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Gamifying mobile-based science education: enhancing self-regulated learning skills in middle school students

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Abstract
Gamification has emerged as a promising educational strategy, offering dynamic solutions to address challenges in fostering self-regulated learning (SRL) skills in middle school students, particularly within the context of science education. These skills, including goal-setting, progress monitoring, and reflective practices, are critical for navigating complex scientific concepts. Despite its potential, gaps remain in understanding how gamified mobile learning impacts key educational outcomes. This study investigates the effects of a gamified mobile-based SRL approach on middle school students' academic achievement, motivation, enjoyment, and engagement in science education. Using an experimental design, 64 students were divided into a gamified mobile-based SRL group and a non-gamified control group. The results demonstrated significantly higher outcomes for the gamified group across all measures, highlighting the approach's effectiveness in enhancing interactive, student-centered learning. This study contributes valuable insights into integrating gamification with mobile technologies to support SRL and improve science education outcomes.

Keywords Gamification · Self-regulated learning · Mobile-based learning · Science education · Academic achievement · Enjoyment · Student engagement · Motivation · Middle school students

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1 Introduction

The cultivation of self-regulated learning (SRL) skills is a cornerstone of effective education, particularly in science. SRL encompasses the ability to set learning goals, monitor progress, and critically reflect on outcomes (Chen et al., 2024; Lin & Chang, 2023). These skills empower students to independently navigate the challenges of understanding complex scientific concepts, engaging in problem-solving, and applying critical thinking (Ateş, 2024). Despite its importance, many students struggle to develop SRL skills due to a lack of motivation, strategic learning techniques, and guidance (Borkowski & Thorpe, 2023; Schunk & Zimmerman, (2023). Without structured interventions, students often experience disengagement, hindering their academic performance and long-term learning outcomes (Jin et al., 2023; Murniati et al., 2023).

In recent years, mobile-based learning has emerged as a promising solution to support SRL (Hsu et al., 2024; Zhao et al., 2024). Mobile platforms provide students with accessible tools for goal-setting, real-time progress tracking, and feedback, facilitating a dynamic and adaptive learning environment (Palalas & Wark, 2020; Chen & Hsu, 2020). These attributes are especially valuable in science education, where learning often involves high cognitive demands (Ateş, 2024). However, traditional mobile-based SRL approaches may lack the engaging and motivational components necessary to sustain long-term interest and active participation in learning.

Gamified mobile-based science education introduces an innovative dimension by integrating game design elements—such as immediate feedback, rewards, competition, and progress tracking—into mobile learning environments (Ateş & Kölemen, 2025). Gamification has shown potential to increase motivation and engagement by transforming learning into a more interactive, enjoyable, and goal-oriented experience (Smiderle et al., 2020; Zeng et al., 2020;). These game-like features not only make learning objectives more attainable but also promote behavioral and emotional engagement, critical for fostering SRL skills (Ho et al., 2022). By motivating students to take ownership of their learning journey, gamification may serve as a bridge between theoretical and practical aspects of SRL (Chen et al., 2024). Gamification's ability to foster SRL lies in its alignment with key SRL processes: goal-setting, performance monitoring, and reflection. Studies have highlighted that game-like elements can encourage students to set meaningful learning goals, track their progress, and engage in reflective practices (Li et al., 2022; Qiao et al., 2022). For example, rewards and leaderboards can provide immediate feedback, reinforcing goal-oriented behaviors, while reflective activities embedded within gamified systems allow students to evaluate their learning strategies critically (Chen et al., 2024).

Despite these promising results, evidence remains mixed regarding the long-term impact of gamified learning environments on SRL development, particularly in science education (Yıldırım & Şen, 2021). Although gamification has been widely applied across various educational contexts, its specific application to middle school science education and its role in fostering SRL remain underexplored. Research by Yıldırım and Şen (2021) demonstrates gamification's potential to boost academic achievement and motivation, yet its influence on deeper cognitive engagement and SRL skills has been inconsistent. For instance, while Chen et al. (2024) report significant SRL improvements through gamified interventions, other studies highlight only marginal or short-term effects. This inconsistency points to a need for research that systematically examines the mechanisms through which gamified mobile-based science education influences SRL behaviors and identifies the contextual factors that contribute to its effectiveness.

Middle school represents a critical period for developing SRL skills, particularly in science education, where students are required to tackle complex topics and engage in higher-order thinking processes. However, traditional teaching methods often fall short of capturing students' interest or making learning relatable, which can lead to disengagement, low motivation, and suboptimal participation in learning activities (Heilporn et al., 2021). Bridging this gap is necessary to equip students with the competencies they need for academic and professional success. By incorporating gamification into mobile-based science education, this study aims to address these challenges by fostering greater motivation, active engagement, and self-regulation among middle school students. Gamified learning environments are designed to make educational experiences more interactive and meaningful, ultimately preparing students for lifelong learning.

To explore this potential, this study examines the effectiveness of a gamified mobile-based SRL approach compared to a traditional mobile-based SRL approach in the context of middle school science education. The gamified approach incorporates elements such as immediate feedback, structured reward systems, and competitive tasks to foster self-regulation and engagement. Specifically, the study focuses on the following research questions:

1. How does the integration of gamified elements in a mobile-based SRL approach affect middle school students' academic achievement and understanding of scientific concepts compared to a conventional mobile-based SRL approach?
2. What differences exist in students' motivation for science learning when using a gamified mobile-based SRL approach versus a traditional mobile-based SRL approach?
3. How does the use of a gamified mobile-based SRL approach impact students' enjoyment of science learning compared to the conventional mobile-based SRL approach?
4. How does the use of a gamified mobile-based SRL approach influence middle school students' engagement in science learning compared to the conventional mobile-based SRL approach?

