011), integrating educational content and objectives into the gamified design, and transforming learning tasks into challenging and rewarding activities. Key elements such as points, rewards, competition, and real-time feedback are incorporated to enhance the learning experience. In recent years, the application of gamified learning in medical education has grown significantly, showing considerable potential in improving student engagement and learning outcomes (Xu et al., 2023; May et al., 2023; Dabbous et al., 2023). This study aims to integrate gamification Learning with Collaborative Inquiry Learning to explore how this hybrid model can further stimulate students' intrinsic motivation, improve their deep learning, critical thinking, and teamwork skills in clinical problem-solving, and thus better align with the learning objectives of the course while creating a more dynamic and interactive educational experience.

2 Materials and methods

2.1 Participants

This study involved all 47 undergraduate students from the 2022 cohort of the Biotechnology program at Guilin Medical University, all of whom were enrolled in the "Molecular Diagnostic" course. These students were also taking the related "Molecular Biology" course concurrently. At the start of the course, each student completed a scale (Table 1), measuring six core competencies: curiosity, searching ability, critical thinking, communication, collaboration, and creativity. Based on the assessment results, students formed study groups of 4–5 members, ensuring diversity and complementary strengths in each group.

2.2 Construction of gamified learning units

This study utilized "Clinical Molecular Diagnostics Application Case Studies" (Liu et al., 2023) as a learning resource, selecting one representative case from each of the four chapters on molecular

TABLE 1 Six core competencies assessment scale.

Please select one of the following descriptions that best matches your abilities
1. Curiosity
A. I am generally not interested in the things around me
B. I am interested in specific areas and ask relevant questions
C. The questions I ask are ones that can be explored further
D. I often ask investigable questions during discussions with others
E. I am curious about all unfamiliar fields and look forward to exploring them with others
2. Searching ability
A. I typically only use Baidu to search for information
B. I tend to rely solely on reference books for information
C. In addition to the methods mentioned, I also search for information from academic platforms such as CNKI and PubMed
D. Besides the methods above, I also gather information from sources like China University MOOC, Bilibili, and AI tools
E. I use multiple channels to gather information and can assess its reliability
3. Critical thinking
A. I can distinguish between facts and opinions in the information I read
B. I can analyze the development of viewpoints, their limitations, biases, and how they differ from other viewpoints
C. I can develop my own perspective based on the information I have obtained
D. I can support my viewpoint with sound evidence
E. I can identify the strengths and weaknesses of both my own views and opposing views
F. I can further develop or refine my viewpoints based on new insights
G. I can explain the internal and external factors, as well as motivations, behind both my own and opposing viewpoints
4. Communication
A. I am able to listen attentively to others and respect different perspectives
B. I can build on previous statements made by others to ask questions or delve deeper into information
C. I can respond to others' questions and address their doubts
D. I can drive the discussion forward by asking and answering questions
E. I can introduce new directions for discussion and encourage deeper dialog
5. Collaboration
A. I can follow the agreed rules of the team and fulfill my assigned role
B. I can independently and actively fulfill my role in collaboration
C. I can establish appropriate personal roles and partnerships within the team as needed
6. Creativity
A. I can organize existing evidence around the core of an issue
B. I can connect evidence logically and progressively to deepen my understanding of the issue's core
C. I can organize evidence in a coherent manner to enhance understanding of the core issue
D. I can continuously acquire new evidence and create a coherent whole to deepen my understanding of the core issue

A, B, C, D, E, F, G correspond to ability levels 1, 2, 3, 4, 5, 6, and 7, respectively.

diagnostics of infectious diseases, clinical pharmacogenomics, tumors, and genetic disorders to create four learning units. Unit 1 focused on the molecular diagnostics of infectious diseases, involving conventional PCR and quantitative real-time PCR techniques. Unit 2 addressed the molecular diagnostics of clinical pharmacogenomics, incorporating PCR and first-generation sequencing technologies. Unit 3 explored the molecular diagnostics of tumors, utilizing ARMS-PCR and next-generation sequencing techniques. Unit 4 covered the molecular diagnostics of genetic disorders, involving quantitative real-time PCR, chromosome karyotyping, and fluorescence *in situ* hybridization techniques. The four learning units were designed to progressively increase in difficulty, reflecting the complexity of molecular biology techniques and the cases, providing a step-by-step learning experience.

