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Research Article

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A role-playing tabletop game on laboratory techniques and chemical reactivity: a game-based learning approach to organic chemistry education

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Abstract: The teaching laboratory is central to chemistry education, but student engagement has declined in recent years. Game-based learning (GBL) offers a promising strategy to increase motivation and interactivity. Here, we present the design and assessment of a tabletop, narrative-driven GBL intervention for the organic chemistry lab, focused on the "Identification of an Unknown" challenge. Students used in-game currency, earned by solving chemistry problems and completing laboratory tasks, to acquire analytical data (infrared spectra, elemental analysis) and perform wet chemistry tests. The game fostered collaboration, problem-solving, and integration of theoretical and practical skills. To evaluate impact, we compared performance in the GBL year (n = 126) to the two prior years, analyzing grades, effect sizes (Cohen's d), and variance. The practical mean grade increased by 0.56 points (p = 0.02, d = 0.32); the theoretical mean by 0.37 (p = 0.045, d = 0.31). Surveys (46 % response) indicated perceived gains in motivation and understanding, though some students found resource management challenging. Both quantitative and qualitative data support GBL's potential to enhance engagement and learning in organic chemistry labs and other STEM courses.

Keywords: game-based learning; organic chemistry; teaching laboratory; student engagement

1 Introduction

Laboratory classes are fundamental to chemistry education, providing students with hands-on experience that enhances their understanding of scientific concepts and methods.[1,2] These sessions enable students to apply theoretical knowledge, develop critical thinking, and gain proficiency in essential laboratory techniques.[3,4] However, despite their educational benefits, laboratory courses pose logistical and financial challenges, requiring significant preparation from both students and instructors. Optimizing laboratory learning through enhanced student engagement and learning effectiveness is therefore crucial.[5] Engagement is a key determinant of success in laboratory settings, as active participation fosters deeper conceptual understanding and problem-solving skills.[2,6,7] However, traditional laboratory teaching methods, which often involve following predetermined protocols, can limit student autonomy and reduce opportunities for exploration and decision-making.[2,6] Broader

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educational challenges, such as digital distractions and passive learning environments, have further exacerbated these issues.[8,9] The disruptions caused by the COVID-19 pandemic underscored the need for innovative instructional approaches to sustain student engagement and ensure meaningful learning experiences.[10–13]

To address these challenges, instructional strategies must promote active engagement, autonomy, and deeper conceptual understanding.[8,14] GBL offers a promising solution by transforming passive learning experiences into interactive and immersive activities, encouraging students to engage through problem-solving, decision-making, and collaboration.[15–18] Unlike gamification, which applies game-like elements (e.g., points, leaderboards, badges) to non-game contexts to enhance motivation, GBL fully integrates learning objectives into game mechanics and narrative structures.[19–23] Research has shown that GBL enhances student motivation, engagement, and retention of complex subject matter, particularly when it fosters active problem-solving and teamwork.[15–18,24,25] In chemistry education, where abstract concepts and intricate laboratory techniques often pose learning barriers, GBL has been explored to create interactive, problem-driven learning environments that help students apply their knowledge in meaningful ways.[26–28] While GBL and gamification research in chemistry education has focused largely on digital simulations and competitive game elements, their application in laboratory-based learning remains underexplored or primarily aimed to reinforce theoretical understanding.[27–31] Moreover, few studies have examined how narrative-driven, role-playing tabletop games can seamlessly integrate theoretical and experimental components into a cohesive, immersive learning experience.[26,27,32] Additionally, although GBL has shown promise, its broader adoption in higher education is still limited, due to concerns on the effectiveness being dependent on instructional design and learner preferences, the time-intensive nature of game design and scepticism about the rigor of game-based and gamification approaches.[33,34] Addressing these gaps, our study explores how GBL can enhance engagement and conceptual retention in laboratory settings by integrating storytelling, strategic decision-making, and collaborative problem-solving.

Discussions on GBL's impact further underscore the importance of grounding this approach in solid theoretical frameworks. Constructivist and experiential learning theories offer valuable insights into why GBL can be particularly effective in laboratory education.[2,35,36] Constructivist learning emphasizes active participation in knowledge construction, wherein students learn by interacting with their environment, making decisions, and solving problems in context. Experiential learning similarly highlights the importance of action, reflection, and feedback, enabling students to develop deeper understanding through direct experience. By aligning GBL with these theories, we strengthen its educational validity and practical applicability in chemistry education.

Building on this foundation, we introduce *An Adventure in the Land of ORGO*, a role-playing tabletop game designed to enhance engagement in organic chemistry laboratory courses. To achieve this, we fully integrated laboratory content into both mechanics and narrative, transforming the traditional "Identification of an Unknown" exercise into an interactive quest. Through story-driven challenges, collaborative problem-solving, and strategic decision-making, students engage deeply with chemical concepts and laboratory techniques while navigating an immersive fantasy setting. This study evaluates the impact of this novel GBL approach on student learning, engagement, and performance. Specifically, we investigate how narrative-driven gameplay influences motivation and conceptual understanding, while addressing the challenges associated with self-directed and game-based learning formats. By situating GBL within constructivist and experiential learning frameworks, this research explores its potential to transform chemistry education and provide students with a more engaging, immersive laboratory experience.

2 Materials and methods

To facilitate the transition from traditional laboratory teaching to a game-based learning environment, this section introduces a modular design framework structured around four core components. These elements serve both pedagogical and motivational purposes, enabling instructors to foster critical thinking, collaboration, and sustained engagement throughout a laboratory course.