This study contributes to the growing body of research on gamification by addressing its role in enhancing SRL within middle school science education. By bridging the gap between traditional and gamified learning environments, this research aims to provide evidence-based insights into how gamification can transform science education into a more engaging, effective, and student-centered process.

2 Literature review

2.1 Self-regulated learning in science education

SRL is characterized by an active and intentional process in which students establish learning objectives and work to oversee, adjust, and control their cognitive processes, motivational states, and behaviors in alignment with their goals and the surrounding contextual factors, as described by Pintrich (2000). Similarly, Schunk and Zimmerman (2011) define SRL as the method by which students intentionally engage and maintain their thoughts, emotions, and actions systematically to achieve their learning goals. Zimmerman (2002) further breaks down SRL into three key stages: the forethought phase, the performance phase, and the self-reflection phase. In the forethought phase, students evaluate their learning tasks and set specific goals, alongside planning strategies to meet these goals (Lai & Hwang, 2016). The performance phase focuses on students actively tracking and managing their learning progress (Zimmerman & Moylan, 2009). Lastly, the self-reflection phase requires students to assess how effective their learning has been and evaluate the success of the strategies they employed (Lai & Hwang, 2016).

SRL is increasingly acknowledged as a critical component of effective education, particularly within the domain of science education (Ateş, 2024). In science education, where students are often required to understand intricate concepts, conduct experiments, and engage in critical analysis, SRL skills are especially crucial (Tran et al., 2022). These skills empower students to manage their learning more effectively, facilitating the development of scientific reasoning, problem-solving abilities, and independent inquiry. According to Higgins et al. (2021), applying SRL in science education improves students' capability to tackle scientific problems with a structured and strategic approach. Cengiz-Istanbullu and Sakiz (2022) highlight that setting clear and specific goals allows students to focus their efforts on mastering scientific theories and principles. Monitoring their progress enables students to maintain focus, acknowledge their accomplishments, and pinpoint areas that need further attention or alternative learning strategies, as noted by Higgins et al. (2023). Reflective practices, as discussed by Tran et al. (2022), allow students to critically assess their learning experiences, modify their strategies, and enhance their grasp of scientific concepts. This continuous cycle of goal-setting, monitoring, and reflection, as described by Ateş (2024), fosters stronger engagement with scientific material and cultivates a deeper understanding of the subject matter. Furthermore, SRL contributes to the development of key competencies in science education, such as analytical thinking, logical reasoning, and the ability to conduct rigorous investigations (Taub et al., 2020). As students learn to self-regulate, they become more adept at designing experiments, interpreting data, and drawing evidence-based conclusions. These skills are fundamental to scientific literacy and are essential for students to become successful in their academic pursuits and future scientific endeavors (Connelly, 1973; Hidayat et al., 2024). Moreover, SRL promotes independent learning, encouraging students to take initiative, ask questions, and explore scientific topics beyond the constraints of the classroom environment (Ng et al., 2024; Sletten, 2017). This autonomy is fundamental for fostering a lifelong interest in science and cultivating the ability to adapt to new scientific knowledge and technological advancements.

Empirical studies underscore the critical role of SRL strategies in science education, highlighting their impact on enhancing academic performance, engagement, and motivation (Ateş, 2024). For instance, Lai and Hwang (2016) demonstrated that students utilizing SRL techniques achieve significantly higher academic success due to improved goal-setting and reflective practices. Kumar et al. (2023) further emphasize that SRL fosters critical thinking and problem-solving skills, equipping students to tackle complex scientific challenges. Beyond improving academic outcomes, SRL plays a transformative role in empowering students to become self-directed learners, a necessary skill for fostering independence and adaptability. Self-directed learners are better equipped to manage their learning processes, seek out resources, and apply knowledge in novel contexts—qualities essential for navigating the ever-evolving demands of science education and beyond. By integrating SRL into teaching practices, educators can cultivate students' ability to take ownership of their education, thereby promoting lifelong learning and resilience. This study builds on these theoretical and empirical insights by examining how a gamified mobile-based SRL approach can address the challenges of engagement and motivation in middle school science education. By integrating gamification elements, the research aims to create an interactive learning environment that not only enhances students' ability to self-regulate but also empowers them to become proactive and independent learners, bridging the gap between theoretical frameworks and practical applications in science education.

2.2 Gamification in science education

Gamification, the practice of incorporating game design elements into non-game contexts, has emerged as a powerful strategy for enhancing student engagement and motivation in educational settings (Hellín et al., 2023). In science education, gamification leverages the appeal of game mechanics—such as points, badges, leaderboards, challenges, and instant feedback—to create interactive and dynamic learning environments (Kalogiannakis et al., 2021). These elements are designed to make learning more engaging (Papadakis et al., 2022) and enjoyable (Zourmpakis et al., 2023), encouraging students to actively participate and invest in their educational experiences (Lampropoulos et al., 2023). The application of gamification in science education holds significant promise for improving student outcomes, fostering a deeper understanding of scientific concepts, and promoting a sustained interest in science.