2.3 Implementation of gamified learning activities

Each learning unit was divided into two main sections: "Gene Detective" game and Collaborative Inquiry Learning. In the "Gene Detective" game section, students first received basic patient information, clinical symptoms, and physical examination findings. Students then independently selected the appropriate molecular biology techniques and molecular targets to investigate in order to uncover potential clues. Afterward, they reached a consensus in group discussions on which key clues to unlock, as the number of available clues was limited. Subsequently, students obtained the relevant clues from the instructor (e.g., quantitative real-time PCR results, sequencing data, or fluorescence *in situ* hybridization images). Each student analyzed the unlocked clues, inferred an individual molecular diagnosis, and the group voted on the final diagnosis. If the diagnosis was correct, the game task was completed; if the diagnosis was incorrect, students could retry until they succeeded or choose to exit. During the game, each key clue unlocked earned the student 10 exploration skill points. Each correct individual molecular diagnosis or each correct vote earned the student 10 inference skill points. Upon game task completion, the group shared their process, strategies, and insights. The instructor provided a summary of the case, offered additional materials, and presented relevant literature. Following the game, the Collaborative Inquiry Learning section began. In this section, the group formulated unresolved questions that arose during the game and proceeded to an iterative process of dialog and feedback. These questions were addressed sequentially by other groups, with each group providing their answers and supporting evidence based on their understanding and research. Other groups were encouraged to challenge the responses, ask probing questions, or request deeper explanations. Ultimately, the original group that posed the question synthesized the feedback, formed a final conclusion, and extended the case story. To conclude the session, groups participated in peer evaluations by voting for the team with the best overall performance.

After completing each learning units, students engaged in individual and group reflections. The individual reflection focused on personal highlights, challenges faced, strategies for overcoming those challenges, and plans for the next steps. The team reflection addressed overall group performance, including communication effectiveness, mutual support, conflict resolution, division of labor, and areas for improvement.

At the end of the course, students participated in a final presentation session, where each group created a poster to summarize their learning journey, including their exploration of the game case studies, individual contributions, and teamwork dynamics. Each group also selected a Most Valuable Player (MVP) based on their contributions, with the MVP earning an additional 20 bonus points. Finally, groups presented their posters, explained their work, and participated in a peer evaluation session. The top three members received 30, 20, and 10 bonus points respectively (Figure 1).

2.4 Data and analysis

This study employed a multi-dimensional data collection approach to evaluate students' performance in gamified learning activities, the development of their core competencies, and the overall effectiveness of the course. Data sources include students' game-task-based skill value accumulated during the "Gene Detective" game and self-assessment scales completed by students at the beginning and end of the course to evaluate their core competencies. The self-assessment scale was designed based on established educational psychology theories, including Bandura's self-efficacy theory (Bandura, 1997), Deci and Ryan's self-determination theory (Deci and Ryan, 2000), and other related theories (Facione, 1989; Johnson and Johnson, 2013). The internal consistency of the scale was assessed using Cronbach's α reliability test and was refined through multiple pre-tests to ensure its validity. A paired sample *t*-test was used to compare students' self-assessed competencies at the start and end of the course, aiming to assess changes in core competencies. Additionally, non-parametric Spearman's rank correlation analysis was applied to examine the relationships between game-task-based skill value, self-assessment data of personal core competencies at the beginning and end of the course, and the final exam scores of the concurrent "Molecular Biology" course. At the conclusion of the course, the research team distributed a survey to students to gain further insight into their engagement, learning outcomes, and feedback on the course.

3 Results

3.1 Assessment of game-task-based skill values

During the game, students accumulated exploration and inference skill points (with a maximum of 190 and 140 points). The MVP of each group and the top three members in the peer evaluations earned additional bonus skill points. Each student's total skill value was calculated by summing their exploration, inference, and bonus skill points, with a maximum total of 380 points.

As shown in Figure 2, the minimum values for exploration, inference, and total skill are 50, 40, and 100, respectively. The first quartile values are 70, 70, and 170, the medians are 100, 90, and 220; and the third quartile values are 120, 110, and 230, with maximum values of 140, 130, and 290, respectively. The distribution indicates that exploration and inference skills are relatively concentrated, with most students' abilities clustered around the mid-range. The interquartile ranges are narrow, and extreme values are rare, suggesting that most students have relatively balanced skills in these areas.

