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RECEIVED 12 August 2025

ACCEPTED 20 October 2025

PUBLISHED 05 November 2025

CITATION

Mirmotahari O, Grun HN and Berg Y (2025)
Gamification as a transferable pedagogical
innovation for technology education:
developing 21st-century skills through
collaborative game-based learning.
Front. Educ. 10:1684459.
doi: 10.3389/feduc.2025.1684459

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Gamification as a transferable pedagogical innovation for technology education: developing 21st-century skills through collaborative game-based learning

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Introduction: Technology literacy has become essential across all academic disciplines, yet traditional pedagogical approaches often struggle to engage students while simultaneously developing twenty-first-century collaborative competencies. This study investigates gamification as an innovative pedagogical method for technology education, examining its effectiveness in developing technology awareness, digital literacy, and collaborative skills.

Methods: We conducted a case study of two pilot implementations in an introductory computer science course ($n = 117$ students across two cohorts). The intervention consisted of a narrative 10 driven, collaborative game-based learning track offered alongside a traditional course format. We employed mixed-methods analysis to assess student engagement, motivation, technology comprehension, and learning outcomes. Participation in the gamified track was voluntary and cohorts were not randomized.

Results: The gamified approach achieved 100% completion rates in the first pilot and 88–92% satisfaction rates across both implementations. Participation in the gamified track was associated with higher reported motivation and collaborative skill development compared to the traditional track. In the second pilot, students who chose the gamified track achieved higher exam scores than peers in the traditional track; however, due to voluntary participation and non-randomized cohorts, these differences represent associations rather than causal effects. Platform consistency emerged as a critical factor: when bonus tasks required platform switching, completion rates significantly dropped across three chapters, indicating that integrated digital learning environments are essential for managing cognitive load and optimizing learning outcomes.

Discussion: These findings demonstrate that gamification can effectively teach technology concepts through game mechanics whilst simultaneously developing collaborative competencies. We propose a transferable framework for implementing gamification in technology education across disciplines. This research contributes to understanding how innovative pedagogical approaches can address the growing need for technology literacy in higher education.

KEYWORDS

gamification, technology education, 21st-century skills, collaborative learning, digital literacy, cognitive load theory

1 Introduction

The rapid digitalization of society demands that graduates from all disciplines possess not merely technical proficiency, but comprehensive technology awareness, digital literacy, and collaborative problem-solving skills (Prensky, 2001; Spector et al., 2014). Traditional pedagogical approaches often struggle to engage students in technology education, particularly when teaching abstract concepts such as algorithmic thinking, system architecture (Mirmotahari et al., 2003), and digital security (Guzdial, 2015). This challenge intensifies in large, diverse student cohorts where varying backgrounds and learning styles must be accommodated within a single educational framework.

Gamification—the application of game design elements in non-game contexts—has emerged as a promising pedagogical innovation for addressing these challenges (Deterding et al., 2011). Unlike game-based learning, which employs actual games, gamification integrates game mechanics such as narratives, progression systems, and rewards into traditional educational structures (Kapp, 2012). This approach holds particular promise for technology education, as it can transform abstract technical concepts into concrete, experiential learning opportunities whilst fostering the collaborative skills essential for modern workplace environments (Hamari et al., 2014; Bovermann and Bastiaens, 2020).

The theoretical foundation for gamification in education draws from multiple frameworks. Cognitive Load Theory (Sweller, 1988) suggests that learning environments should minimize extraneous cognitive load whilst maximizing germane load—the mental effort devoted to schema construction. Gamification can achieve this by providing structured, progressive challenges that scaffold learning whilst maintaining engagement. Additionally, Self-Determination Theory indicates that gamification elements can support intrinsic motivation through autonomy, competence, and relatedness—particularly relevant in collaborative learning contexts.

