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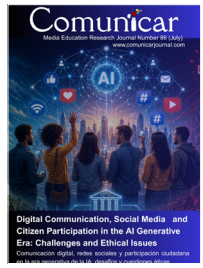

Immersive Gamification in STEM: Educational Escape Rooms for Engagement and Formative Assessment

Gamificación inmersiva en STEM: Escape rooms educativos para la implicación y la evaluación formativa

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ABSTRACT

Gamification has emerged as an innovative educational approach to foster engagement, critical thinking, and collaboration. Although most research on educational escape rooms has focused on higher education, empirical evidence in secondary STEM contexts remains scarce. This study addresses this gap by analysing the design, implementation, and evaluation of an interdisciplinary escape room for 68 first-year IGCSE students in Portugal. Biology, chemistry, and mathematics content was integrated into scenario-based challenges to promote both subject-specific knowledge and transversal competencies. Data were collected through observations, post-activity discussions, student questionnaires, and analysed thematically. Results showed high levels of cognitive and emotional engagement: 92.6% of participants reported enhanced knowledge, and 95.6% affirmed learning gains. Students valued the experience as educational, fun, and engaging, while challenges such as prior knowledge gaps and time constraints revealed the escape room's diagnostic potential. The findings align with the CREATE framework for escape room design and resonate with international policy agendas (OECD, UNESCO) that emphasise 21st-century skills and formative assessment. This study contributes empirically by extending evidence to secondary STEM education, methodologically by positioning escape rooms as diagnostic as well as motivational tools, and theoretically by connecting gamification with media literacy and digital culture as transformative strategies in contemporary pedagogy.

RESUMEN

La gamificación se ha consolidado como una estrategia educativa innovadora para fomentar la motivación, el pensamiento crítico y la colaboración. Aunque la mayoría de las investigaciones sobre escape rooms educativos se han centrado en la educación superior, la evidencia empírica en contextos STEM de secundaria sigue siendo limitada. Este estudio aborda dicha laguna mediante el análisis del diseño, la implementación y la evaluación de un escape room interdisciplinar con 68 estudiantes de primer curso del programa IGCSE en Portugal. Los contenidos de biología, química y matemáticas se integraron en desafíos basados en escenarios para promover tanto el conocimiento disciplinar como competencias transversales. Los datos se recopilaron mediante observaciones, discusiones posteriores a la actividad y cuestionarios, y se analizaron temáticamente. Los resultados mostraron altos niveles de implicación cognitiva y emocional: el 92,6% del alumnado indicó una mejora en sus conocimientos y el 95,6% afirmó haber aprendido con la experiencia. También se identificaron dificultades como lagunas de conocimientos previos y limitaciones de tiempo, que revelaron el potencial diagnóstico del escape room. Los hallazgos se alinean con el marco CREATE y con las agendas internacionales de política educativa (OCDE, UNESCO). Este estudio contribuye empíricamente al ampliar la evidencia en la educación STEM de secundaria, metodológicamente al situar

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los escape rooms como herramientas diagnósticas y teóricamente al vincular la gamificación con la alfabetización mediática y la cultura digital.

KEYWORDS | PALABRAS CLAVE
Educational Escape Rooms, Gamification, STEM Education, Formative Assessment, Media Literacy, Collaborative Learning. Escape rooms educativos, Gamificación, Educación STEM, Evaluación formativa, Alfabetización mediática, Aprendizaje colaborativo.

1. Introduction

Interactive teaching and learning strategies, such as gamification, are increasingly essential in addressing the needs of contemporary learners who often struggle to engage with traditional methods (Dahalan et al., 2024). Raised in a digital and multimedia-rich environment, today's students tend to exhibit shorter attention spans and a preference for participatory, interactive learning experiences (Kennedy et al., 2009). In this context, gamified approaches help educators harness students' natural curiosity and motivation, making learning both meaningful and engaging. These strategies align well with the cognitive and emotional demands of modern learners, fostering deeper involvement and sustained motivation (Taraldsen et al., 2022; Tsirulnikov et al., 2023). Gamification has gained significant attention in education for its ability to integrate game mechanics like rewards, challenges, and leaderboards, transforming learning into an enjoyable, interactive process. Such techniques are proven to enhance knowledge retention, accommodate diverse learning styles, and promote critical thinking skills (Sannathimmappa et al., 2022; Sawarkar et al., 2024). A systematic review has confirmed the increasing use of gamification in primary and secondary education, although much of the evidence remains fragmented and focused on motivational rather than learning outcomes (Vrcelj et al., 2023). By providing immediate feedback and progress tracking, gamification supports the development of a growth mindset and sustained academic performance.