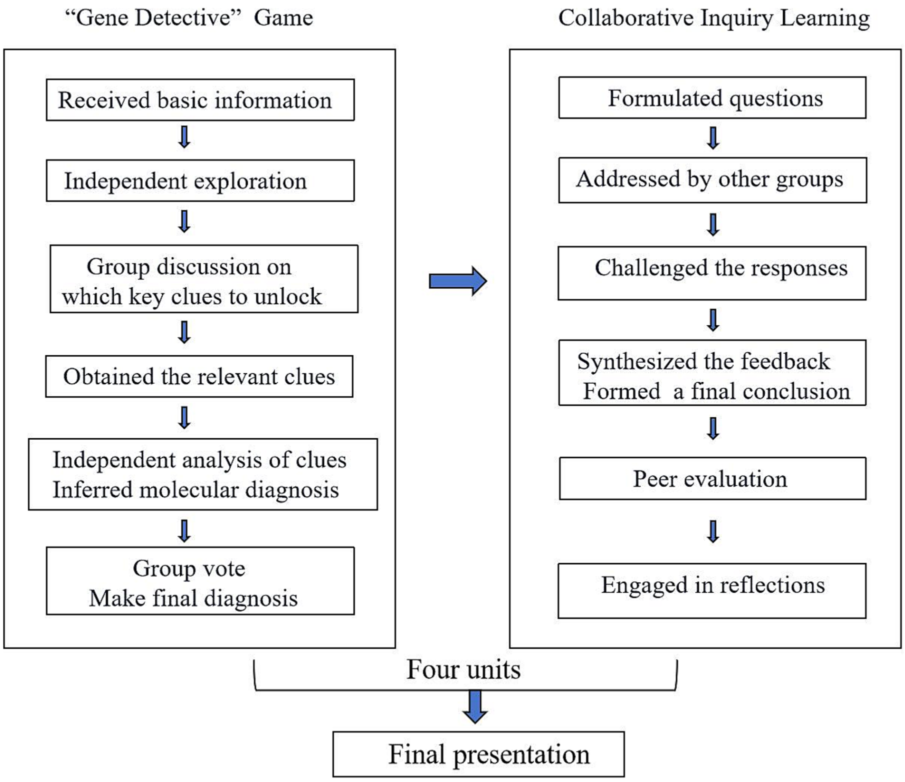

FIGURE 1
Workflow of gamified learning activities.

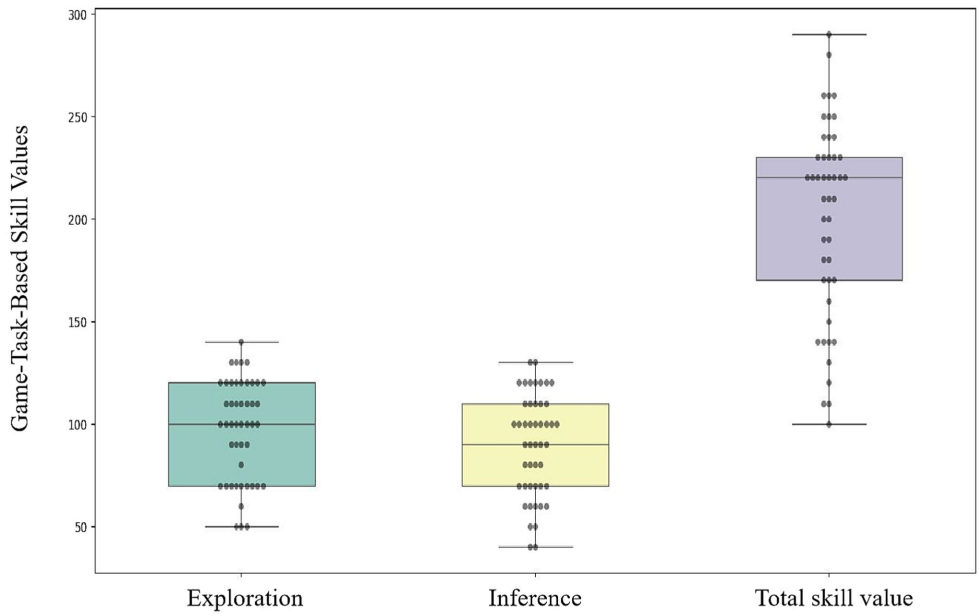

FIGURE 2
Assessment of game-task-based skill values.

However, the total skill value shows greater variation; the range between the median and the first quartile is significantly larger than that of the third quartile. This indicates a broader fluctuation in total skill levels, with some students excelling in multiple areas and possessing strong, well-rounded abilities, while others display weaker total skills with more pronounced differences.