We first present a generalizable framework for implementing game-based learning in chemistry laboratories (Section 2.1), followed by a description of how this approach was adapted and applied in an introductory organic chemistry lab course (Section 2.2).

2.1 Framework for transforming chemistry labs through game-based learning

GBL research demonstrates that integrating mechanics from tabletop role-playing games (RPGs) can foster engagement, autonomy, and deeper learning in educational contexts.[37,38] Drawing on established frameworks in GBL and RPG design, including the use of quests, resource management, narrative immersion, and structured social interaction,[39,40] we developed a modular approach tailored for chemistry laboratories. This approach adapts five core mechanics: (1) a central, long-term challenge ("main quest") to promote goal-oriented, problem-based learning; (2) a finite, acquirable resource to encourage strategic planning and decision-making; (3) supplementary challenges and encounters to sustain motivation and reinforce key concepts; (4) narrative and thematic elements to create a cohesive, immersive environment; and (5) optional interaction mechanisms to promote teamwork and negotiation. Each element is grounded in educational theory, with the goal of scaffolding critical thinking, collaboration, and self-directed inquiry throughout the laboratory course.

2.1.1 A central challenge ("main Quest")

At the heart of the game-based laboratory experience is a long-term, non-competitive objective analogous to the "main quest" in RPGs. This central challenge is designed to mirror authentic scientific practice by requiring students to collect, interpret, and combine experimental data over multiple sessions to solve a complex problem. The challenge can be **differentiated**, assigning each student or team a unique variation of a problem to solve over the course of several laboratory sessions. This approach increases randomness, simulates authentic scientific discovery, and requires each team to develop its own research strategy. Alternatively, the challenge can be **shared** – with all students or teams working toward the same goal – which can foster greater peer exchange, collaborative troubleshooting, and the development of collective problem-solving skills. Importantly, regardless of the format, the emphasis is placed on exploration and learning, not on competition: there are no incentives for early completion or ranking, and progress is measured by the depth of engagement and quality of the solution, rather than speed. This flexibility allows instructors to tailor the central challenge to the specific educational context and group dynamic, balancing elements of collaboration, differentiation, and game-like variability.

2.1.2 Finite and controlled resources

Progression through the laboratory "quest" is governed by a finite, acquirable resource – often conceptualized as in-game currency. This mechanic, inspired by resource management in games, is critical for fostering decision-making, prioritization, and strategic planning. Students must evaluate trade-offs as they decide when and how to spend resources to access information (e.g., purchasing analytical data, requesting verification), mimicking real-world scientific practice. Additionally, finite resources open opportunities for collaboration and negotiation, as students or teams can share costs, exchange assets, or develop agreements to optimize collective progress and reinforce communication and teamwork skills. This structure parallels the "side quest" or task-reward systems in RPGs, which encourage ongoing engagement beyond the central objective.

2.1.3 Supplementary challenges and encounters

To sustain engagement and reinforce learning between major tasks, the framework incorporates randomized or scenario-driven challenges tied to course content. These supplementary encounters can take many forms – puzzles based on reaction mechanisms, dilemmas rooted in chemical principles, or narrative conflicts that require the application of theoretical knowledge. These activities, modelled on RPG "side quests", serve dual roles: they provide low-stakes opportunities to apply content, and they break up routine to maintain motivation throughout the laboratory sessions.

2.1.4 Narrative and thematic elements

Immersion is enhanced through the incorporation of narrative, fictional setting, and thematic "lore". While not strictly required, a cohesive storyline and in-game characters can anchor learning activities, increase emotional engagement, and help students contextualize their scientific work in a memorable way. Incorporating the storytelling elements of RPGs transforms the laboratory environment from a conventional teaching space into an immersive setting where students take on active roles as discoverers.

2.1.5 Optional interaction mechanisms

While the framework is fundamentally cooperative, additional mechanics may be layered to promote structured interaction, negotiation, and teamwork. These mechanisms can include item trading, shared objectives, or cooperative problem-solving tasks that encourage students to form alliances and collaborate strategically. Such interactions mirror RPG systems where player cooperation is rewarded and where social dynamics enrich gameplay – here, they provide a powerful engine for collaborative learning in the lab.

Taken together, these five components constitute a robust, adaptable scaffold for designing game-based chemistry laboratory courses. This framework is intended to be transferable across scientific disciplines and flexible for diverse institutional contexts. In the following section, we illustrate its application in an undergraduate organic chemistry laboratory course.

2.2 Approach to introductory organic chemistry labs

In this section, we demonstrate how the proposed game-based learning framework was applied in our undergraduate organic chemistry laboratory courses. To contextualize our implementation, we first describe the student population and learning environment in which the game was piloted. We then detail how each element of the framework was mapped to specific course objectives and classroom practices, providing concrete examples and insights for instructors seeking to adapt game-based learning strategies to their own laboratory settings. Section S1 of the Supplementary Material includes additional information of the game structure, content and mechanics.

2.2.1 Learning environment and student population

The GBL approach was implemented in the Organic Chemistry (OC) curricular unit at the Lisbon School of Health Technology (ESTeSL), a public higher education institution within the Polytechnic University of Lisbon (IPL), Portugal. ESTeSL offers degree and master's programs in health technologies and emphasizes practical training in accordance with the Bologna Process. OC is a mandatory 5-credit module (ECTS) for first-year students in Environmental Health, Dietetics and Nutrition, and Pharmacy programs.