According to Alahmari et al. (2023) and Kalogiannakis et al. (2021), gamification in science education helps address several key challenges faced by educators, including maintaining student engagement with complex and abstract scientific content, motivating persistence through difficult tasks, and encouraging collaborative learning. Jones et al. (2023) suggest that incorporating elements of competition, rewards, and recognition can enhance students' motivation, making them more inclined to invest time and effort into their studies. For example, as Kalogiannakis et al. (2021) note, the opportunity to earn points for completing assignments, unlock badges for mastering specific topics, or progress on a leaderboard can create a sense of achievement and advancement, which boosts students' confidence and increases their willingness to tackle challenging material.

Moreover, gamification supports the development of critical thinking and problem-solving skills, which are essential in science education (Alahmari et al., 2023; Morris et al., 2013). Science often involves inquiry-based learning, where students must hypothesize, experiment, analyze data, and draw conclusions. Gamified activities can mirror these scientific processes by encouraging exploration, experimentation, and iterative learning (Fleischman & Ariel, 2016). For instance, digital simulations (Pirker & Gütl, 2015) and virtual labs (Alptekin, & Temmen, 2020) that use game mechanics allow students to conduct experiments in a risk-free environment, test hypotheses, and receive immediate feedback on their actions. This hands-on, interactive approach not only reinforces theoretical knowledge but also helps students develop practical skills and scientific reasoning.

In addition to individual engagement, gamification fosters collaboration (Kalogiannakis et al., 2021; Khattib & Alt, 2024) and social interaction among students. Many gamified learning platforms incorporate multiplayer features (Tavakkoli et al., 2014), team-based challenges (An, 2021), and collaborative problem-solving tasks (Stoeffler et al., 2020). These elements encourage peer learning, communication, and cooperation, which are fundamental for building a supportive learning community. Collaborative gamified activities can lead to deeper discussions, shared learning experiences, and collective problem-solving, which enhance students' understanding of scientific concepts and improve their ability to work effectively in groups.

According to research, gamification positively influences students' attitudes towards science, as observed by Yildirim (2017), enhances their engagement levels (Alsawaier, 2018), and improves academic performance (Kaya & Ercag, 2023; Yıldırım & Şen, 2021). These studies suggest that when students perceive the learning process as enjoyable and rewarding, they are more inclined to engage actively, retain information for longer periods, and show a heightened interest in pursuing science-related careers. However, the success of gamification largely depends on its thoughtful design and implementation. It is essential for educators to carefully choose game elements that are directly aligned with educational objectives, offer meaningful and constructive feedback, and minimize dependence on extrinsic rewards, which could potentially undermine motivation over time (Kalogiannakis et al., 2021). By focusing on these aspects, educators can harness the full potential of gamification to create a more engaging and effective learning environment.

2.3 Gamified approaches to supporting Self-Regulated learning

The integration of gamification with SRL is grounded in their complementary functions. SRL, as conceptualized by Zimmerman (2002), comprises a cyclical model of forethought, performance, and self-reflection—each of which can be effectively supported through specific gamified features. Gamification enhances SRL by providing motivational scaffolds and structural cues that guide students through these phases, especially within mobile and digital learning environments.

In the forethought phase, learners are required to set specific learning goals and plan their approach. Game elements such as digital goal-setting interfaces, confidence self-assessments, and progress-based incentives (e.g., digital badges or unlocking levels) help students develop clear intentions and promote commitment to learning objectives (Chen et al., 2024; Maimaiti & Hew, 2025). By embedding goal-directed tasks in a game-like context, students are more likely to internalize their goals and initiate learning with purpose.

In the performance phase, students must monitor their engagement, apply strategies, and stay motivated. Gamified systems support this phase by providing real-time feedback, progress bars, point-based systems, and in-app rewards that allow students to track their learning and performance continuously (Qiao et al., 2022). These elements increase task persistence and metacognitive awareness, enabling learners to evaluate their approach in the moment and adjust strategies when needed. Furthermore, time-on-task data and immediate performance analytics provide transparent indicators of effort and progress, reinforcing the self-monitoring process.

In the self-reflection phase, gamification encourages evaluative thinking through performance dashboards, achievement summaries, and leaderboards. These elements prompt learners to reflect on both outcomes and behaviors. For instance, students can compare their performance to prior sessions or peer benchmarks, which encourages self-evaluation and goal revision—key elements of reflective learning. Research suggests that visualized performance feedback fosters deeper reflection and accountability, particularly in collaborative and competitive learning environments (Zimmerman & Moylan, 2009; Fleischman & Ariel, 2016).

Moreover, the motivational affordances of gamification—such as autonomy, competence, and relatedness—align well with SRL's emphasis on fostering learner agency and sustained effort (Deci & Ryan, 1985; Li et al., 2022). While SRL equips students with the cognitive and metacognitive skills for regulating their learning, gamification enhances the motivational and emotional climate necessary to activate and maintain these skills in real time. This synergy is particularly beneficial in science education, where complex content and high cognitive demands often require structured support and sustained engagement (Kaya & Ercag, 2023; Tran et al., 2022).

Several empirical studies support this integration. For example, Chen et al. (2024) demonstrated that a gamified mobile SRL framework significantly improved students' goal-setting, reflective performance, and science achievement. Similarly, Ateş and Polat (2025) found that gamified SRL environments enhanced students' engagement in inquiry-based science learning. These findings underscore the value of gamification not only as an engagement tool but as a structural enhancement of the SRL process itself (Ferreira et al., 2024).