3.2 Development of students' core competencies: statistical analysis of self-assessment data from the beginning and end of the term

At the end of the semester, students were asked once again to complete a self-assessment of six core competencies. The self-assessment data from the beginning and end of the course were compared using a paired-sample *t*-test to evaluate the trajectory of student development in these competencies. The aim was to objectively assess the impact of the learning model on the enhancement of students' abilities.

As shown in Figure 3: (1) The distribution of curiosity values indicates that the minimum and maximum values remained unchanged (2–5) from the beginning to the end of the term, the median increased from 4 to 5, the first quartile rose from 2 to 4, and the third quartile stayed at 5. With a *p*-value of 2.63e-04, this suggests that most students made significant progress in curiosity. (2) For searching ability, the minimum value increased from 1 to 2, while the maximum value remained at 5. The median stayed at 4, and the interquartile range increased from 3 to 5 at the start of the term to 4–5 at the end, showing improved consistency in students' searching ability. The *p*-value of 2.75e-02 is statistically significant. (3) In terms of critical thinking, the minimum and maximum ranges shifted from 1 to 7 initially to 3 to 7 by the end of the term, with the median rising from 4 to 5, and the first and third quartiles increased from 3 and 5 to 4 and 6, respectively. The *p*-value of 6.43e-04 indicates a notable improvement in students' critical thinking skills. (4) For communication skills, the minimum and maximum values increased from 1 to 5 initially to 2 to 5 by the end of the term, while the median remained unchanged at 4. However, the interquartile range increased from 2–4 to 4–5, and the *p*-value of 2.41e-05 indicates significant improvement in students' communication skills, even though the median remained the same. The extreme values suggest improvement. (5) Changes in collaboration skills were minimal, with no change in both the median and interquartile range (both remaining at 2 and 2–3). The *p*-value of 4.71e-01 shows no statistical significance, likely due to the limited number of assessment levels (only three) and the fact that most students had already reached a certain level, making it difficult to detect subtle changes. Alternatively, the learning methods may not have sufficiently enhanced students' collaboration skills. (6) For creativity, the minimum and maximum values remained unchanged (1–4) from the beginning to the end of the term, and the median stayed at 3. The interquartile range shifted from 2 to 3 at the start to 3–3.5 by the end. A *p*-value of 5.36e-04 indicates a significant improvement in students' creativity. 7. Comprehensive Competency Evaluation: The minimum value increased from 11 to 15, and the maximum value increased from 27 to 28. The median rose from 19 to 23, and the first and third quartiles increased from 16 and 21.5 to 22.5 and 25, respectively. This comprehensive improvement reflects the course's overall promotion of students' six core competencies, with a highly significant *p*-value of 1.80e-08.

3.3 Analysis of the correlation between game-task-based skill values, self-assessment, and academic performance

Using the non-parametric Spearman rank correlation coefficient method, we analyzed the relationship between game-task-based skill values (exploration + inference), students' initial and final self-assessments of comprehensive competency at both the start and end of the course, and their final exam scores in Molecular Biology course (Table 2). A moderate positive correlation was observed between game-task-based skill values (exploration + inference) and both the final self-assessment of comprehensive competency and the final exam scores in the Molecular Biology course. This suggests that as students'