Escape rooms exemplify a novel gamification strategy that immerses students in scenario-based learning environments. These activities integrate subject-specific knowledge into collaborative challenges, encouraging the application of concepts in real-world contexts (Lim, 2024). When aligned with curriculum objectives, escape rooms not only foster critical thinking, problem-solving, and teamwork but also provide an enjoyable way to engage with academic content (Nicholson, 2018). Tailoring the difficulty and scope of these activities to participants' age and proficiency ensures their effectiveness in achieving learning outcomes. Recent studies show escape rooms not only foster engagement but also improve retention rates and academic performance, making them highly effective supplementary tools in educational settings (Juan Roig et al., 2024; Kim et al., 2024; Pais et al., 2023).

This study aimed to design and implement an educational escape room to enhance engagement and learning outcomes among International General Certificate of Secondary Education (IGCSE) students. By integrating biology, chemistry, and mathematics, the escape room sought to enhance both subject-specific knowledge and critical 21st-century skills, such as teamwork and strategic thinking. The design of the activity was inspired by evidence that gamification fosters active and interdisciplinary learning, allowing students to apply their knowledge in a dynamic and collaborative context while also developing essential problem-solving skills for real-world situations. The implementation of the escape room also provided an excellent opportunity to observe how students dealt with complexity and time constraints, aspects that the literature suggests are fundamental to the development of 21st-century skills (Taraldsen et al., 2022).

Beyond offering an immersive experience, the educational escape room explored in this study aligns with the broader context of digital culture and media literacy. Recent studies reinforce that immersive practices grounded in digital culture can empower students as critical and creative individuals (Sánchez-López et al., 2021), while media literacy emerges as a key strategy strengthen critical citizenship competencies (Walter-Antonio et al., 2022). It fosters essential 21st-century competencies such as critical thinking, collaboration, and problem-solving—skills fundamental to developing students as active and participatory citizens. While the activity does not rely on external digital platforms, it incorporates digital elements (e.g., electronic media, computer-based challenges, and multimodal symbolic cues) that reflect the practices and communicative codes of the digital generation. This integration highlights the potential of escape rooms as innovative tools for pedagogical mediation. This perspective is consistent with systematic evidence showing strong connections between digital literacy and the acquisition of STEM skills, underscoring the need for integrative approaches that combine both domains (Govender, 2025). However, despite these promising insights, important gaps remain unexplored.

Although gamification and escape rooms have shown considerable potential, empirical research in secondary education, particularly in STEM subjects, remains scarce. Most studies have focused on higher education and on motivational outcomes, with limited attention to cognitive gains, collaborative competencies, and diagnostic functions. While most escape room research has been conducted in higher education, recent studies demonstrate their growing adoption in secondary contexts, with promising evidence of their impact

on engagement and learning outcomes (Grepperud, 2025). This study addressed these gaps through the following research questions: (1) How does participation in an educational escape room influence cognitive and emotional engagement in STEM? (2) In what ways does the activity foster transversal competencies such as collaboration and critical thinking? (3) Can escape rooms act as diagnostic tools to identify learning gaps in biology, chemistry, and mathematics? (4) What challenges and limitations are perceived by students and game masters, and what are their implications for future pedagogical practices?

To respond to these questions, a qualitative approach was adopted, enabling an in-depth analysis of perceptions, behaviours, and engagement patterns that cannot be fully captured through quantitative measures alone. The escape room was chosen as the focus of this study because it brings together gamification, interdisciplinarity, and collaboration in an immersive setting, aligning with both curricular goals and the demands of 21st-century learning.

Accordingly, this investigation makes three main contributions: (i) it provides empirical evidence on the use of escape rooms in STEM at the secondary level, a context still underexplored in the literature; (ii) it expands the understanding of escape rooms as not only motivational tools but also diagnostic mechanisms to uncover conceptual gaps; and (iii) it connects gamification to broader discussions on media literacy and digital culture, reinforcing its role as a transformative strategy in contemporary pedagogy.

2. Materials and Methods

2.1. Research Objectives and Contributions

The general objective of this research was to analyse the effects of an interdisciplinary STEM educational escape room on students' cognitive, emotional, and collaborative engagement, as well as its potential as a diagnostic tool for identifying learning needs. Specifically, the study sought:

1. Evaluate students' perceptions of the escape room in reinforcing biology, chemistry, and mathematics knowledge.
2. Examine how the activity fosters transversal competencies such as collaboration, critical thinking, and problem-solving.
3. Identify challenges and limitations reported by students and observed by game masters.
4. Explore the diagnostic role of escape rooms in uncovering learning gaps.

This study contributes at three levels: (i) empirically, by providing novel evidence of the implementation of educational escape rooms in secondary STEM education, a context still underexplored in the literature; (ii) methodologically, by expanding the role of escape rooms beyond motivation, positioning them as potential diagnostic tools; and (iii) theoretically, by connecting gamification with media literacy and digital culture, reinforcing its transformative potential for contemporary pedagogy and contributing to discussions on policies for active and interdisciplinary learning.