Over two semesters, a total of 126 students participated in the GBL intervention. Laboratory instruction included weekly theoretical lectures (3 h per week) to build foundational knowledge, complemented by biweekly laboratory sessions (2 h each, typically with 10–15 students per class) providing hands-on experience. Laboratory facilities were equipped with standard OC instrumentation, including fume hoods, analytical balances, and apparatus for synthesis, purification, and analysis of organic compounds.

Participation in *An Adventure in the Land of ORGO* (hereafter, “the game”) was voluntary. Students had the option to conduct the laboratory work in the traditional format or as part of the game-based approach. Feedback on the game’s effectiveness and student experience was collected through anonymous surveys at the end of the course.

2.2.2 GBL Framework applied to introductory organic chemistry laboratory practice

2.2.2.1 Central challenge (“main quest”)

Prior to the start of the laboratory sessions, students were divided in teams of three to five students, depending on class size and laboratory constraints. Each team was randomly assigned a unique unknown organic compound at the beginning of the semester. This central challenge is a reinterpretation of the classic “identification of an unknown” exercise commonly used in organic chemistry education. To successfully identify their compound, teams needed to systematically acquire and analyze several types of information, such as a list of possible structures, infrared spectra (IR), elemental analysis (EA), and targeted wet chemistry tests. Access to each data type required in-game currency, which was primarily earned through the successful completion of core laboratory tasks. This design ensured that all mandatory laboratory activities (described briefly in section S2 of the Supporting Information) remained essential, while reframing them as game “missions”. A smaller fraction of currency could also be earned through optional game-related challenges or events, maintaining academic rigor, while enhancing engagement and immersion. This structure enabled the seamless integration of established laboratory coursework into the game narrative without compromising education content or standards.

Strategic planning was essential: students had to decide which information to purchase and in what order, often collaborating to use their resources efficiently. The self-paced progression, without rewards for speed, encouraged a non-competitive, inquiry-driven environment. This structure mirrored real-world scientific investigation, reinforced critical thinking, and encouraged students to integrate experimental and theoretical knowledge across multiple sessions – transforming a classic identification exercise into a more dynamic and engaging learning experience.

2.2.2.2 Finite and controlled resources

Student progress through the laboratory quest was governed by a finite in-game currency – “Avogadros” – earned through successful completion of laboratory tasks and in-game activities. Avogadros were required to unlock essential information (e.g., lists of possible compounds, IR spectra, elemental analysis, chemical tests), creating a resource management system that encouraged students to weigh priorities, assess trade-offs, and, in some cases, collaborate or negotiate with other teams to share expenses or resources. This mechanic introduced a layer of strategic decision-making that closely resembled real-world scientific constraints. In a typical playthrough, laboratory tasks provided a total of 80 Avogadros, while up to an additional 20 Avogadros could be earned by completing optional randomized challenges and special requests. The overall cost for the information required to complete the main challenge varied between 60 and 100 Avogadros, depending on the students’ strategy, interpretation of analytical data and compound complexity. The use of limited resources added depth to the learning experience while reinforcing careful planning and data analysis.

2.2.2.3 Supplementary challenges and encounters

To sustain engagement, diversify student experience, and reinforce course content, the game incorporated a series of randomized, scenario-driven supplementary challenges. These optional activities were designed to break up the routine of core laboratory tasks and deepen immersion in the game´s narrative. These events were typically triggered during laboratory “downtime” (e.g., while waiting for a mixture to warm up or cooldown or the elution of a thin-layer chromatography experiment). During these moments, students could encounter:

– **A Hostile Creature**: Students drew an ***Enemy card*** from a randomized deck, which leads to combat. Each creature has specific vulnerabilities to chemical items listed in the “Bestiary” section of the Manual (e.g., Zombies, in this game, are weak against oxidizing compounds). Defeating a creature rewards players with additional ***Item cards.***

- **A Benevolent Creature**: Students drew a ***Helper card*** and were posed a chemistry-themed riddle. The type of creature determines the topic of the question (e.g. Nomenclature or Stereochemistry). A correct answer earns students ***Item cards***.
- **A Special Request**: In each class session, students can respond to special requests to earn extra ***Avogadros***. The tasks associated with these requests range from solving an organic chemistry reactivity problem to combining ***Item cards*** to obtain solutions or reagents.

These challenges were designed to be low-stakes and inclusive: participation was open to all teams, and failure did not penalize progress but instead created opportunities for learning and collaboration. By structuring these activities around moments that might otherwise become idle or disengaged, the game maintained engagement and reinforced course concepts through application and repetition. These encounters not only strengthened students' mastery of organic chemistry techniques and theory, but also encouraged their teamwork, adaptability, and critical thinking.

2.2.2.4 Narrative and thematic elements

The immersive experience of *An Adventure in the Land of ORGO* is grounded in an original, chemistry-inspired fantasy narrative that permeates every aspect of the game. Students enter the fictional world of ORGO, a once-prosperous land shaped by alchemical experiments, wars between dragons and humans, and ancient civilizations. The storyline, introduced in the Game Manual, provides a cohesive and memorable context for all laboratory activities.