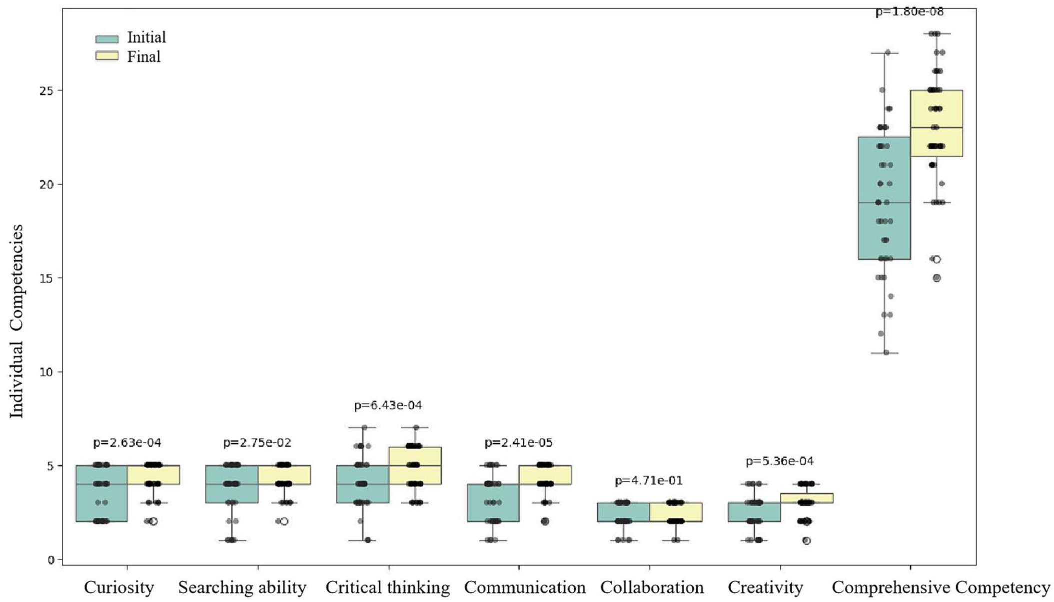

FIGURE 3
Development of students' core competencies.

TABLE 2 Correlation analysis between game-task-base skill values, self-assessment, and academic performance.

	Game-task-based skill values (exploration + inference)	Initial self-assessment of comprehensive competency	Final self-assessment of comprehensive competency	Molecular biology course final exam score
Game-task-base skill values (exploration + inference)	–	0.140 ($p = 0.348$)	0.316 ($p = 0.031$)	0.322 ($p = 0.027$)
Initial self-assessment of comprehensive competency	0.140 ($p = 0.348$)	–	0.487 ($p = 0.001$)	0.072 ($p = 0.633$)
Final self-assessment of comprehensive competency	0.316 ($p = 0.031$)	0.487 ($p = 0.001$)	–	0.100 ($p = 0.504$)
Molecular biology course final exam score	0.322 ($p = 0.027$)	0.072 ($p = 0.633$)	0.100 ($p = 0.504$)	–

Values represent Spearman rank correlation coefficients, with *p*-values in parentheses.

skills accumulate, their self-assessment of comprehensive competency improves accordingly. Furthermore, students with stronger exploration and inference skills tend to perform better in theoretical exams. There was also a strong positive correlation between students' initial and final self-assessments, indicating consistent self-evaluation throughout the course. This suggests that self-assessment data can effectively reflect the development of students' comprehensive competency. However, no significant correlation was found between students' self-assessment data (both initial and final) and their final exam scores in the Molecular Biology course. This indicates that students' self-assessments do not always align with their objective test performance. This finding highlights that a single exam score mainly reflects a student's understanding of specific subject matter, but is insufficient to comprehensively assess the student's comprehensive competency. It underscores the importance of using multiple evaluation tools in educational practice to gain a more comprehensive understanding and better support students' learning and development.

3.4 Questionnaire survey

At the end of the course, the research team distributed questionnaires to the students to gain a deeper understanding of their engagement and overall experiences, as well as to gather their feedback and suggestions for course improvement.

Survey Questionnaire:

1 How would you rate your overall participation in classroom activities (e.g., group tasks, case analysis, discussions)? (1 = Very Low, 5 = Very High).
2 Do you feel that gamified learning in the course has increased your interest in learning? (1 = Not at all, 5 = A lot).
3 How much new knowledge and how many new skills do you think you have gained through this course? (1 = None, 5 = A lot).
4 Do you think the course content has been helpful to your professional studies? (1 = Not helpful at all, 5 = Very helpful).
5 Do you think your ability to collaborate in a team has improved through group work in this course? (1 = Not at all, 5 = A lot).
6 Do you feel your confidence has improved through this course? (1 = Not at all, 5 = A lot).
7 What part of the course do you find the most helpful? Why?
8 What part of the course do you think needs the most improvement? Why?
9 Do you have any suggestions or opinions for future improvements in course design? (Including but not limited to learning methods, course structure, course resources, learning style, assessment methods, etc.)
10 Please share your overall experience and feelings about this course.