2.2. Students' Characterization

This study follows a qualitative approach to explore the impact of an educational escape room on student engagement in science and mathematics. Participants were selected through convenience sampling, as all first-year students from the International General Certificate of Secondary Education (IGCSE) cohort at an international high school in Porto, Portugal, were invited to participate voluntarily during the academic year 2022-2023. The escape room activity was designed to assess student's knowledge and understanding of biology, chemistry and mathematics through collaborative, problem-solving challenges. A total of sixty-eight students, aged 13-14 years, participated in the activity. The students were randomly divided into 10 groups of 6-7 participants, ensuring a balanced gender distribution across the teams. Participation in the escape rooms developed for this project was voluntary. The answers collected from the questionnaires were anonymous and consent.

Sampling Rationale: This age group represents the beginning of upper secondary education, a critical transition stage where attitudes towards STEM and foundational knowledge are consolidated. Examining engagement and learning at this point is pedagogically strategic and policy-relevant (OECD, 2018; UNESCO, 2021). Including the entire IGCSE cohort ensured ecological validity, curricular

alignment with standardised STEM content, and equitable participation. For a qualitative study, adequacy is determined by the richness of information rather than statistical representativeness: eleven sessions produced sufficient observation notes and open responses to achieve thematic saturation through triangulation of data sources (observations, group debriefs, and questionnaires). While sampling from a single school limits generalisation, transparency of context and thick description enhance transferability to similar STEM secondary settings.

2.3. Design, Development, and Implementation of the Escape Room

Premises and Design: The design of the escape room took in consideration the premises of (1) being centred on the participating students; (ii) consider the students' collective aspirations and their level of engagement with the subjects being tested. Also, the escape room challenges were tailored to match the group's characteristics, including (i) the appropriate degree of difficulty and the specific skills, (ii) knowledge required to complete the tasks and (iii) intended learning outcomes with the topics students have studied in science and mathematics. In the escape room, fourteen key learning outcomes from sciences and mathematics were addressed:

1. Identify the characteristics of living organisms and use learned mnemonics associated to them (e.g. MRS GREN).
2. Understand the concept of osmosis and predict the effects of immersing animal and plant cells in solutions of different concentrations.
3. Understand the process of genetic translation and use the genetic code to determine the amino acid sequence from mRNA triplets.
4. Identify the organs of the digestive system and circulatory system, using a torso model.
5. Operate an optical microscope to observe specimens on slides.
6. Identify plant organs by observing transverse sections of structures under a microscope (e.g. root tissues).
7. Conduct food tests to identify nutrients in various samples (e.g. Biuret test to identify proteins, iodine test to identify starch).
8. Demonstrate knowledge of the structure of an atom and its subatomic particles.
9. Interpret 3D models of studied molecules and identify them based on their chemical composition (e.g. simple carbohydrates).
10. Recognize the properties of acids and bases and predict the products of their reactions.
11. Perform paper chromatography and calculate the Rf value to identify solutes.
12. Apply trigonometry by using the Pythagorean theorem and the SOHCAHTOA mnemonic.
13. Measure and apply mathematical equations in problem-solving.

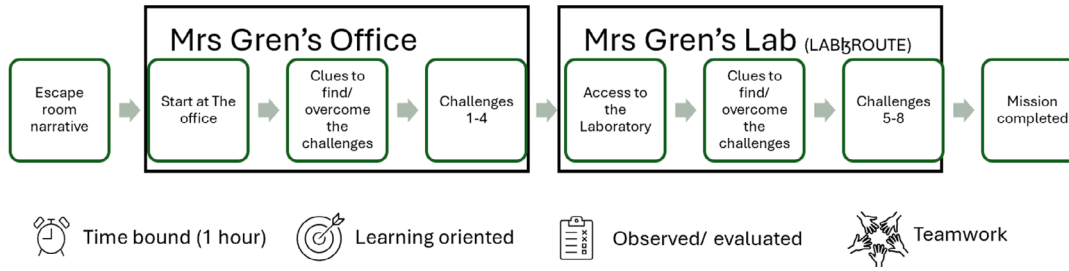
Decode Morse code sequences by using a Morse key to interpret patterns of short and long bursts of sound.

These design choices are consistent with recent recommendations for STEM escape games, which emphasise balancing disciplinary content with engaging puzzle mechanics to ensure both motivation and learning (Gruber & Faßbender, 2025).

Framework Narrative: A framing narrative was created to enhance the students' engagement: the students' team represents a group of internship students at the LABƗROUTE company. Intrigued by the enigmatic researcher, Mrs. Gren, and the highly restricted access to her laboratory, the students decide to sneak into the secret enclosure. What they don't realize is that a different key is required to exit Gren's workspace. To retrieve the key, they must solve a series of riddles—within a strict time limit (the students have one hour to complete the game). The game begins in the office room, and the students must gain access to Gren's laboratory to escape. Each of these rooms contains four sequential enigmas (as illustrated in the flowchart, Figure 1). If they fail to escape within the one-hour time frame, they would find themselves trapped and become unwilling test subjects in Mrs. Gren's mysterious experiments.