Despite growing interest in gamification for education (Subhash and Cudney, 2018; Khaldi et al., 2023; Pelizzari, 2023; Manzano-León et al., 2021), limited research examines its application specifically for teaching technology concepts and digital literacy. Most studies focus on engagement metrics rather than examining how gamification can simultaneously develop technical understanding and 21st-century skills (Dicheva et al., 2015). Furthermore, the transferability of gamification approaches across different educational contexts remains underexplored, limiting their broader adoption.

This paper addresses these gaps by presenting a comprehensive case study of gamification implementation in technology education, supported by quantitative and qualitative data. We examine two pilot implementations of a gamified learning environment designed to teach foundational computer science concepts whilst developing collaborative problem-solving skills. Our research questions are:

1. How does gamification affect student engagement, motivation, and completion rates in technology education?
2. What role does platform consistency play in the effectiveness of gamified learning environments?
3. How can gamification simultaneously develop technology literacy and 21st-century collaborative skills?

4. What design principles enable the transfer of gamification approaches across different educational contexts?

By investigating these questions, we contribute to understanding how innovative pedagogical methods can address the growing need for technology education across all academic disciplines, providing a transferable framework for educators seeking to integrate technology awareness into their curricula.

The paper is structured as follows: we first detail our methodology, including participant characteristics and data collection procedures. We then present our findings to illustrate key outcomes. Finally, we discuss implications and limitations, concluding with a transferable framework for implementing gamification across educational contexts.

2 Methods

This study employed a mixed-methods approach combining quantitative data on student performance and engagement with qualitative insights from surveys and interviews. Two pilot implementations were conducted, one each year: Pilot 1.0 ($n = 42$) using a paper-based approach with digital elements, and Pilot 2.0 ($n = 73$) using a fully digital platform. This iterative design allowed for refinement based on student feedback and observed outcomes, enabling us to identify critical factors affecting gamification effectiveness in technology education.

2.1 Course context and participants

The study was conducted within a first-semester introductory computer technology course serving 500+ students annually across six informatics programmes. This 10-credit foundational course provides a broad introduction to computer technology, covering major fields without excessive depth in any single area. The curriculum encompasses low-level programming, network architecture, cyber security fundamentals, and computer architecture including hardware components. This breadth presents unique pedagogical challenges, as students must grasp diverse technical concepts whilst understanding their interconnections.

The traditional course structure requires students to complete three compulsory assignments throughout the semester. For Pilot 1.0, the gamified alternative concluded with an “Endgame” event where teams solved complex tasks under time restrictions. Pilot 2.0 participants took the same open-book digital multiple-choice examination as all other students in the course, enabling direct comparison of learning outcomes between the gamified pilot group and the traditional course participants who served as a control group. Our gamified pilots were offered as a voluntary alternative to the compulsory assignments, allowing students to fulfill course requirements through an innovative learning pathway. This voluntary nature was crucial to our research design, as it ensured participants were genuinely interested in exploring alternative learning methods rather than being compelled to participate. Pilot 2.0 participants completed the same open-book digital multiple-choice final examination as the traditional track, under the same invigilation, timing, and resource conditions, enabling direct

comparison. For Pilot 1.0, the culminating Endgame was blueprint-aligned to course learning objectives and exam topic coverage (cryptography, networks, Boolean logic, computer architecture) and matched on duration and allowed resources; the primary difference was group-based problem solving vs. individual testing.

Student recruitment occurred through online registration forms where interested students provided demographic information and group preferences. For Pilot 1.0, 105 students registered interest, from which we randomly selected 42 participants. Pilot 2.0 had 188 registrations, from which 73 students were randomly selected. The registration form asked students whether they wished to form groups with specific peers they already knew or preferred random group assignment. Groups were constrained to three or four members to ensure effective collaboration whilst maintaining manageability.

The demographic distribution of selected participants showed encouraging diversity, with 49% female participation in the pilots compared to 39% in the general course cohort. Age distribution also differed, with 63% of pilot participants aged 19–21 compared to 47% in the overall student population. This demographic variation suggests the gamified approach appealed particularly to younger students and helped address gender balance in technology education. To contextualize outcome comparisons, we summarized baseline demographics for the gamified cohort vs. the remainder of the course (control). The pilots included a higher share of women and younger students than the full cohort (e.g., 49% vs. 39% women; 63% vs. 47% aged 19–21), reflecting the voluntary sign-up process. These differences underscore the need to interpret between-group results as associations.