A total of 44 out of 47 students completed the survey anonymously and provided the following results (Figure 4): (1) More than half of the students (50.0%) rated their participation at the highest level of 5 points for overall engagement in classroom activities (indicating "very high"). Additionally, 38.6% gave a rating of 4 points, further reflecting a positive attitude and generally high levels of engagement in classroom activities. This data suggests that the course design was successful in fostering student participation, thereby creating a dynamic and interactive learning environment. (2) The gamified learning elements introduced were widely acknowledged by the students. Specifically, 43.2% perceived the gamified learning approach as having "greatly" (5 points) increased their interest in learning, while 36.4% chose "considerably" (4 points). Only 4.5% of the students believed that gamification had little effect on their interest (Rated 2 points). This demonstrates that most students had a positive view of gamified learning and found it effective in enhancing their interest in learning. (3) Regarding the acquisition of new knowledge and skills, 40.9% of students believed they had acquired substantial new knowledge and skills, rating 4 points, while 34.1% rated 5 points, indicating a significant gain. Together, these two groups account for over 75%, indicating that the majority found the course effective in developing both knowledge and skills. Only 2.3% of students rated it 2 points, believing they learned little, and none rated it at 1 point, which further supports the success of the course. (4) 85% of students reported that the course content was very or moderately helpful for their professional studies, with 40.9% rating it 5 points and 34.1% rating it 4 points. Only 2.3% rated it 2 points, indicating limited benefit. These results demonstrate the relevance of the course content to students' professional growth, supporting both academic and career development. (5) With respect to teamwork improvement, 43.2% selected "greatly" (5 points) and 34.1% selected "considerably" (4

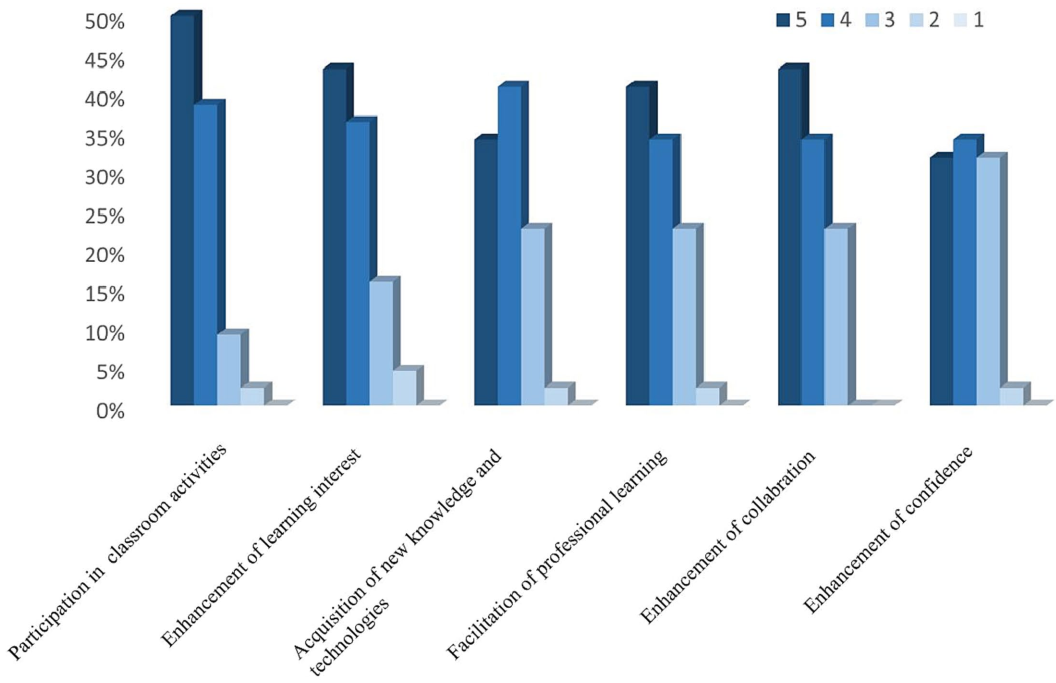

FIGURE 4
Results of the final questionnaire survey.

points). None rated their collaboration experience as negligible, demonstrating that the group activities effectively promoted the development of collaboration skills. (6) Regarding confidence improvement, 34.1% reported a considerable boost in self-confidence (4 points), and 31.8% reported a significant increase (5 points). Together, these two categories account for 65.9%. Only 2.3% felt that their confidence had not improved noticeably (2 points), and no students reported no improvement (1 point). This suggests that the course positively contributed to enhancing students' self-confidence.

Open-ended questions provided more in-depth insights. When asked, "What part of the course do you find most helpful, and why?," students' feedback focused on several key areas: 41% of students felt that the exploratory and inference activities enhanced their independent thinking, information-gathering, and logical inference abilities, while also deepening their understanding of the subject matter. 39% of students highlighted that solving problems through teamwork not only strengthened collaboration but also significantly improved their communication skills. 20% of students stated that case analyses allowed them to bridge the gap between the principles of molecular diagnostics and practical applications, leading to a deeper understanding of the field. Finally, 10% of students mentioned that reviewing, reflecting, and summarizing facilitated better self-evaluation and personal development.