In addition to being read aloud by the gamemaster at the beginning of the game, the framework narrative was also presented in a printed document given to each student participant. This document, titled Internship Report also includes on its second page the five questions of the individual written questionnaire used for assessment.

Figure 1: Flowchart Describing the Implemented Escape Room.



Players are encouraged to search for key elements within the room, keeping in mind that the riddles are designed to align with concepts learned in their science and maths' lessons. They should explore the area thoroughly and examine every detail. Another critical aspect of the escape room is collaboration. Some riddles cannot be solved by a single person; therefore, players must communicate openly about their findings and work together to assemble the pieces of the puzzles.

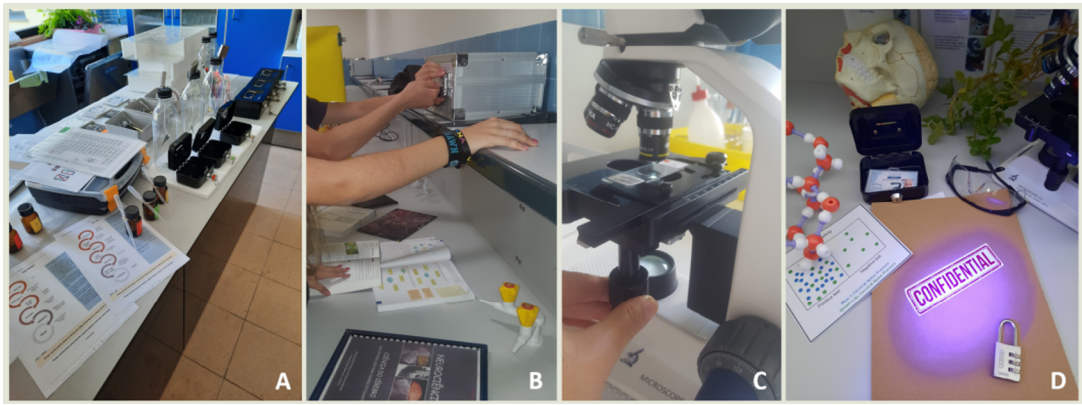
At the entrance, students found a lab coat with a key in its pocket. The key opened a safe box containing an ID card and a USB pen, both belonging to Mrs. Gren. Students had to recognize her name as a mnemonic for the processes that characterize living organisms. The order of the letters corresponds to posters on the wall. Behind each poster, students discovered a book code using UV light. Inside the book, they another riddle: a chemistry enigma. Solving this and providing the correct answers revealed the final word: ATOMS. Inside an acrylic box labelled "ATOMS," there was 3D molecule model of glucose. This model serves as Mrs. Gren's password to access her computer. On her desktop, students found an icon titled Escape. This icon opened a quiz, and by correctly answering a series of science and mathematics multiple-choice questions, students gained permission to enter the laboratory. Once inside the lab, students a folder on the bench containing information essential for interpreting a chromatogram. They must calculate the Rf values for all the amino acids highlighted in the document.

Meanwhile, the USB pen from the office contained a Morse code message. By cross-referencing it with a Morse code chart found in the folder, they decoded a word corresponding to an organ. Also on the bench, students found a torso model. By locating the organ identified by the Morse code, they uncovered a new code hidden within it: 0(W+T). In the chromatogram, W corresponded to an Rf value of 20, and T to 21. Using this formula, the three-digit code 041 unlocked a padlock on safe box 2. Inside, they found a microscope slide, which revealed an image of a root when observed under a microscope. Nearby, among the roots of discovered one of the potted plants in the lab, students discovered two unidentified reagents along with instructions for performing a test, though it was not explicitly labelled as a Biuret test. On the bench, there was also be a rack of test tubes labelled with random numbers (irrelevant to the game) and accompanied by some general information about food tests. Adding the reagents to the test tubes caused one to turn purple, indicating the presence of protein. The word PROTEIN was the final exit code. Typing it into the computer unlocked the laboratory door, completing the challenge.

Place and Implementation of the Escape Room: The escape room took place in the biology and chemistry laboratories in a high school at Porto. Before the game, the teacher responsible for supervising the team during the activity acted as the "game master" and prepared the room, accordingly, setting up all the clues, locks, and puzzles in their designated positions (some images can be seen in Figure 2). The sixty-eight students, (divided in 11 groups), arrived 10 minutes before the start of the game. During this time, the game master explained the rules necessary for the activity (e.g., each clue is used only once, and all clues are accessible within the game space) as well as the narrative and mission for the escape room.