3 A gamified mobile approach to Self-Regulated learning in science education

This study adapts and extends the gamified mobile SRL approach outlined by Chen et al. (2024) to enhance middle school science education, specifically focusing on environmental topics such as climate change, resource conservation, and sustainable development (See Table 1). The original framework successfully integrated gamification elements into mobile-based SRL activities, demonstrating significant improve-

Table 1 Learning flow of the gamified mobile self-regulated learning in science education

Phase	Learning Activity	SRL Stage	Gamification Component
1	Students analyze their weekly science tasks (e.g., problem sets, reading assignments, higher-level questions)	Fore-thought Stage	Gamified rules (points for task analysis and goal-setting)
2	Students set specific weekly science learning goals using a digital goal-setting sheet on mobile devices	Fore-thought Stage	Goal-setting with digital badges and confidence self-assessment
3	Students complete science homework, conduct experiments, and take quizzes using the "Idle Carbon City" app	Perfor-mance Stage	Immediate feedback and rewards (e.g., points, badges) for task completion
4	Students record their daily progress, learning strategies, and any distractions in a digital monitoring sheet	Perfor-mance Stage	Daily progress tracking with points system for consistency and engagement
5	Students participate in interactive science activities, such as constructing biomass facilities in the app	Perfor-mance Stage	Real-time feedback from teachers, peer competition, and team-based challenges
6	Students reflect on their weekly learning experiences and outcomes using digital reflection sheets	Self-Re-flection Stage	Display of a gamified dashboard (e.g., progress, behavior, ranking) in the classroom
7	Students evaluate their learning strategies and set goals for improvement based on feedback and self-reflection	Self-Re-flection Stage	Competitive elements (class leaderboards, public recognition for achievements)

ments in students' goal-setting, reflection performance, and academic outcomes. By leveraging game mechanics such as immediate feedback, rewards, and competitive tasks, the gamified mobile SRL approach provides a structured environment that supports students in setting learning goals, monitoring their progress, and reflecting on their achievements.

This study further develops these principles by incorporating the "Idle of Carbon City" app, a gamified platform designed to engage students in interactive environmental science tasks. This app is central to the experimental group's learning process, where it helps facilitate self-regulated learning by embedding game-like elements—points, badges, and leaderboards—within a science curriculum that mirrors the Turkish Ministry of National Education's 8th-grade science framework. The app focuses on tasks such as constructing and upgrading virtual biomass facilities, enhancing energy efficiency, and addressing environmental sustainability. These tasks, designed to mimic real-world environmental challenges, allow students to apply theoretical knowledge in a practical, gamified setting.

The gamified mobile SRL science learning approach is structured around the three core SRL stages outlined by Chen et al. (2024): the forethought stage, the performance stage, and the self-reflection stage. In the forethought stage, students are introduced to weekly learning tasks that align with their science curriculum, including activities such as analyzing environmental problems, completing problem sets, reviewing content, and setting learning objectives. Students use the app to establish specific learning goals and self-assess their confidence levels. Gamified rules provide a framework for earning points and rewards based on their performance, fostering motivation and accountability.

During the performance stage, students engage in completing quizzes, simulations, and virtual science experiments within the app. These tasks require them to construct and manage environmental solutions, such as reducing carbon emissions and optimizing energy usage in the virtual world. Students use the app to record their daily progress on monitoring sheets, which track various aspects of their learning, such as time spent on tasks, strategies employed, and any distractions encountered. Teachers review these monitoring sheets daily and provide immediate feedback, adjusting students' gamified scores based on their performance and behavior. This real-time feedback loop helps students stay focused, encourages persistence, and promotes effective learning strategies in an engaging, interactive environment.

Finally, the self-reflection stage involves students reviewing their progress and reflecting on their learning experiences using reflection sheets in the app. A gamified dashboard, visible both in the classroom and within the app, displays students' progress, positive and negative behaviors, and their overall ranking compared to their peers. This visual representation encourages students to critically reflect on their learning strategies, recognize areas for improvement, and make adjustments for future learning. Competitive elements, such as class leaderboards and public recognition for achievements, motivate students to improve their self-regulation and continuously engage with the learning process.

By incorporating the app and gamified mobile SRL approach into science education, this study aims to provide a robust framework that not only enhances students' engagement and motivation but also improves their ability to self-regulate their learning effectively. This approach is particularly suited for the complexities of science education, where continuous practice, critical thinking, and adaptive learning strategies are essential. The strategic use of gamification in this context aims to support SRL in science classrooms, ultimately leading to better educational outcomes and a deeper understanding of scientific principles.

4 Method

4.1 Research design

This study employed an experimental design with a pre-test/post-test control group framework, in which participants were randomly assigned to groups after being stratified based on their digital literacy levels. The objective was to compare the conceptual understanding of middle school students taught using a gamified mobile-based SRL approach to those taught using a traditional mobile-based SRL approach without gamification.

In the experimental group, students engaged with the gamified mobile-based SRL approach, which incorporated game-based elements into their learning activities. This method was intended to enhance self-regulation by encouraging students to set personal learning goals, monitor their progress, and reflect on their achievements, all facilitated through mobile devices. The gamification aspect aimed to create a more interactive and engaging learning environment, thereby improving motivation, engagement, and academic performance in science education.