2.2 Design of the gamified learning environment

The gamification design evolved from extensive collaboration with previous students and course instructors, following design thinking principles to create an engaging yet academically rigorous alternative to traditional assignments. At its core, the gamified environment featured a cohesive narrative structure spanning three chapters, each representing a distinct phase in students' technical learning journey. Students progressed through the narrative by solving technology-related puzzles and challenges that directly taught course concepts whilst maintaining story coherence.

Central to our approach was collaborative gameplay, with students working in their assigned groups throughout the pilot. This group structure served multiple pedagogical purposes: promoting peer learning, developing collaborative problem-solving skills, and creating accountability mechanisms that encouraged sustained engagement. The mix of self-selected and randomly assigned groups made it possible to compare the effects of group formation on retention, performance, and collaborative dynamics.

The progression system aligned with Bloom's Taxonomy, beginning with knowledge and comprehension tasks before advancing to application, analysis, and synthesis challenges. Early chapters introduced fundamental concepts through cryptography puzzles and Boolean logic exercises, whilst later chapters required students to integrate multiple concepts in complex scenarios such as network troubleshooting and system design challenges.

This scaffolded approach ensured students built foundational understanding before tackling advanced problems.

The reward systems differed between pilots, providing valuable comparative data. Pilot 1.0 implemented "joker cards" earned through bonus tasks, which students could strategically deploy during the final "endgame" assessment. These tangible rewards provided clear incentives for additional effort. Pilot 2.0 shifted to narrative-based rewards, where completing bonus tasks unlocked alternative story paths and endings. This change allowed us to examine how different reward structures affected student motivation and engagement.

All gamified content directly addressed course learning objectives. Cryptography challenges taught security fundamentals whilst students decoded messages to advance the story. Network troubleshooting scenarios embedded protocol understanding within narrative problem-solving. Boolean algebra and circuit design became puzzle mechanisms rather than abstract exercises.

2.3 Implementation and support structure

The implementation began with a physical "kick-off" meeting where students received initial materials and formed their groups. This face-to-face introduction proved essential for establishing group dynamics and clarifying expectations. Each group was assigned to a teaching assistant who served as both technical support and progress monitor, documenting time investment and identifying potential obstacles. Each teaching assistant supervised between seven and ten groups, allowing for regular interaction whilst maintaining manageable workloads.

Throughout the pilots, students could ask for "status-update" sessions with their assigned teaching assistants. These sessions provided formative feedback on group progress and allowed for real-time adjustments to address emerging challenges. The support structure also included flexibility for students to return to the traditional course track if they found the gamified approach unsuitable.

Pilot 1.0 concluded with the Endgame event—a culminating assessment where groups solved complex technical challenges under time constraints, demonstrating both conceptual understanding and practical application skills developed throughout their journey. The Endgame format incorporated competitive elements whilst maintaining academic rigor through comprehensive problem-solving requirements. In contrast, Pilot 2.0 participants completed the standard course examination alongside traditional track students, providing direct comparative data on learning outcomes.

2.4 Data collection and analysis

Our mixed-methods approach drew from multiple data sources to develop comprehensive insights into the gamification experience. Quantitative metrics included completion rates for each chapter and bonus task, time investment data collected by teaching assistants, and performance scores. For Pilot 1.0, this included Endgame performance, whilst Pilot 2.0 provided examination scores directly comparable to the control group of traditional track

students. These objective measures provided clear indicators of engagement and learning outcomes.

Qualitative data collection occurred at multiple points throughout the pilots. After completing each chapter, students completed online questionnaires combining Likert-scale items measuring motivation, perceived learning, and stress levels with open-ended questions capturing detailed experiences. The questionnaires evolved between pilots based on emerging insights, allowing increasingly nuanced understanding of student perspectives.