The students then had 60 minutes to solve all eight challenges and complete the mission. During the game, two teachers remained in the room to assist students by providing guidance and additional clues when necessary.

Figure 2: Images captured on the day of the game (A) Organization of some of the Materials and Equipment needed for the setup and preparation of the escape room, (B) Students facilitating a phase of solving a riddle, (C) Student Observing the "Mystery" Slide Under the Microscope, (D) Image Capture of the Cover of Documents Provided at the Entrance of Mrs. Gren's Laboratory.



2.4. Game Assessment

After completing the mission, the students spent an additional 15 minutes discussing the activity and filling out a questionnaire. During the game time, the game masters provided the necessary guidance and some assistance to help the students' progress in solving the challenges. They were also asked to take note of any irregularities/unforeseen occurrences and/or comments from the students about the game. At the end of the escape room, students completed a questionnaire to evaluate their level of satisfaction and engagement with the activities. Some of the questions were adapted from questionnaires used in previous studies (Fraguas-Sánchez et al., 2022; Gómez-Urquiza et al., 2019).

Multiple-Choice Questions:

1. Do you think this type of activity helps enhance knowledge and improve student learning?
2. Did you learn something while participating in the escape room?

Would you recommend this activity to your classmates?

3. Open-Ended Questions:
4. Describe what you liked most about the escape room in three words and elaborate your answer.

Describe what you liked least about the escape room in two words and elaborate your answer.

Questions 1, 2, and 3 were multiple-choice, with the options "yes" and "no." Under each question, there was a prompt to answer, "Why or why not?". Questions 4 and 5 were open-ended to gather detailed feedback about the students' perceptions. At the end, after the questionnaire was filled out, the game masters based on the notes taken during observation discussed with the students the advantages of using this activity as a teaching-learning strategy compared to other teaching strategies in the school.

2.5. Methodology

Data were collected through two main sources: (a) observational notes taken by game masters during and after each escape room session, and (b) open-ended responses in a post-activity questionnaire completed by all participants. These qualitative data sources provided rich insights into student behaviour, engagement, and perception of the learning experience. To ensure a rigorous and transparent interpretation of the data, a thematic analysis was conducted, following the six-phase process proposed by Braun and Clarke (2024). The procedure is detailed below.

Data Analysis Procedure: The data collected in this study were analysed using a qualitative thematic

analysis approach, which is particularly suitable for interpreting patterns and meanings in open-ended responses and observational data. Following the six-phase framework by Braun and Clarke (2024), the analysis aimed to identify recurring themes that emerged from both the game masters' observations and students' questionnaire responses.

1. Familiarization with the data - All qualitative material, including observation notes from the eleven escape room sessions and open-ended student responses, was read multiple times to gain a holistic understanding of the content. This step allowed the researcher to become immersed in the context and tone of the feedback.
2. Initial coding - Key segments were identified and coded manually using Excel. Codes captured recurring ideas such as time pressure, collaboration, engagement, confusion about content, and learning outcomes. Both positive and negative aspects were included to ensure a balanced interpretation.
3. Theme development - Similar codes were grouped into broader thematic categories. For instance, codes like "problem-solving," "strategic thinking," and "multi-step reasoning" were combined under the theme cognitive engagement, while "working together," "team coordination," and "communication" fell under collaborative learning.
4. Review and refinement of themes - Themes were compared across the data set to ensure consistency and internal coherence. Redundant or overlapping themes were refined, and those lacking sufficient support were excluded or merged with others.
5. Definition and naming of themes - Each theme was clearly defined with a descriptive label to encapsulate its core meaning. Final themes included: cognitive engagement, collaborative learning, emotional motivation, perceived difficulty, and interdisciplinary thinking.

Interpretation and reporting - The final themes were interpreted in the context of the study's objectives—particularly regarding student engagement and the development of transversal competencies in STEM subjects. Where relevant, simple frequency counts were used to illustrate how often certain themes were mentioned or observed across sessions. For example, reasoning skills, teamwork, and knowledge application were consistently referenced in all eleven sessions.

This analytical process allowed understanding of how students perceived and interacted with the escape room activity. Furthermore, it ensured that both subjective experiences and observable behaviours were captured systematically.

3. Results

The thematic analysis of observational notes and student questionnaires revealed five major themes: cognitive engagement, collaborative learning, emotional motivation, perceived difficulty, and interdisciplinary thinking. These themes reflect students' engagement during the escape room activity. Although this study follows a qualitative design, simple descriptive statistics (e.g., percentages of yes/no responses) are presented to complement the thematic analysis. These figures are not intended for statistical inference but to illustrate the prevalence of responses and increase transparency. The robustness of the findings derives from the triangulation of multiple data sources (observations, post-session discussions, and questionnaires) and from the achievement of thematic saturation across the eleven escape room sessions. This combined presentation of qualitative themes and descriptive frequencies is consistent with established recommendations for qualitative research reporting. Recent guidelines for qualitative research (e.g., Braun & Clarke, 2024; Sinha et al., 2024) emphasise that presenting descriptive frequencies can be appropriate when complemented by thematic saturation and triangulated data sources. The eleven sessions of this study generated sufficient information richness and theme recurrence to satisfy saturation criteria according to current debate (Ahmed, 2025).