In contrast, the control group followed a traditional mobile-based SRL approach, which involved similar self-regulated learning activities—such as goal setting, progress monitoring, and reflection—without the inclusion of gamified elements or additional mobile-based tools. This standard SRL method provided a structured framework for learning but lacked the interactive and motivational features characteristic of the gamified approach.

By implementing this experimental design, the study sought to determine the impact of the gamified mobile-based SRL approach on students' conceptual understanding of science topics compared to the traditional mobile-based SRL method. The pre-test/post-test framework enabled the assessment of changes in students' knowledge before and after the intervention, offering valuable insights into how gamification can enhance the effectiveness of self-regulated learning strategies. The findings are expected to contribute to the development of evidence-based educational practices aimed at improving student engagement and learning outcomes in science education.

4.2 Study context

This study was conducted within the framework of the 8th-grade science curriculum, specifically focusing on the units related to "Matter Cycles, Environmental Issues, and Sustainable Development," as outlined by the Turkish Ministry of National Education in 2018. These units were chosen because they play a critical role in developing students' understanding of key environmental concepts and their ability to propose practical solutions to real-world challenges. The curriculum aims to foster critical thinking and awareness of environmental sustainability, equipping students with the knowledge and skills necessary to address pressing environmental issues.

The learning activities were designed to engage students deeply with topics such as global climate change, resource conservation, and the principles of sustainable development. By addressing these themes, the curriculum seeks to cultivate a sense of responsibility among students towards the environment. A significant focus is placed on exploring the causes and consequences of global climate change. Students start by learning about fundamental concepts such as the greenhouse effect, which serves as a foundation for understanding broader environmental implications. This foundational knowledge is expanded through discussions that encourage students to contemplate the potential impact of climate change on both the Earth's future and human life.

To enhance their critical thinking and creativity, students are encouraged to express their ideas and predictions about environmental changes through artistic projects. These activities not only help students connect scientific concepts with their creative expression but also promote a deeper engagement with the subject matter. Personal responsibility is another key theme, with activities such as calculating individual ecological footprints using reliable online tools. This task allows students to reflect on their environmental impact and consider how their daily choices contribute to sustainability.

The curriculum also emphasizes global efforts to address climate change, including discussions about international agreements like the Kyoto Protocol. This helps students understand the collective nature of environmental action and the importance of global cooperation. In addition to these global perspectives, the curriculum promotes practical, local solutions for resource conservation. Students are encouraged to design projects that focus on the efficient use of resources, waste reduction, and recycling. By examining the economic and environmental benefits of recycling, students gain insight into how sustainable practices can positively impact both the environment and the economy.

4.3 Sample

The research was conducted at a co-educational middle school in a mid-sized city in Turkey, serving a diverse student population within an urban context. The school is equipped with modern technological resources, including advanced computer labs and classrooms with interactive smartboards, enhancing the educational environment and facilitating innovative teaching methods. A total of 64 eighth-grade students enrolled in science courses participated in this study, ranging in age from 13 to 14 years. The gender distribution was relatively balanced, with 35 males and 29 females. The participants displayed a range of academic performance levels: approximately 25% were classified as high achievers, 55% as average performers, and the remaining 20% as needing academic improvement based on their most recent science assessments.

A preliminary assessment was conducted to gauge students' technological proficiency and access. The results indicated that 95% of the students had regular access to the internet and digital devices at home, demonstrating basic familiarity with technology for educational purposes. The remaining 5% had limited access, indicating some variability in digital literacy skills.

Before assigning participants to groups, an evaluation was conducted to determine each student's level of digital literacy and access to technology. This evaluation ensured that none of the students had prior experience with gamified mobile self-regulated learning tools in their science education, making the intervention a novel experience for all participants. This step was crucial for establishing a baseline of digital proficiency and ensuring comparability between the experimental and control groups.

Following this assessment, participants were assigned to groups using a stratified random assignment process (Creswell & Creswell, 2018). Students were first categorized based on their digital literacy scores. Within each of these stratified groups, participants were randomly assigned to either the experimental group or the control group. This method ensured that both groups had similar distributions of digital literacy, controlling for potential confounding variables related to technology use. The stratified random assignment aimed to enhance the internal validity of the study, ensuring that observed differences in outcomes could be attributed more confidently to the gamified mobile SRL approach rather than differences in digital proficiency.

The study was structured around two distinct groups: an experimental group and a control group, each consisting of 32 students. The experimental group engaged in a gamified mobile-based SRL approach to science education, which integrated game-based elements such as immediate feedback, rewards, and competitive tasks to support and enhance self-regulated learning. These students participated in interactive and individualized activities facilitated by mobile devices as part of their science curriculum.

In contrast, the control group participated in a traditional mobile-based SRL approach without gamification or additional game-like elements. Their instruction focused on self-regulated learning methods, including goal setting, progress monitoring, and reflection, but lacked the interactive and competitive features of the gamified approach. This distinction between the groups allowed for a clear comparative analysis of the impact of gamified learning strategies on students' conceptual understanding, motivation, and engagement in science education.