Semi-structured interviews with selected groups provided deeper insights into collaborative dynamics and learning processes. These interviews explored how groups approached challenges, distributed work, and resolved conflicts. Teaching assistants also contributed observational data, documenting group meeting patterns, problem-solving strategies, and notable incidents throughout the pilots.

Platform analytics in Pilot 2.0 offered additional behavioral data, tracking interaction patterns with the digital environment and external tools. This technical data proved particularly valuable in understanding the platform consistency issues that emerged as a critical finding.

Analysis followed established mixed-methods protocols. Quantitative data underwent descriptive statistical analysis, with comparisons drawn between pilots, between self-selected and assigned groups, and against traditional course performance metrics. For Pilot 2.0, examination results enabled direct comparison between gamified participants and the control group. Qualitative data were analyzed thematically, with initial coding conducted independently by two researchers before collaborative refinement.

We assessed four constructs with questionnaires; motivation, collaboration, perceived stress and satisfaction. Students reported that they looked forward to working on the course activities, which indicate greater motivation. Several teams worked together effectively, which reflect better collaboration.

3 Results

3.1 Engagement and completion rates

The gamified approach yielded markedly different engagement patterns between the two pilot implementations. In Pilot 1.0, all 42 students who commenced the programme successfully completed every component, including voluntary bonus tasks, representing a 100% completion rate across all elements. This comprehensive engagement extended throughout the three-chapter progression without any observable decline in participation.

Pilot 2.0 presented a more complex engagement profile. Whilst all 73 students who continued beyond the initial week completed the core programme requirements, participation in bonus tasks revealed a pronounced downward trajectory. Initial engagement with bonus content stood at 57.9% in Chapter 1, declining to 31.5% in Chapter 2, and reaching only 26% by Chapter 3. This progressive disengagement coincided with the requirement to transition from the primary learning platform, “Night at IFI”, to an external system, Feedback Fruits, for bonus task completion.

Student feedback explicitly identified platform transitions as a significant barrier to engagement. Participants reported experiencing disconnection between the main narrative environment and the external platform, with several noting confusion arising from interface differences and navigation requirements. The contrast between pilots suggests that platform consistency plays a crucial role in maintaining student engagement with supplementary learning activities.

3.2 Learning outcomes and performance

Assessment data demonstrated strong academic achievement across both pilot implementations. The Endgame assessment in Pilot 1.0 showed consistent high performance across all participating groups, with successful completion of complex, time-constrained technical challenges. More significantly, Pilot 2.0 provided direct comparative data through the common examination taken by both pilot participants and traditional track students.

Pilot 2.0 participants achieved examination scores ranging from 68 to 92%, with a distribution skewed toward the upper range. The traditional course cohort, serving as a control group, achieved a pass rate of 42% on the same examination, average 62% and max 95%. This substantial performance differential occurred despite pilot participants completing the course content one month earlier than their traditional track counterparts, suggesting that the gamified approach not only maintained but potentially enhanced learning effectiveness.

The gamified group’s distribution is shifted upward with fewer low scores, consistent with the aggregate differences reported above and show divergence across quantiles rather than isolated tail effects, supporting comparability of the underlying instrument rather than differing exam difficulty.

Analysis of specific competency areas revealed particular strength in practical application tasks. Pilot participants demonstrated superior ability to synthesize multiple technical concepts when solving complex problems, reflecting the integrated nature of the gamified challenges they had encountered throughout their learning journey.

3.3 Development of 21st-century skills

Quantitative assessment of group experiences revealed that 76% of participants rated their collaborative experience positively across both pilots. Qualitative data provided rich insights into the nature of these collaborative dynamics. Students consistently reported that group work enhanced their commitment to the course, with many noting that responsibility to group members created additional motivation for engagement and preparation.

“I feel the group work made me prioritize the course more. When you’re responsible to others in the group, it becomes more important.”

“Group work has been excellent! We met regularly about once a week, and if not everyone could attend, we updated each other next time.”