Upon "arrival" in ORGO, students learned they must identify a primordial compound and take it to the legendary Ruins of Catallor to find their way home. Along the way, they encountered well-developed characters who offered narrative-driven tasks and challenges linked to organic chemistry concepts. This cast of characters and their backstories enriches the learning environment and provides context for laboratory missions, tests, and problem-solving encounters.

The setting is further brought to life by a map depicting in-game locations, narrative-driven events, and a cast of enemies with chemistry-based vulnerabilities and abilities that require students to apply conceptual knowledge in creative ways. Narrative-driven encounters, such as helping Bridge Trolls with their scent chemistry or synthesizing a cure for petrified Gnomes, tie directly to organic chemistry reactions and reinforce classroom learning through engaging scenarios.

The instructor acted as the "Game Master", mediating these story elements while guiding scientific inquiry. In this way, the laboratory became more than an instructional space: it evolved into a dynamic, story-rich world where students are not just learners, but protagonists in a chemically inspired adventure.

2.2.2.5 Optional interaction mechanisms

While the core gameplay centered on intra-team cooperation, additional mechanics encouraged structured interaction across teams. Students could trade item cards, share analytical data by pooling resources for high-cost items, or collaborate on in-game requests. These interactions mirrored RPG systems that reward alliance-building and collaborative strategy, and further developed communication and negotiation skills in a laboratory context.

2.2.3 Materials used in *An Adventure in the land of ORGO*

To support the implementation of the GBL approach, a comprehensive set of instructional and game materials was developed. This section provides an overview of the key resources used in the ORGO game, including the game manual (which outlines the narrative, rules, and in-game characters), a collection of custom-designed cards, and a set of wet-chemistry tests.

2.2.3.1 Game manual

The game manual served as the central resource for both students and instructors, providing narrative context, detailed rules, and comprehensive instructions for participating in *An Adventure in the Land of ORGO*. Modelled after the reference books used in tabletop role-playing games such as *Dungeons & Dragons*, the manual enabled students to consult lore, mechanics, and character information independently as they navigated the game. In addition to introducing the game's objectives, setting, and cast of characters, the manual included sections on locations, creatures, and game procedures. Importantly, it also featured a dedicated collection of organic chemistry problems and challenges, directly linking gameplay to course content and laboratory tasks. By integrating story, rules, and curriculum-driven challenges, the manual functioned as both a laboratory companion and a storytelling device, supporting independent learning and deep immersion in the game-based environment.

2.2.3.2 Cards

A suite of custom-designed cards was created to support gameplay and reinforce laboratory learning objectives. Primordial compound cards (8 total) were used at the start of the game to randomly assign each team a unique unknown compound for the central identification challenge. Enemy cards (10) represented a variety of chemistry-themed adversaries – such as zombies, oozes, or other creatures – each with different characteristics or groupings to diversify encounters and maintain unpredictability. Item cards (30 in total, representing 20 unique items) included chemical reagents (e.g., sodium hydroxide, hydrochloric acid, silver nitrate), laboratory equipment (e.g., gas masks, shields), and special potions, some with multiple copies included for probability balancing. Request cards (13) introduced side missions or special challenges, with three randomly selected for each laboratory session to further enrich gameplay and laboratory integration. Figure 1 depicts representative examples of custom-designed cards used in this game.

The card system played a central role in introducing randomization and variability into the game, ensuring that each playthrough offered a distinct sequence of events and challenges. This enhanced student engagement and encouraged adaptability, as teams encountered new problems and scenarios with every session. Collectively, the cards functioned as both narrative devices and educational tools, facilitating resource management, problem-solving, and creative laboratory strategies within the game framework.

2.2.3.3 Game board and map

A custom game board was developed featuring the Map of ORGO – a two-dimensional, visually engaging landscape created using the Inkarnate.com map-making platform. The board illustrates the various locations students could "visit" during gameplay and includes designated slots for placement of Enemy, Helper, Item, and Request cards, visually integrating these elements into the unfolding narrative (Figure 2). While the board itself was not essential to the core game mechanics or laboratory procedures, its primary purpose was to promote immersion, provide a sense of place and progression, and enhance the overall game-based learning environment.

2.2.3.4 Wet chemistry test kit

A dedicated wet chemistry test kit was prepared to enable each team to perform practical identification of their assigned unknown compound. The kit included all the reagents and solutions required to carry out 11 distinct classical organic chemistry tests: Chromic Acid (Jones) Test, Lucas ($Zncl_2$/HCl) Test, Silver Nitrate Test, Sodium

Figure 1: Representative examples of cards in *An Adventure in the Land of ORGO*. From left to right: Unknown compound; enemy creature; helper creature; item; request.

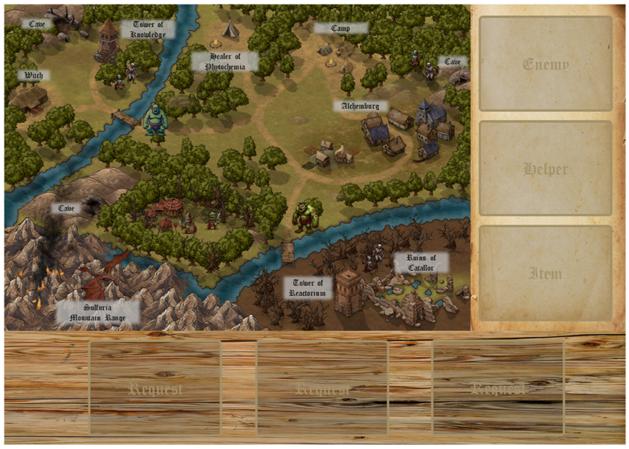

Figure 2: The game board with a graphical landscape of ORGO and card placement slots. Translated from the original.