4.4 Experimental procedure

The experimental procedure spanned eight weeks, aiming to assess the impact of a gamified mobile-based SRL approach on middle school students' conceptual understanding, motivation, enjoyment, and engagement within the context of science education. The experimental group utilized the *Idle Carbon City* app, a gamified mobile platform designed to enhance self-regulated learning through interactive environmental science tasks. In contrast, the control group followed a non-gamified mobile-based SRL approach that maintained the same curriculum content, structure, and duration but excluded game elements such as points, badges, leaderboards, and real-time feedback. Instead, students in the control group engaged in SRL strategies such as goal-setting, self-monitoring, and reflection using a digital interface or paper-based worksheets, with teacher-delivered feedback provided at regular intervals. Both groups studied the same science topics—climate change, resource conservation, and sustainable development—aligned with the Turkish Ministry of National Education's 8th-grade science framework. Figure 1 presents the flow chart of the experimental procedure, detailing the sequence of activities for both the gamified experimental group and the non-gamified control group, from the introduction of the SRL systems to the pre-test/post-test assessments and ongoing monitoring throughout the eight-week study.

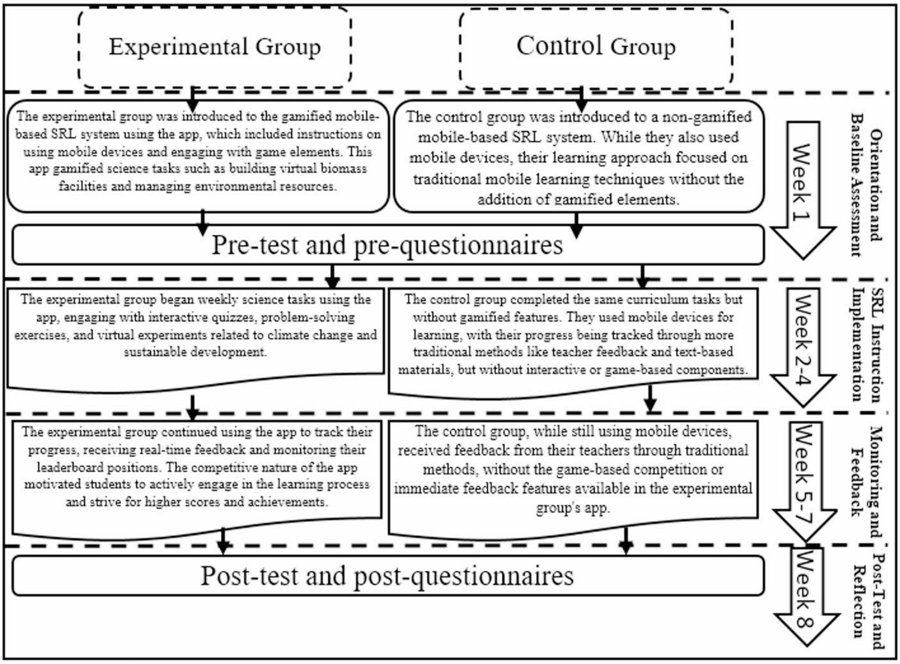

Fig. 1 Study timeline illustrating the experimental procedure for both the gamified mobile-based SRL group and the non-gamified mobile-based SRL control group

Week 1: Orientation and baseline assessment During the first week, students from both groups were oriented to the study's objectives and the learning tools they would use. The experimental group was introduced to the gamified mobile SRL system, receiving instructions on navigating the mobile app, which included features such as goal setting, progress tracking, immediate feedback, and gamification elements like points, badges, and leaderboards. Meanwhile, the control group received training on a non-gamified SRL approach, which also involved goal setting and monitoring but lacked gamified elements. Baseline assessments were administered to measure students' initial conceptual understanding of environmental science topics, as well as their motivation and engagement. Digital literacy and access to technology were also evaluated to ensure both groups started from a comparable level. To address the potential influence of the novelty effect, the experimental group underwent a structured familiarization period during this first week. Students explored the full range of app features without performance expectations or competitive scoring. This approach allowed students to become comfortable with the gamified interface before the intervention officially began. In addition, student engagement and motivation were monitored throughout the eight-week study through weekly reflection sheets and teacher observations. No notable decline in engagement was observed over time, suggesting that the motivational gains were not solely driven by the novelty of the app, but rather by its integration with self-regulated learning principles.

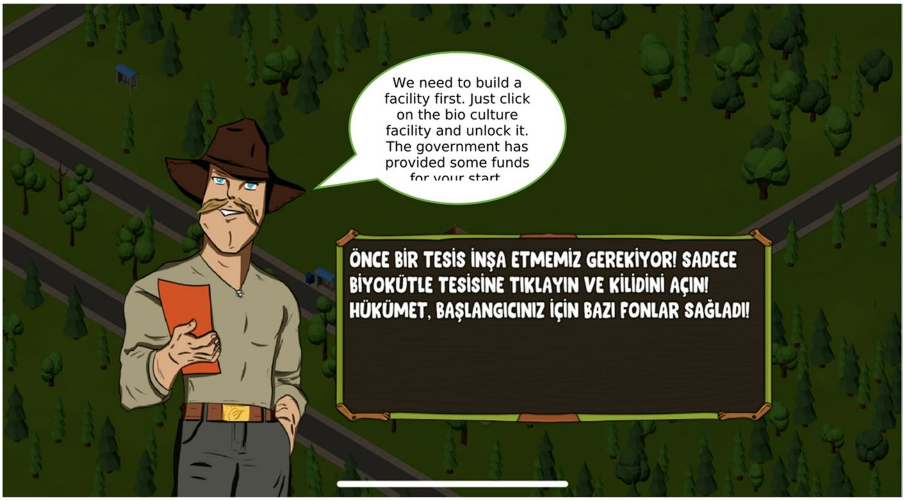

Fig. 2 Screenshot of the gamified mobile-based interface introducing the construction of a biomass facility