The peer learning dimension emerged strongly in student reflections. Participants described regular group meetings, typically weekly, where they engaged in reciprocal teaching when individual members encountered conceptual difficulties. This peer instruction appeared to reinforce understanding for both the explaining and receiving students, creating a multiplier effect for learning within groups.

“When someone didn’t fully understand something, it was good practice to explain to others in the group.”

“Working with the course felt important, not just for myself but also for others in the group.”

However, collaborative experiences were not uniformly positive. Approximately 24% of groups reported challenges with uneven contribution levels among members, particularly during high-pressure periods such as approaching chapter deadlines. Notably, all student withdrawals from the pilots occurred within randomly assigned groups, whilst self-selected groups maintained complete retention throughout both implementations.

3.4 Motivation and stress patterns

Longitudinal tracking of student motivation revealed sustained high levels throughout both pilots, albeit with evolving patterns. In Chapter 1, 91.2% of students reported that the pilot met or exceeded their initial expectations, with 75.4% experiencing increased motivation following chapter completion. Chapter 2 maintained high satisfaction at 90.7%, though the proportion reporting increased motivation moderated to 59.3%. By chapter 3, satisfaction remained robust at 88%, whilst motivation increases were reported by 42% of participants.

This pattern suggests an initial surge of enthusiasm that gradually stabilized into sustained but less dramatically increasing engagement. The maintenance of high satisfaction levels throughout, even as motivation increases, indicates that the gamified approach successfully sustained student interest beyond initial novelty effects.

Stress measurements revealed expected variations across different pilot phases. Baseline stress levels during regular chapter progression remained low to moderate for most students. However, assessment periods showed increased stress levels, with Pilot 1.0’s Endgame generating the highest reported stress. Students characterized this stress as comparable to traditional examination anxiety but noted it felt more purposeful given the collaborative nature and practical focus of the challenges.

Temporal analysis of stress patterns revealed that pilot participants experienced more evenly distributed stress across the course duration compared to traditional track students’ reports of concentrated pre-examination stress. This distribution appeared to facilitate better stress management and preparation strategies among pilot participants.

3.5 Emergent design principles

Analysis of student performance and feedback across both pilots revealed consistent patterns regarding effective gamification

elements. Narrative coherence emerged as fundamental to sustained engagement, with students reporting that story progression provided meaningful context for technical challenges. The strength of narrative integration correlated positively with task completion rates and reported satisfaction levels.

Progressive difficulty scaffolding proved essential for skill development. Students who encountered appropriately challenging tasks at each stage showed higher completion rates and satisfaction than those who experienced difficulty spikes. The careful calibration of challenge progression appeared to maintain what students described as optimal engagement without overwhelming frustration.

Reward structures showed differential effectiveness between pilots. Pilot 1.0’s tangible joker card system, providing strategic advantages in the Endgame, achieved universal participation in bonus tasks. Pilot 2.0’s narrative-based rewards, whilst appreciated by engaged students, failed to motivate consistent bonus task completion across the cohort. This difference suggests that reward tangibility and clear utility influence student engagement with optional content.

Platform consistency emerged as perhaps the most critical technical factor. The contrast in bonus task completion between Pilot 1.0’s integrated approach and Pilot 2.0’s multi-platform requirement demonstrated that cognitive load from platform switching significantly impacted student willingness to engage with supplementary content.

Group formation methods showed clear influence on retention and satisfaction. Self-selected groups demonstrated superior cohesion, communication patterns, and ultimately, completion rates compared to randomly assigned groups. This finding held consistent across both pilots despite different technical implementations and reward structures.

Analysis revealed key principles for successful gamification implementation:

1. Narrative coherence: strong storyline integration maintains engagement and contextualizes abstract concepts.
2. Progressive scaffolding: difficulty progression aligned with learning objectives supports skill development.
3. Meaningful rewards: rewards must provide tangible benefits (Pilot 1.0’s strategic advantages vs Pilot 2.0’s narrative outcomes).
4. Platform consistency: minimizing platform switches reduces cognitive load and maintains flow states.
5. Flexible participation: allowing self-selected groups and voluntary participation increases commitment.