3.1. Cognitive Engagement

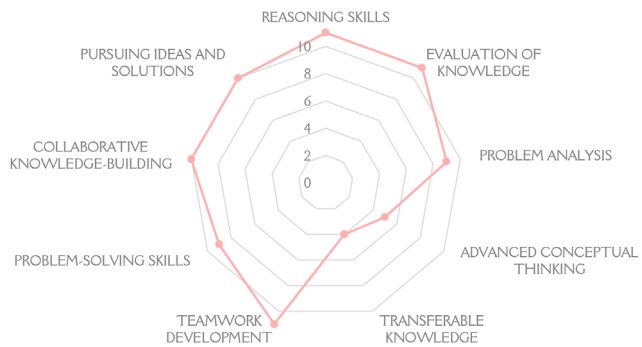
Students demonstrated high levels of cognitive engagement through their active participation in problem-solving and logical reasoning tasks. In post-session discussions, participants consistently mentioned that the escape room helped them develop reasoning skills, critical thinking, and the ability to evaluate knowledge under pressure. These competencies were the most frequently cited across the 11 sessions, as shown in Figure 3. Students noted that their conceptual thinking improved as a result of applying abstract scientific

concepts in a game-based context. For instance, while solving multi-step puzzles, they reflected on the importance of reasoning and collaboration in achieving success, acknowledging the escape room's role in fostering both individual and group learning. For a more comprehensive set of student statements illustrating each dimension, see the supplementary material (Appendix 3).

3.2. Collaborative Learning

Teamwork emerged as a central element in students' success. In every session, collaboration and communication were highlighted as key to overcoming the escape room's challenges. According to the game masters, effective coordination within groups significantly influenced performance. In contrast, one session where team members failed to communicate and remained scattered resulted in the group being unable to complete the game. Students expressed that the experience promoted teamwork development, including division of labour and peer support, and emphasized how collaborative strategies contributed to solving complex tasks (see Figure 3).

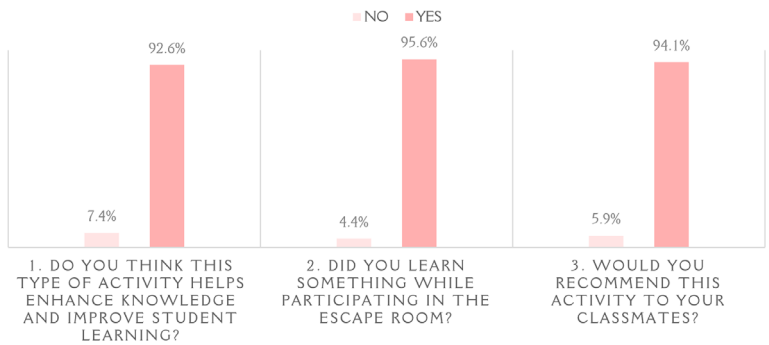
Figure 3: Graph of Addressed Competencies in the 11 Sessions and Mentioned by Students in Post Escape Room Discussions.



3.3. Emotional Motivation

Participants frequently described the activity as fun, engaging, and exciting, demonstrating its motivational impact. Questionnaire responses confirmed this perception, with 92.6% of students agreeing that the escape room was an effective way to enhance knowledge and learning. Moreover, 95.6% reported that they learned something while participating (Figure 4). Many students noted that the activity felt unlike traditional lessons, with one stating that the excitement they experienced "was unlike anything they had felt in school," which inspired them to explore new learning strategies. Word cloud analysis (based on Excel frequency data) revealed that the most common positive descriptors were educational, fun, and engaging.

Figure 4: Bar Graph Illustrating the Distribution of Students' Responses to the Multiple-choice Questions.



3.4. Perceived Difficulty

Despite the overall positive reception, both students and game masters identified several challenges. In two sessions, participants were so anxious about the time limit that it hindered their ability to focus. Some students also noted that the number of challenges felt excessive for the time available. The most common content-related difficulties reported included:

1. Chromatogram interpretation and Rf value calculation.
2. Microscope slide analysis, particularly distinguishing plant organs (e.g., failing to identify root structures).