In response to the question, "Which part of the course do you think needs the most improvement, and why?" students' feedback primarily focused on several key areas: 18% of students suggested reducing the difficulty of the cases or providing more explicit information to help them solve problems more effectively during the game-based activities. However, 5% of students expressed a desire to increase the difficulty of the cases to enhance the course's level of challenge. Additionally, 16% of students anticipated the development of more realistic and effective simulation software to further enhance the course's engagement. Furthermore, 10% of students emphasized the need to ensure fair grading practices to uphold the integrity of the course and sustain student motivation.

In response to the question, "What suggestions or opinions do you have for future course design?" students articulated their specific expectations for improving the course. Their suggestions included continuing the use of gamified learning, developing practical and realistic simulation software, and introducing relevant foundational knowledge before exploring the cases. These recommendations not only align with their views on areas needing improvement but also provide us with clear guidance for course development.

In response to the question "Share your overall experience and impressions of this course," 66% of the students reported that the course was innovative and engaging, with a strong sense of involvement and an immersive experience. Additionally, 43% of the students reported that they had gained substantial knowledge and skills, giving them a significant sense of accomplishment. This positive feedback strengthens our confidence in the effectiveness of the course design and motivates us to continue refining our teaching methods and course content.

4 Discussion

4.1 Stimulation of learning motivation

In this study, we designed and implemented a series of gamified learning activities, integrating various gamification elements (Ofosu-Ampong, 2020). In the "Gene Detective" game, students took on the role of "gene detectives," solving problems by unlocking clues and making diagnoses, which enhanced their immersion in the learning process. The four learning units were designed with increasing levels of difficulty, forming a coherent task chain that allowed students to progressively master complex knowledge and experience a growing sense of achievement. Students earned skill points by unlocking key clues, making correct inferences, and voting, which motivated them to actively engage in the tasks. During the game, students received immediate feedback, including unlocked clues and teacher feedback, helping them track their progress and receive the necessary support. In group discussions, students reached a consensus on which key clues to unlock and engaged with other groups during the Collaborative Inquiry Learning sessions, which enhanced both the interactivity and enjoyment of the learning experience. Although the game also involved elements such as MVP selection and peer evaluations, which are typically associated with leaderboards, the study focused more on individual student development rather than competition, so these elements were not emphasized. These gamified designs aimed to stimulate students' intrinsic motivation by meeting their psychological needs for autonomy, competence, and social relatedness, thereby increasing their interest in and engagement with learning (Ofosu-Ampong et al., 2021; Ryan and Deci, 2000; Sailer et al., 2017).

According to the survey results, 88.6% of students rated their classroom participation above 4, and 79.6% of students believed that gamification increased their interest in learning, with ratings also exceeding 4. Additionally, in terms of overall experience, 66% of students reported that the course was novel and engaging, with a strong sense of participation and experience. This positive feedback validates that the gamification elements used in this study successfully stimulated students' learning motivation and engagement, thereby achieving the intended course objectives.

4.2 Improvement of core competencies

The main goal of the course is to develop six core competencies: curiosity, searching ability, critical thinking, communication skills, collaboration, and creativity. Among them, curiosity is the first core competency we focus on, as it drives students to actively explore, identify problems, and achieve deep learning (Loewenstein, 1994; Kidd and Hayden, 2015; Oudeyer et al., 2016; Modirshanechi et al., 2023). Searching ability helps students efficiently gather information to quickly tackle complex problems; critical thinking cultivates students' analytical and evaluative skills, helping them evaluate different perspectives and evidence to make sound decisions. Communication skills enable students to express their ideas clearly and listen effectively to others; collaboration promotes teamwork, improving collective problem-solving efficiency. Lastly, creativity drives students' innovative thinking, exploring new methods to solve complex problems. These core competencies complement each other and collectively form transferable lifelong learning abilities, helping students better respond to future academic and professional challenges (Pellegrino and Hilton, 2012).

To this end, we combine gamified learning with collaborative inquiry learning, aiming to stimulate students' motivation through the challenges in gamified case studies, and encourage them to spontaneously pose questions during subsequent Collaborative Inquiry Learning. Through collective discussion and engaging in meaning-making, they further achieve deep learning. In the gamified tasks, we designed the accumulation of exploration and inference skill values. Exploration skill values primarily depend on curiosity, searching ability, and communication skills, while inference skill values mainly rely on critical thinking, creativity, communication skills, and collaboration. Collaborative Inquiry Learning further enhances curiosity, critical thinking, communication skills, and creativity.