4 Discussion

The implementation of gamification in technology education represents a significant departure from traditional pedagogical approaches, offering unique opportunities to address contemporary educational challenges. Our findings indicate that a narrative-driven, collaborative gamified experience was associated with stronger engagement and performance indicators relative to the traditional track, with platform consistency emerging as a salient factor for cognitive load. It is important to note that due to the voluntary nature of participation and non-randomized design,

these differences should be interpreted as associations rather than causal effects. This multifaceted relationship positions gamification as a particularly valuable approach in technology education, where both technical proficiency and interpersonal skills are increasingly recognized as essential graduate attributes.

The theoretical foundations of our approach align closely with established learning frameworks. Cognitive Load Theory, as articulated by Sweller (1988) and further developed by Kalyuga (2011), provides crucial insights into why platform consistency emerged as such a critical factor. When students navigated between different digital environments, they expended cognitive resources on reorienting themselves rather than engaging with learning content. This extraneous cognitive load directly competed with the germane load necessary for meaningful learning. In contrast, when students operated within a unified environment, whether the paper-based system of Pilot 1.0 or the integrated digital platform portions of Pilot 2.0, they could dedicate their full cognitive capacity to understanding concepts and solving problems.

Self-Determination Theory offers additional explanatory power for the sustained motivation observed throughout both pilots. Ryan and Deci (2000)'s framework identifies three fundamental psychological needs that promote intrinsic motivation: autonomy, competence, and relatedness. The gamified environment addressed each of these needs through specific design elements. Autonomy manifested through voluntary participation and strategic decision-making within gameplay. Competence developed through carefully scaffolded challenges that provided achievable yet stretching goals. Relatedness emerged through intensive group collaboration that created meaningful peer connections. The interaction of these elements appears to have created a robust motivational ecosystem that sustained engagement even as initial novelty effects diminished.

4.1 Developing technology literacy through experience

Traditional approaches to technology education often struggle with the abstract nature of technical concepts, particularly when students lack prior experience with system-level thinking. The gamified approach transformed this abstraction into concrete, experiential learning opportunities. Rather than studying encryption algorithms as mathematical constructs, students experienced encryption as a practical tool for protecting information within their game narrative. Network protocols ceased to be abstract specifications and became functional elements that students manipulated to achieve narrative goals.

This experiential transformation appears particularly significant for developing what (Martin and Grudziecki, 2006) term critical digital literacy—not merely the ability to use technology, but the capacity to understand, evaluate, and make informed decisions about technology's role and impact. By embedding technical challenges within meaningful narrative contexts, students developed understanding of not only how technologies function, but why they matter and how they interconnect within larger systems. This contextual understanding represents a crucial educational outcome, preparing students to engage thoughtfully

with technological change throughout their careers rather than merely mastering current tools or platforms.

The narrative framework provided essential scaffolding that made complex technical concepts accessible and memorable. Stories create cognitive structures that facilitate information retention and retrieval, a phenomenon well-documented in educational psychology literature. Students reported that story progression helped them understand relationships between different technical domains, seeing how security, networking, and system architecture interconnect rather than viewing them as isolated topics.

4.2 Collaborative learning and 21st-century skills

The emphasis on group-based learning throughout both pilots reflects growing recognition that modern technology professionals rarely work in isolation. The collaborative structures we implemented went beyond simple group assignments to create genuine interdependence among team members. This design choice yielded observable development in several key competency areas that extend beyond technical knowledge.

Communication skills emerged through the necessity of explaining technical concepts to peers with varying levels of understanding. Students reported that the act of articulation deepened their own comprehension, supporting constructivist learning theories that emphasize the importance of verbalization in knowledge construction. Problem-solving capabilities developed through exposure to diverse perspectives within groups, as students learned to synthesize different approaches and negotiate optimal solutions. Digital collaboration skills, increasingly vital in distributed work environments, developed naturally through the coordination required for group success.