Iodide (Finkelstein) Test, 2,4-DNPH (Brady) Test, Tollens Test, Permanganate (Baeyer) Test, Bromine Test, Ferric Hydroxamate Test, Nitrous Acid Test, and Bicarbonate Test. These assays covered a broad range of functional group analyses and provided students with hands-on experience in qualitative organic identification techniques. In addition to reagents, the kit also contained reference samples of each of the eight "primordial compounds" used as unknowns in the game: 1-chlorobutane, butan-1-ol, tert-butanol, hexylamine, butanone, ethyl acetate, butyric acid, and cyclohexanecarbaldehyde. This comprehensive kit allowed for authentic laboratory experimentation, tightly integrated with the narrative and structure of the game-based learning approach.

2.3 Student survey and instructor observations

To evaluate student engagement, motivation, and perceptions of the GBL approach, we employed a combination of anonymous surveys and structured classroom observations.

Classroom observations were conducted by course instructors throughout all laboratory class sessions. Observational data were recorded as personal notes, focusing on key elements such as: the frequency and nature of group discussions about course content (often prompted by in-game events or the central challenge), the number and type of additional challenges undertaken by students during experimental downtime, and visible indicators of collaborative problem-solving and teamwork. Regular meetings (weekly or biweekly) were held among instructors to share observations, discuss notable classroom dynamics, and synthesize findings. These qualitative data served to provide context for engagement and participation trends, and supported the interpretation of the GBL intervention's effects on classroom dynamics.

At the end of the semester, students were invited to complete an anonymous, voluntary survey designed to evaluate their experiences with the GBL approach. The survey was administered online and included both quantitative and qualitative components. It consisted of the following sections:

- Previous experience: Students were first asked whether they had prior experience with RPGs in a fantasy setting.
- Perceptions of the GBL approach: Students rated their agreement with several statements on a 5-point Likert scale (1 = Strongly disagree, 5 = Strongly agree), addressing:
  - Motivation compared to traditional methods
  - Interest in organic chemistry classes
  - Relevance of in-game challenges to course content
  - Communication and discussion with classmates
  - Helpfulness in understanding laboratory techniques
  - Perceived level of challenge
  - Consolidation of organic chemistry knowledge

  - Freedom and confusion in information acquisition
  - Preference for more structured versus open-ended navigation of the central challenge
- Contribution to learning specific techniques: Students rated the extent to which participation in the game contributed to their understanding of various laboratory and analytical techniques (distillation, decantation, extraction, recrystallization, filtration, TLC, melting point determination, wet chemical tests, IR, elemental analysis). Responses were measured on a scale from "Not at all" to "Fully," with a neutral midpoint.
- Collaboration and satisfaction: Students rated their satisfaction with instructor support, overall satisfaction with the GBL experience, and collaboration with classmates (scales ranged from 0 to 10, with 0 representing not very satisfied to 10 representing very satisfied).
- Preparation and commitment: Students indicated the number of hours they spent preparing for practical classes outside scheduled hours.
- Support for future use: Students were asked whether they would like to see this learning method applied to other courses and whether the GBL approach should be continued in future years (yes/no).
- Open-ended feedback: A free-response section allowed students to share additional comments or suggestions regarding the GBL approach.

This comprehensive evaluation aimed to capture both the breadth and depth of student perceptions across engagement, learning outcomes, teamwork, and the overall effectiveness of the GBL format in the organic chemistry laboratory context.

2.4 Student performance assessment

Student performance was evaluated separately for theoretical and practical components. The theoretical component was based on either the mean grade of three tests given throughout the semester or, if the student chose, the grade of a final exam. This component focused on students' understanding of organic chemistry principles and the chemical reactivity of functional groups. The practical component was assessed through a written exam, emphasizing laboratory materials and safety, the purpose and application of separation and purification techniques, and the ability to interpret analytical data (Infrared spectroscopy, Elemental Analysis and Wet chemistry tests) for characterizing an organic compound. Both components were graded on a 0–20 scale.

3 Results and discussion

3.1 Effect of implementing GBL in student engagement and motivation

All 126 students from the Dietetics and Nutrition, Environmental Health, and Pharmacy programs actively participated in the semester-long game. No student dropped out, and all successfully completed the required laboratory tasks demonstrating sustained engagement throughout the course. During class, particularly in experiment downtimes, students worked in teams to tackle and solve in-game problems and challenges, manage resources strategically and analyze newly acquired data. These behaviors indicate that the GBL environment fostered teamwork, critical thinking and active participation. During these periods, students engaged in several challenges, from fighting monsters to solving problems, applying both theoretical and practical knowledge in new contexts. The randomization challenges through dice rolls and card draws provided all teams with diverse scenarios and opportunities for additional engagement during downtime. While cognitive skill development was not directly assessed, students' approaches to resource management, task sequencing, and problem-solving were documented in classroom observations and are consistent with principles from constructivist and experiential learning theories.

A key feature of the game was the task of identifying an unknown organic compound, requiring students to apply their chemistry knowledge both practically and strategically. The team "The Wizards of ORGO" exemplified successful strategies, with their detailed methods and outcomes documented in Section S3 of the Supporting Information.