Research data show that students have made significant improvements in critical thinking, curiosity, creativity, and communication skills, with the most notable improvements in critical thinking and curiosity. This aligns with the accumulation of exploration and inference skill values in the gamified tasks and their positive correlation with the final self-assessment of comprehensive competency, indicating that students have effectively developed critical thinking, proactive exploration, and innovative thinking. However, there is still considerable room for improvement in searching ability and collaboration, particularly in collaboration, suggesting that the course design and learning tasks may have certain limitations. Future teaching can place greater emphasis on improving group collaboration tasks and enhancing information retrieval skills to support students' progress in teamwork and problem-solving.

Additionally, the study found a positive correlation between game-task-based skill values and final exam scores in the Molecular Biology course, revealing a close connection between the development of practical skills and the mastery of theoretical knowledge. These findings are further corroborated by feedback from the survey, indicating that the course teaching model effectively combines skill development with theoretical learning, thereby promoting dual progress in both knowledge and skills.

4.3 Educational implications of gamified learning

Based on the feedback from the survey, many students expressed a desire for the development of more realistic and effective game-based software. This suggests that they wish to enhance their learning outcomes through higher engagement and immersive experiences. Such feedback underscores students' strong interest in diverse, interactive learning methods. Furthermore, the findings indicate significant individual differences in students' mastery of knowledge and skill levels, which may result from the course failing to provide sufficient support for all students, causing some to fall short of reaching their full potential. These findings highlight the importance of adopting personalized learning strategies. With the advancement of artificial intelligence, the vision of truly individualized instruction is becoming increasingly feasible. By effectively integrating AI into gamified learning, we can adjust the difficulty and content dynamically based on students' performance, providing personalized guidance and feedback. This approach not only enhances the interactivity and enjoyment of learning but also facilitates genuine personalized learning, enabling each student to optimize their learning outcomes according to their own abilities and pace, thus fostering more effective personal development.

5 Conclusion

This study explores the integration of gamified learning and collaborative inquiry learning in the molecular diagnostics course, examining its potential to enhance students' learning motivation and comprehensive competencies. The results indicate that gamified teaching strategies effectively stimulate students' intrinsic motivation and, through collaborative inquiry, facilitate deep learning. This, in turn, enhances students' critical thinking, curiosity, creativity, and communication skills. These findings provide valuable empirical evidence for the innovation of curriculum design and pedagogical approaches in medical education.

This study has significant practical implications. First, integrating gamification with collaborative inquiry learning offers an innovative pedagogical approach, particularly beneficial in highly practical and specialized fields such as medical education. This approach enhances students' self-directed learning and problem-solving abilities. Furthermore, the study demonstrates that as students develop comprehensive competencies, their theoretical exam performance also improves. This suggests that the development of competencies and academic achievement are interconnected rather than mutually exclusive. Therefore, educators should place greater emphasis on fostering students' holistic competencies rather than solely focusing on exam performance. By adopting this approach, medical educators can extend its application to other disciplines, fostering interdisciplinary competencies and lifelong learning skills.

This study also offers new insights for future educational research. First, further exploration is needed on how to effectively implement and scale the integration of gamified learning and collaborative inquiry learning across different disciplines and educational levels. Second, the competency assessment model proposed in this study, particularly its application in medical education, holds strong theoretical value. Future research could further explore how to design appropriate learning tasks aligned with clearly defined performance-based learning objectives and develop scientifically sound assessment rubrics to effectively evaluate students' deep learning outcomes, while also examining their applicability across different cultural contexts. Additionally, this study highlights the importance of self-directed learning and collaborative learning in competency development, providing a practical framework and research direction for future studies.

Despite its valuable insights, this study has several limitations. First, the sample size was relatively small and focused on a specific academic discipline. Future research should validate these findings across a broader range of disciplines, such as clinical medicine and nursing, and with a larger sample size. Second, this study primarily assessed students' learning motivation and competency development but did not track their long-term learning outcomes. Future studies should employ longitudinal tracking and multi-dimensional assessments to further investigate the long-term impact of gamified collaborative inquiry learning on students' academic performance and professional development. Finally, the technological support and AI-driven personalized learning assistant in this study are still in their early stages. Future research could explore how to optimize AI-driven tools to better interact with students during the learning process, enhancing personalized learning experiences.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Teaching Ethics Committee of Guilin Medical University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

HZ: Conceptualization, Data curation, Project administration, Software, Writing – original draft, Writing – review & editing. WZ: Writing – review & editing. LC: Funding acquisition, Investigation, Writing – review & editing.

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Conflict of interest

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.

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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