The pronounced difference in outcomes between self-selected and randomly assigned groups merits careful consideration. While random assignment might seem to better simulate real-world team formation, the voluntary nature of our pilot created different dynamics, leading to associations rather than direct causal inferences regarding group performance (Shadish et al., 2002). Self-selected groups likely shared existing social bonds or common motivations that facilitated trust and communication. The complete retention within self-selected groups vs. withdrawals from random groups suggests that, for voluntary educational innovations, allowing student agency in group formation may enhance commitment and success. This finding has important implications for implementing gamification in different educational contexts.

4.3 Transferability across educational contexts

The design principles emerging from our implementation provide a foundation for adapting gamification approaches across diverse disciplinary contexts. The core elements—narrative structure, progressive challenges, collaborative gameplay, and

integrated assessment—are not inherently bound to computer science education. Legal education could employ similar structures to teach regulatory compliance through narrative scenarios. Journalism programmes might use gamified approaches to develop investigative skills whilst teaching about algorithmic bias and data protection. Business curricula could integrate gamification to simultaneously develop strategic thinking and technology awareness.

The scalability of the approach also warrants discussion. While our implementation occurred within a large introductory course, the principles could adapt to various scales. Small seminar courses might implement more sophisticated narratives with greater individual customization. Massive open online courses could employ automated systems to manage group formation and progress tracking. The key lies not in rigid replication but in understanding the underlying mechanisms that make gamification effective: meaningful context, appropriate challenge, social learning, and clear progression.

Cultural and disciplinary considerations must inform any adaptation. The competitive elements that motivated our informatics students might require modification for disciplines with different cultural norms. The specific technologies taught would obviously vary, but the approach of teaching through application rather than abstraction remains broadly applicable. Local educational traditions, assessment requirements, and resource constraints would all influence implementation details whilst maintaining core design principles.

4.4 Limitations and future directions

Several limitations of our study warrant acknowledgment and suggest directions for future research. The voluntary nature of participation, whilst ensuring genuine engagement, introduces self-selection bias. Students who chose the gamified alternative may have possessed characteristics—such as openness to innovation, collaborative preferences, or gaming familiarity—that influenced their success. Future research might explore mandatory implementation to assess effectiveness across a more representative student population.

The single-institution context limits claims about generalisability. While our student body exhibited considerable diversity in background and demographics, institutional culture and resources undoubtedly influenced implementation and outcomes. Multi-institutional studies would provide valuable comparative data about how local contexts shape gamification effectiveness. We acknowledge several statistical limitations in our current analysis. First, while we observed substantial differences in examination performance between tracks, these results should be interpreted cautiously given the self-selection of participants. To address this partially, we conducted sensitivity analyses by controlling for prior GPA and found that the positive association between gamified track participation and performance remained significant (adjusted $\beta = 0.31$, $p < 0.01$). However, we cannot rule out unmeasured confounding factors such as motivation or learning style preferences that may have influenced both track selection and outcomes. Second, the small sample size of

TABLE 1 Practical implementation considerations for educators.

Design element	Key consideration	Implementation recommendation
Narrative structure	Coherence with learning objectives	Develop storyline in parallel with curriculum mapping
Challenge design	Progressive difficulty	Create scaffolded challenges with 15%–20% difficulty increase between stages
Platform integration	Cognitive load management	Minimize transitions between systems; aim for ≤ 1 platform change per learning module
Group formation	Balance between self-selection and diversity	Allow partial self-selection with strategic additions for diversity
Assessment alignment	Authentic evaluation	Design assessments that mirror gamified activities while maintaining academic rigor
Support systems	Scalable assistance	1:7–10 ratio of teaching assistants to student groups

our pilot implementations ($n = 42$ and $n = 73$) limits statistical power, particularly for subgroup analyses. Future studies should consider randomized designs with larger samples to strengthen causal inference.

The relatively compressed timeframe of our pilots prevents assessment of long-term retention and transfer. While immediate learning outcomes appeared strong, questions remain about whether the experiential learning approach yields durable knowledge that students can apply in subsequent courses and professional contexts. Longitudinal tracking of pilot participants through their academic progression would provide crucial data about lasting impacts.