Survey results from 58 respondents (46 % response rate) and classroom observations together provide a comprehensive picture of the effects of the GBL approach on student engagement and motivation (Figure 3). Most students reported that the game-based format increased their motivation compared to traditional teaching methods and heightened their interest in organic chemistry classes. The integration of challenges that were closely aligned with the curriculum was cited as a factor that made course content more engaging and relevant. Collaboration and communication were also enhanced, with students rating their teamwork experience during game activities highly (an average of 8.6 out of 10). The structure of the game encouraged frequent problem-solving and strategic discussions among team members, particularly during downtime in the laboratory. These interactions provided structured opportunities for peer learning, aligning with educational research that emphasizes the value of group activities in developing teamwork and communication skills. Regarding laboratory skills and conceptual understanding, students indicated that the game helped them better understand the laboratory techniques practiced in class and promoted a deeper consolidation of organic chemistry knowledge. Many students felt that the level of challenge presented by the game fostered a better understanding of each technique's purpose and application.

However, student opinions diverged regarding the resource management and information-gathering components of the game. While most appreciated the freedom to choose their own approach to the central challenge, approximately 30 % expressed a preference for more direct or linear pathways to information, finding the abundance of options occasionally confusing. Nevertheless, the majority felt that navigating these options and managing resources enhanced their learning and encouraged more strategic thinking.

Overall, the integration of interactive tasks, narrative structure, and resource management not only captured students' interest but also created a more engaging and effective learning environment. These results are consistent with constructivist and experiential learning theories, which emphasize the importance of active, collaborative, and context-rich experiences. Student feedback indicated strong support for continuing and expanding the use of GBL approaches in the curriculum, reflecting the potential for this methodology to further transform chemistry laboratory education.

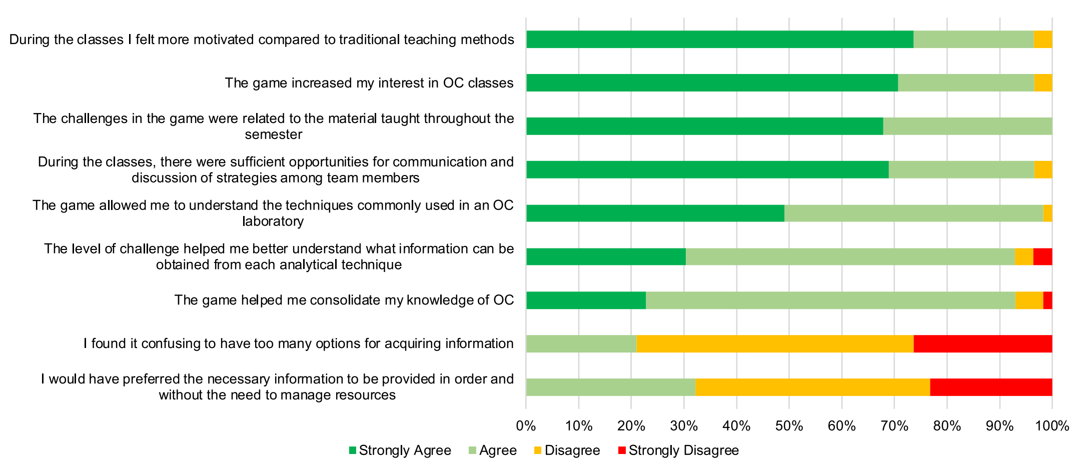

Figure 3: Results of student responses to Likert-scale survey questions evaluating the effectiveness of the GBL approach in an organic chemistry course.

3.2 Effect of implementing GBL in learning and performance

To evaluate the impact of the GBL approach on learning outcomes and student performance, we assessed students' perceptions from the survey replies and conducted a comparative analysis of the final grade in the theoretical and practical components of the OC course over the past three academic years. This time range was selected to ensure comparability, as the student evaluation format for both components remained consistent across these years. Prior to 2021/22, practical assessment relied primarily on group laboratory reports, making direct comparison with later cohorts inappropriate. While every effort was made to maintain similar instructional and grading practices, we acknowledge that, as in any real-world educational setting, unmeasured variables such as cohort composition, instructor dynamics, and external factors (e.g., pandemic effects) may have contributed to year-to-year variation, as discussed in prior chemistry education studies.[41,42]

The survey explored how students felt that participating in the game influenced their understanding of various practical techniques taught in the OC course. The results on this aspect (Figure 4) show that most respondents reported a perceived improvement in their understanding of purification and analysis techniques as a result of the game-based approach. However, due to institutional ethical guidelines, we could not establish a comparable control group (i.e., a cohort without the GBL component), making it difficult to separate the effects of GBL from the normal progression students would achieve through standard laboratory instruction. It is important to note, however, that techniques most closely tied to the game's central challenge – such as elemental analysis, infrared spectroscopy, and other wet chemistry tests – received more positive responses, with students giving higher ratings in these areas. This suggests that embedding practical skills within a narrative-driven, problem-solving context can enhance engagement and perceived learning. Conversely, techniques less central to the storyline, such as melting point determination or thin-layer chromatography, elicited more mixed feedback. This pattern may indicate that the role-playing scenario primarily supported learning in those skills most closely linked to the central challenge, suggesting potential for further refinement to integrate additional laboratory techniques.