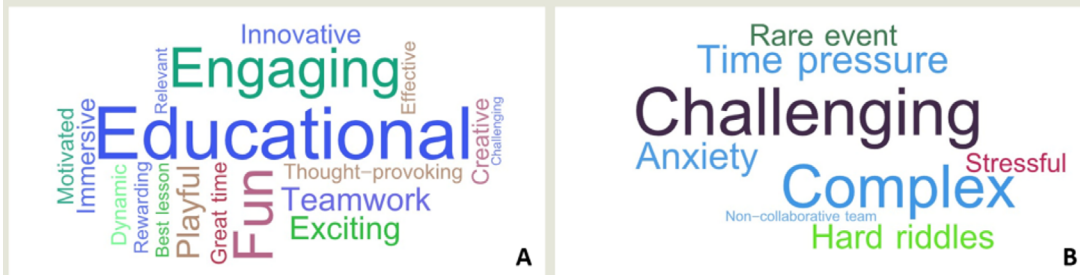
Mathematical substitutions, where students made errors inserting values into formulas.

These challenges were acknowledged during debriefing discussions, where unresolved tasks were reviewed collaboratively, between students and with the gamemaster, to reinforce learning and close knowledge gaps. Negative descriptors in the word cloud included challenging, complex, and time pressure, supporting this theme of perceived difficulty (Figure 5).

3.5. Interdisciplinary Thinking

The escape room's integration of biology, chemistry, and mathematics was consistently recognized by students as a strength. Many reported that this interdisciplinary approach encouraged holistic thinking, helping them understand how concepts from different subjects intersect. Participants highlighted how trial-and-error, time-sensitive decisions, and pattern recognition were essential to progress in the game. These elements contributed to the development of abstract reasoning and strategic thinking, reinforcing the value of interdisciplinary learning.

Figure 5: Word Clouds (A) Words Representing what Students Liked Most about the Escape Room. (B) Words Representing what Students Liked Least about the Escape Room.



3.6. Recommendation and Social Value

To explore the social value of the experience, students were asked whether they would recommend the activity to their peers. Most responded "yes," with only 5.9% answering "no." Only one student explained their response, commenting that the activity was "short-timed and too infrequent." This overwhelmingly positive response highlights the escape room's perceived relevance and appeal among adolescents, both as a learning tool and as a social experience (Figure 4).

4. Discussion

Since the first well-documented Real Escape Game in Kyoto in 2007, escape rooms have evolved into innovative pedagogical tools, primarily in higher education contexts, and are now gaining traction in secondary education (Taraldsen et al., 2022). This study demonstrates how an escape room can integrate key STEM subjects—biology, chemistry, and mathematics—to promote interactive learning, engagement, and interdisciplinary thinking in a secondary school context. The overwhelmingly positive feedback collected through both observations and student questionnaires supports the escape room's effectiveness as an educational tool. Descriptors such as educational, fun, and engaging emerged most frequently in the word cloud analysis, indicating that the activity successfully combined cognitive rigor with emotional engagement.

4.1. Learning Gains and Motivation

A significant majority of students (92.6%) reported that the escape room enhanced their knowledge, reinforcing the pedagogical value of gamification in science and mathematics. This aligns with broader research indicating that interactive learning strategies improve retention and conceptual understanding by situating learners in immersive, problem-based scenarios (Byusa et al., 2022; Plass et al., 2015). Moreover, 95.6% of students reported learning something during the activity, and the vast majority stated they would recommend the experience to others—further evidence of its motivational impact.

These results can also be interpreted through the CREATE framework for educational escape rooms (Lim, 2024), which stresses content integration, real-life applications, educational alignment, adaptability, social integration, and evaluation as key design dimensions. The strong emphasis students placed on teamwork and interdisciplinarity supports the importance of the collaboration and relevance principles. At the same time, the diagnostic potential observed during the activity connects with the evaluation and adaptability components of the framework, suggesting that escape rooms can function not only as engaging tools but also as formative assessment instruments. These results are consistent with a recent meta-analysis showing that escape rooms produce strong effects on knowledge acquisition and moderate effects on attitudinal variables such as motivation and collaboration (Kim et al., 2024). Similar findings were reported by Krouska et al. (2025), who showed that digital escape rooms in environmental education foster high levels of acceptance and motivation, reinforcing their potential as immersive and scalable strategies across disciplines.

4.2. Areas for Improvement: Time Pressure and Cognitive Load

While most students responded positively, feedback from a minority (4.4%) pointed to dissatisfaction related to time constraints, task complexity, and uneven preparation. Some groups experienced difficulty managing the number of challenges within the allocated time, a sentiment echoed by game master observations. These findings highlight the need for refinement, particularly regarding the duration, task scaffolding, and clarity of instructions. Future implementations could integrate tiered challenge levels and pre-activity scaffolding, aligning with the adaptability dimension of the CREATE framework and with policies that encourage differentiated instruction to support diverse learners (UNESCO, 2021). This resonates with the findings of Bessas et al. (2024), who emphasised that transitioning from traditional classroom instruction to escape-room environments requires careful scaffolding to manage cognitive load and ensure inclusivity.