Future research should also explore optimal group formation strategies more systematically. Our binary comparison between self-selected and random groups only scratches the surface of this complex issue. Hybrid approaches, such as allowing students to form partial groups that are then completed through selective assignment, might balance the benefits of student agency with diversity goals.

The platform consistency finding opens important technical questions about learning management system design and integration. As educational technology ecosystems become increasingly complex, with multiple specialized tools for different purposes, understanding how to maintain cognitive coherence whilst leveraging diverse functionalities becomes crucial. Research into seamless platform integration and unified user experience design could significantly impact the viability of complex gamified learning environments.

4.5 Implications for practice

Table 1 summarizes the key implementation considerations for educators based on our findings. The insights gained from our implementation offer practical guidance for educators considering gamification in technology education. First and foremost, the

importance of coherent design cannot be overstated. Gamification is not simply the addition of points and badges to existing content but requires fundamental rethinking of how learning experiences unfold. The narrative must meaningfully connect to learning objectives, challenges must scaffold appropriately, and all elements must work in concert toward educational goals.

Investment in initial design pays substantial dividends. Our collaboration with previous students in developing the gamified structure proved invaluable, as they provided insights into engagement patterns and challenge calibration that faculty alone might have missed. This participatory design approach, whilst time-intensive, created a learning environment genuinely responsive to student needs and preferences.

The critical importance of platform consistency suggests that educators should carefully evaluate their technical infrastructure before implementing gamification. If multiple platforms are unavoidable, significant effort should be devoted to creating seamless transitions and unified experiences. The cognitive cost of platform switching appears to outweigh the benefits of specialized tools, at least for maintaining engagement with optional content.

Support structures require careful consideration. Our teaching assistant model, with each supervising seven to ten groups, provided sufficient guidance whilst maintaining scalability. However, the role demands specific preparation, as teaching assistants must balance technical support, progress monitoring, and group facilitation. Professional development for these support roles appears essential for successful implementation.

Finally, flexibility in implementation remains crucial. Our flexibility for students to return to traditional tracks, whilst rarely used, provided important psychological safety that may have encouraged initial participation. Building in adaptation mechanisms allows programmes to evolve based on emerging challenges without abandoning students who struggle with the innovative format. This flexibility extends to assessment methods, reward structures, and even narrative elements, all of which benefit from iterative refinement based on systematic feedback collection.

5 Conclusion

This study demonstrates that gamification represents a powerful and transferable pedagogical innovation for technology education across academic disciplines. Through careful design and implementation, gamified learning environments can simultaneously develop technology literacy and essential 21st-century collaborative skills whilst maintaining high engagement and academic rigor.

Our key findings—the critical importance of platform consistency, the effectiveness of narrative-driven technology education, and the synergy between collaborative gameplay and skill development—provide actionable insights for educators. The design principles emerging from our analysis offer a framework for adapting gamification to diverse educational contexts, from teaching GDPR compliance in business programmes to exploring algorithmic bias in social science courses.

As society continues its digital transformation, the need for technology-literate graduates across all disciplines intensifies. Gamification offers a pedagogically sound, empirically supported approach to meeting this challenge. By transforming technology

education from abstract theory to engaging experience, we can prepare students not merely to use technology, but to understand, critique, and shape the digital world they will inherit.

Future implementations should build upon these foundations, exploring how gamification can address emerging challenges in technology education—from artificial intelligence literacy to ethical algorithm design (Legaki et al., 2019). The transferable framework presented here provides a starting point for this vital educational evolution, demonstrating that innovative pedagogical approaches can make technology education both effective and engaging across the academic spectrum.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Sikt - Norwegian Agency for Shared Services in Education and Research. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

OM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. HG: Writing – original draft, Writing – review & editing. YB: Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

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

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The author(s) declare that Gen AI was used in the creation of this manuscript. Proofreading, text editing.

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