The game's difficulty was rated at an average of 3.4 on a scale from 1 (challenging) to 7 (easy), indicating that students generally found the difficulty to be appropriate for their level. This balance was appropriate as students spent an average of 4 h preparing for each class, aligning well with the 5 ECTS credits designated for the course, which corresponds to about 140 total hours of student workload. Students rated the game's usefulness on a scale

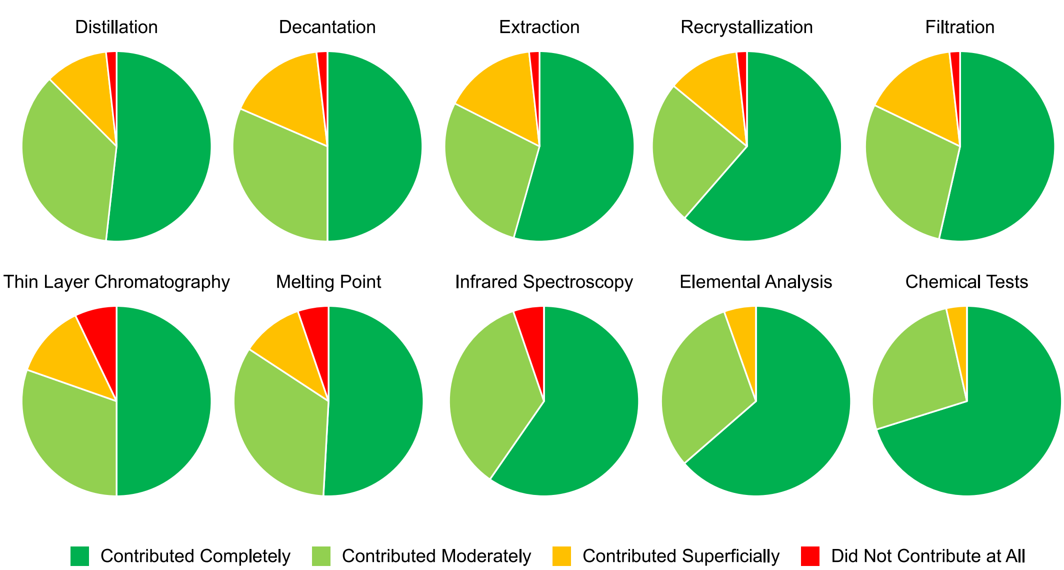

Figure 4: Student assessments of how engaging with the game enhanced their understanding of various practical techniques in organic chemistry, as shown in the charts.

from 1 (very useful) to 7 (not useful), with the average score being 2, indicating that most respondents considered the game useful for their learning. The strong endorsement extended to its future application, with 83 % of respondents expressing a desire to see the GBL approach adopted in other curricular units and 98 % supporting its continued use in the organic chemistry course. These results indicate broad support among respondents for the continued use and potential expansion of GBL in the curriculum.

Qualitative feedback reinforced these findings, with many students describing the game as a more interactive and enjoyable way to learn laboratory chemistry compared to traditional formats. Several comments highlighted how integrating core chemistry concepts into gameplay increased their interest in laboratory procedures and tasks. For instance, one student noted that the game *"incorporated elements from chemistry classes and made them more appealing,"* particularly praising how it facilitated learning about purification tasks and analytical techniques. Another highlighted the lighter, more engaging instructional style and the benefits of structured group work, which allowed active participation from all team members.

However, some feedback also pointed to areas for improvement, suggesting the inclusion of more varied challenges and interactive elements to further enrich the learning experience. A student suggested increasing *"moments of challenges, battles, and 'luck' between places visited on the board"*, to add more dynamism and unpredictability to the gameplay.

This feedback demonstrates both the perceived value of the approach and enthusiasm for its continued use, while also offering a strong foundation for refining of the game to ensure it remains an effective and engaging educational tool.

Regarding student performance, we analyzed the distribution of grades, focusing on mean, median, interquartile range (IQR), and other relevant metrics and compared the results with the two previous academic years to understand the effect of GBL on learning outcomes. To reduce the impact of outliers, we performed the analyses removing the top and bottom 5 % of grades. The results are summarized in Tables 1 and 2 for the practical and for the theoretical components, respectively.

For the practical component, the introduction of the GBL methodology in the 2023–24 academic year led to a noticeable increase in the mean grades of students, from 12.38 to 12.94, alongside a broader distribution of performance as evidenced by a slight widening of the IQR. The widening of the IQR indicates greater variability in student performance following the implementation of GBL, which may reflect differing levels of adaptation to the new format. The ANOVA test, a statistical method used to compare means across groups, confirmed the significance of these changes with a p-value of 0.02, indicating a statistically significant improvement in grades due to the GBL intervention.

Although the theoretical component of the course was not directly targeted by our GBL intervention, an improvement was also observed here. The mean grade increased from 10.72 to 11.43 over the three years (p-value

Table 1: Summary of the metrics for the practical component over the last three academic years.

Year	Mean	Median	IQR	Min	Max
2021–22	12.24	12.5	2.75	5.2	17.0
2022–23	12.38	12.5	2.5	5.3	18.8
2023–24	12.94	13.0	2.8	6.5	19.0

Table 2: Summary of the metrics for the theoretical component over the last three academic years.

Year	Mean	Median	IQR	Min	Max
2021–22	11.05	11.0	3.0	1.0	17.0
2022–23	10.72	11.0	2.5	1.0	16.0
2023–24	11.43	11.5	2.75	1.0	17.0

Table 3: Effect size and variance analysis of GBL approach in practical and theoretical student performance.