4.3. Reflective Dialogue and Deep Learning

Post-session discussions played a critical role in reinforcing learning. These moments of reflection allowed students to address unresolved challenges, correct misunderstandings, and collaboratively reconstruct knowledge. Difficulties such as chromatogram interpretation and microscope-based plant identification revealed deeper conceptual gaps, which became visible only through the activity. This underscores the diagnostic potential of escape rooms, connecting them with current policy trends that prioritise formative assessment and personalised learning (OECD, 2018). By revealing misconceptions in real time, escape rooms offer educators a powerful tool to tailor instruction and remove barriers to understanding, thereby advancing equity and inclusion in STEM education.

In addition, the collaborative problem-solving and post-session reflection required students to interpret multimodal codes, combine symbolic information, and critically evaluate digital and material clues. These processes resonate with key dimensions of media literacy, namely the ability to navigate and interpret diverse communicative modes, question information sources, and engage in reflective dialogue (Walter-Antonio et al., 2022). In this sense, the escape room functioned not only as a disciplinary learning tool but also as a space for practising critical and creative skills grounded in digital culture.

4.4. Policy and Pedagogical Implications

These findings resonate with international agendas that emphasise the importance of 21st-century competencies, such as collaboration, problem-solving, and critical thinking (OECD, 2018; UNESCO, 2021). Escape rooms provide a context where these skills are not taught abstractly but practised in authentic, collaborative tasks, reinforcing calls for education systems to embed transversal competencies within curricula. Furthermore, their integration into secondary education can contribute to the goals of the European Digital

Education Action Plan (European Commission, 2020) and the UNESCO "Futures of Education" initiative, which advocate for innovation, interdisciplinarity, and the meaningful use of digital culture in pedagogy.

Comparable findings have been reported in other disciplinary contexts, such as science education, where Giner-Baixauli et al. (2025) found that escape rooms enhanced both motivation and conceptual understanding, reinforcing their versatility across curricular areas. By bridging gamification, media literacy, and digital culture, this study highlights the potential of immersive learning environments as transformative educational strategies. Beyond their immediate classroom impact, escape rooms can inform curricular reforms and educational policies aimed at strengthening student engagement, fostering lifelong learning skills, and ensuring education systems are responsive to the demands of a complex and digitally mediated world.

Moreover, escape rooms also embody practices of digital culture, where students engage with multimodal symbolic systems, narrative framing, and collaborative meaning-making. Such practices are consistent with recent scholarship highlighting the transformative potential of digital creativity in education (Sánchez-López et al., 2021) and the role of media literacy in fostering critical, participatory citizenship (Walter-Antonio et al., 2022). Integrating these perspectives further reinforces the value of escape rooms as not only STEM pedagogical innovations but also as vehicles for advancing media education and critical digital competencies.

5. Conclusion

This study provides empirical evidence that educational escape rooms can serve as effective and engaging tools for promoting learning in STEM disciplines at the secondary level. By integrating interdisciplinary content with collaborative, scenario-based challenges, the activity fostered not only conceptual understanding but also transversal competencies such as problem-solving, teamwork, and critical thinking.

Beyond engagement, the escape room also demonstrated diagnostic potential, revealing gaps in students' prior knowledge that may not be evident in traditional assessments. This positions escape rooms as valuable instruments for formative assessment and personalised learning, in line with international policy priorities that emphasise inclusivity and equity in education (OECD, 2018; UNESCO, 2021).

The findings further support recent design frameworks such as CREATE (Lim, 2024), showing how collaboration, relevance, and adaptability are central to the effectiveness of gamified learning environments. They also resonate with broader research, including recent meta-analyses (Kim et al., 2024) and disciplinary applications (Giner-Baixauli et al., 2025), reinforcing the versatility and transformative potential of escape rooms across educational contexts.

Challenges related to time pressure, task complexity, and uneven preparation highlight the need for careful scaffolding and differentiated design (Bessas et al., 2024). Future implementations should incorporate tiered levels of difficulty, pre-activity support, and extended opportunities for reflection to ensure accessibility for diverse learners. This study is also limited by its single-site design in one international school and using convenience sampling, which constrains statistical generalisation. Even so, the detailed contextual description supports transferability to similar secondary STEM settings. Future research should expand to multiple schools, apply mixed methods approaches, and examine long-term impacts on learning and assessment.

In sum, this research contributes at three levels: empirically, by addressing the scarcity of studies in secondary STEM education; methodologically, by advancing the use of escape rooms as diagnostic as well as motivational tools; and theoretically, by bridging gamification with media literacy and digital culture. These contributions underline the relevance of escape rooms not merely as classroom innovations but as strategies with broader implications for curricular integration and educational policy. The study also contributes to the mission of *Comunicar* by highlighting the intersection between gamification, media literacy, and digital culture, offering evidence of how innovative pedagogical practices can foster critical, collaborative, and participatory citizenship in secondary education.

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