Fig. 3 Image showing the initiation of the biomass facility construction by selecting a specific location

Week 2: Introduction to gamified SRL and task initiation The experimental group began using the mobile app to engage with environmental science topics, such as constructing and managing virtual biomass facilities (see Figs. 2 and 3). They were introduced to weekly science tasks that included interactive quizzes, problem-solving activities, and virtual experiments. As part of the gamified environment, students earned points and badges for completing tasks efficiently and received instant feedback through the app. Leaderboards displayed individual progress and rankings, fostering a sense of competition and sustained engagement throughout the study. Students in the experimental group primarily used the app individually, although they occasionally engaged in peer discussions during classroom reflections and leaderboard reviews. App activities were accessed both during classroom sessions (2–3 times per week, approximately 40 min per session) and at home as part of weekly assignments. The app's features—such as goal-setting dashboards, progress monitoring tools, and interactive simulations—were designed to support all three phases of self-regulated learning (SRL): forethought, performance, and self-reflection. Teachers monitored app usage via in-app analytics and weekly progress checks to ensure consistent engagement and learning alignment. In contrast, the control group followed a non-gamified mobile-based SRL approach. While the structure and content of weekly tasks were equivalent to the experimental group, the control platform excluded gamified features. Students completed goal-setting and reflection activities using either digital forms or paper-based materials. Feedback for this group was delivered at regular intervals through teacher-led verbal or written comments, rather than being embedded in the system itself.

Weeks 3–4: Immersive learning and science challenges Both groups engaged with science topics related to climate change, sustainable development, and resource conservation. The experimental group, guided by their mobile app, participated in virtual science experiments that simulated real-world challenges, such as reducing carbon emissions and increasing energy efficiency through facility upgrades (see Figs. 4 and 5). These activities were designed to integrate theoretical knowledge with practical application, encouraging students to critically think about environmental sustainability. Points were awarded for successful task completion, and students could compare their progress on the leaderboard, driving motivation. The control group followed a similar curriculum using traditional methods, including classroom discussions and paper-based activities, with feedback provided at regular intervals by the teacher.

Weeks 5–6: Ongoing monitoring, feedback, and reflection During weeks 5 and 6, both groups continued their learning activities. The experimental group tracked their daily progress through the mobile app, with students receiving real-time feedback and monitoring their leaderboard positions. This gamified approach fostered a contin-

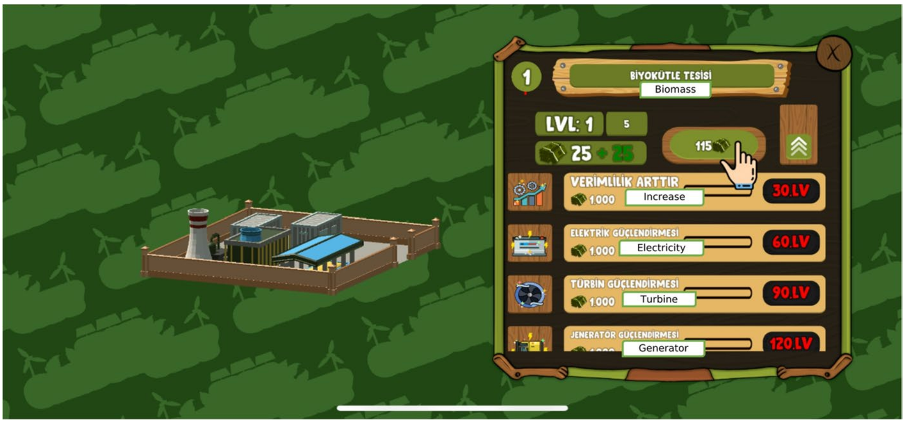

Fig. 4 The interface displaying upgrades for the biomass facility, including options to enhance efficiency, electricity, and turbines

Fig. 5 A congratulatory message after successfully constructing the biomass facility, encouraging further upgrades

uous cycle of goal-setting, task completion, and reflection, keeping students actively engaged. Teachers also provided guidance and support through the app. The control group continued to engage in the science curriculum, but without the competitive or instant feedback elements. Feedback was provided in traditional classroom formats, and students completed reflection activities on paper, assessing their progress and identifying areas for improvement.

Week 7: Mid-point evaluation and advanced tasks In the seventh week, students in the experimental group completed digital reflection sheets, allowing them to assess their learning strategies and adjust their goals for the remaining week. Peer discussions took place within the app, where students could see leaderboard rankings and discuss their achievements. The reflection activities were aimed at fostering deeper self-regulation and critical thinking about environmental science. The control group conducted similar reflection activities using traditional methods, with teacher-led discussions focusing on their understanding of the content. Both groups were encouraged to propose innovative solutions to environmental issues, such as designing energy-efficient systems or reducing ecological footprints.

Week 8: Final assessment and debriefing In the final week, both groups underwent post-test assessments to measure changes in their conceptual understanding, motivation, and engagement in environmental science. The experimental group also completed a survey assessing their experience with the gamified mobile SRL approach, focusing on how it influenced their learning and engagement. Students shared insights on how the gamification elements, such as instant feedback and leaderboards, affected their motivation and enjoyment throughout the study. A debriefing session was conducted for both groups, allowing teachers to provide feedback and for students to reflect on their learning journey, discussing the strategies they found most effective or challenging. This session provided valuable qualitative data, highlighting the differences between the gamified and non-gamified approaches.