	Cohen's d	Levene's p-value
Practical component	0.32	8×10^{-6}
Theoretical component	0.30	0.125

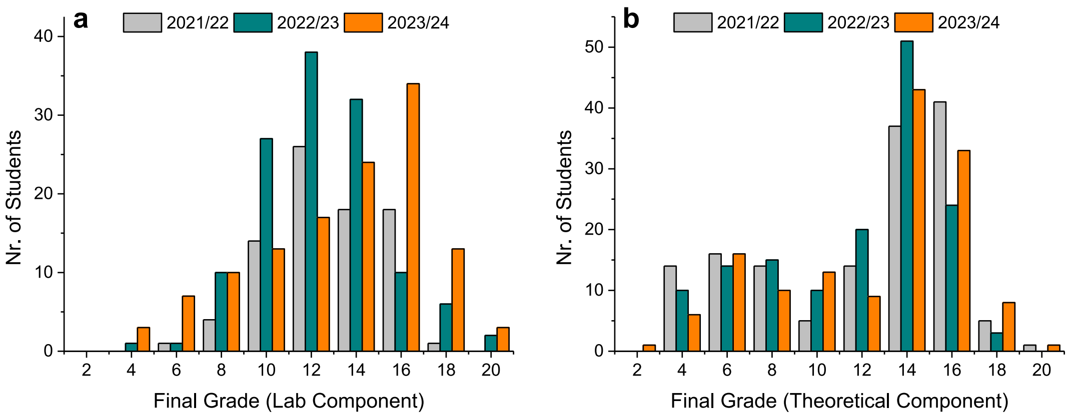

Figure 5: Distribution of student grades in a) practical component final test and b) theoretical component final test, across the last three academic years: 2021/22 (gray); 2022/2023 (blue); 2023/24 (orange).

of 0.045), with the IQR showing stable variability. The grade distribution was slightly more consistent than for the practical component, which may indicate that the GBL approach had a modest, indirect effect on theoretical understanding.

Given the relatively small increase in grades, we decided to assess whether the results are educationally significant by applying Cohen's d to measure the effect size of differences in grade distributions and Levene's Test to examine changes in variance (Table 3). We pooled together the grade distributions from years 2021–22 and 2022–23 (pre-GBL) and compared them with the grades for 2023–24 (post-GBL) to highlight the effects of the GBL approach. The obtained Cohen's d values were similar for both theoretical and practical components and indicate a small-to-moderate positive difference in student learning outcomes after implementation of the GBL approach.

The variance analysis confirmed that while student performance distribution remained stable in the theoretical component ($p = 0.125$), the GBL approach significantly increased variance in the practical component ($p = 0.000008$), showing a significant change in performance patterns following GBL implementation. Further analysis indicated that this variance increase was due primarily to improved performance among a substantial subset of students, supporting the interpretation that GBL contributed positively to practical learning outcomes (Figure 5).

Overall, the findings indicate that the GBL approach complemented traditional teaching methods and was associated with higher engagement and improved performance in the practical component. However, the broader grade distribution in the practical component also suggests that future implementations may benefit from targeted support for students less comfortable with self-directed or game-based learning formats. Continued refinement of the game should focus on balancing educational content and engaging mechanics, while also providing additional guidance for students who may struggle with independent or game-based learning.

4 Conclusions

This study provides evidence that GBL can support student motivation and skill development in higher chemistry education, particularly in the context of identifying an unknown compound. Results demonstrate a positive association between student engagement with the GBL approach and improvements in academic performance, particularly in skills closely aligned with the game's objective. Survey responses and classroom observations suggest that the immersive game environment was associated with active participation and student-reported understanding in both theoretical and practical components, reinforcing the value of student-centered learning in organic chemistry.

While factors like class composition and external influences may influence year-to-year outcomes, our analysis using Cohen's d and ANOVA tests suggests a small-to-moderate educational impact of GBL on learning with statistical significance. In addition, out statistical analysis suggests that while GBL benefited many students, some may require additional guidance in navigating self-directed or game-based learning environments.

In the practical component, students demonstrated measurable improvements in laboratory skills and problem-solving, indicating that the GBL approach may support the integration of theoretical knowledge with hands-on application. Positive student feedback and statistically significant performance gains support the potential value of GBL as a complementary teaching approach. Future adaptations should focus on refining support structures for students who struggle with independent learning while maintaining an engaging balance between educational content and interactive mechanics.

Beyond organic chemistry, GBL holds broader promise as a flexible and adaptable teaching tool for analytical techniques and laboratory-based STEM disciplines. However, to draw more definitive scientific conclusions about the impact of GBL, further data collection and longitudinal studies are needed. Continued application and collaboration among educators will be key for evaluating the broader effectiveness and scalability of GBL approaches.

Finally, the learning environment at ESTeSL, characterized by structures sessions, manageable class sizes, and well-equipped labs, proved conducive to the integration of innovative teaching methods such as GBL. This study supports the potential effectiveness of GBL as a pedagogical tool, consistent with principles from constructivist and experiential learning theories, by reinforcing key concepts, promoting autonomy, and fostering motivation. These findings suggest promising potential for broader application of GBL in higher education, while underscoring the need for further continued research to optimize its implementation into science curricula.

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Use of Large Language Models, AI and Machine Learning Tools: LLMs were used to improved language and text flow.
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