4.5 Data collection tools

To measure the impact of the gamified mobile based SRL approach on various student outcomes, this study employed multiple data collection instruments. These tools were used to assess academic achievement, motivation, enjoyment, and engagement in science education. Each tool was selected for its relevance to the study's objectives and was validated to ensure reliability and accuracy.

4.5.1 Academic achievement test

The Academic Achievement Test used in this study was specifically developed to assess students' conceptual understanding of the science topics addressed during the intervention, with a focus on climate change, resource conservation, and sustainable development—key themes aligned with the Turkish Ministry of National Education's 8th-grade science curriculum. The test comprised 25 multiple-choice items, each with one correct answer and three distractors, designed to assess a range of cognitive skills, including recall, comprehension, application, and reasoning. Each correct answer was awarded four points, resulting in a total possible score of 100. The test was administered as both a pre-test and a post-test to evaluate students' learning gains.

To ensure content validity, the test items were reviewed by a panel of three experienced science educators, each with over ten years of experience in curriculum development and assessment. The reviewers evaluated the items for clarity, alignment with curriculum standards, cognitive level (based on Bloom's taxonomy), and relevance to the study objectives. The Content Validity Index (CVI) was calculated at 0.92, indicating a high level of agreement among experts. Based on their feedback, five items were revised to enhance clarity and precision.

Item analysis was conducted using pre-test data obtained from 64 students. Two psychometric properties were calculated for each item: the item difficulty index (p-value) and the item discrimination index (D-value). The p-values, indicating the proportion of students answering correctly, ranged from 0.34 to 0.78, with a mean of 0.56—suggesting that the items were of moderate difficulty and appropriate for middle school students. The D-values, reflecting each item's ability to differentiate between high- and low-performing students, ranged from 0.28 to 0.62, with a mean of 0.44. Based on these results, three items with D-values below 0.30 were revised, and one item was replaced due to poor discrimination. This process ensured that all items effectively discriminated between differing levels of student performance.

To examine construct validity, exploratory factor analysis (EFA) was performed on the pre-test responses. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.81, and Bartlett's Test of Sphericity was significant ($\chi^2(300) = 972.45$, $p < .001$), indicating that the data were suitable for factor analysis. The EFA revealed a three-factor solution—conceptual knowledge, application, and reasoning—that accounted for 64.2% of the total variance. These findings support the alignment between the test structure and its intended learning constructs.

Internal consistency reliability was assessed using Cronbach's alpha, which yielded a value of 0.86, indicating a high level of reliability. Additionally, a split-half reliability analysis was conducted, yielding a Spearman-Brown corrected coefficient of 0.82, further confirming the internal consistency of the instrument.

In summary, the Science Achievement Test demonstrated strong content validity, effective item functioning, solid construct validity, and high internal reliability, establishing it as a robust and valid instrument for measuring academic performance in the context of both gamified and non-gamified science education.

4.5.2 Motivation scale

To evaluate students' motivation towards science learning, the Science Motivation Scale was adapted. This scale originally developed by Glynn and Koballa (2006), consists of 30 items measuring various dimensions of motivation including intrinsic motivation, extrinsic motivation, self-determination, self-efficacy, and anxiety about science learning. Each item was rated on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Sample items include "*I enjoy learning science even when it is challenging*" and "*Doing well in science is important to me.*" The scale was administered as part of both the pre-test and post-test phases. The overall Cronbach's alpha for the motivation scale in this study was calculated to be 0.87, suggesting strong reliability.

4.5.3 Science learning enjoyment scale

The Science Learning Enjoyment Scale used in this study was adapted from the work of Lu et al. (2023), originally developed from PISA questionnaires aimed at assessing students' enjoyment of science learning. The adaptation was tailored to fit the context of this research while retaining the essential elements designed to measure the extent to which students enjoy learning science. This scale consists of five core items that gauge students' positive attitudes toward science. Participants were asked to respond to statements such as how much fun they have while studying science, their interest in reading about science topics, and the happiness they feel when acquiring new science-related knowledge. Each item was rated on a 4-point Likert scale, ranging from 1 (strongly disagree) to 4 (strongly agree), allowing researchers to quantify the students' level of enjoyment. By summing the scores across all items, a composite score was generated, with possible totals ranging from 5 to 20. Higher scores reflected greater enjoyment of science learning. The internal consistency of the scale in this study was found to be strong, with a Cronbach's alpha value of 0.91, indicating high reliability.

4.5.4 Student engagement scale

This study utilized a Student Engagement Scale adapted from Wang et al. (2016) to assess how students interacted with science learning activities. The scale consisted of 33 items, including 17 positively worded and 16 negatively worded questions, all measured on a 5-point Likert scale ranging from 1 ("strongly disagree") to 5 ("strongly agree"). The scale was designed to evaluate four dimensions of engagement: behavioral, emotional, cognitive, and social.

Behavioral engagement refers to the participation in academic and class-related activities, demonstrating effort, persistence, and positive conduct while avoiding disruptive behaviors. An example item for this dimension is, "*I put effort into learning science.*". Emotional engagement measures the presence of both positive and negative emotional reactions towards teachers, peers, and classroom activities, as well as students' interest in learning and their valuation of the learning content. An example item is, "*I feel excited when I learn something new in science.*". Cognitive engagement involves the use of deep learning strategies, self-regulated learning, and cognitive strategies to understand complex ideas and solve problems. A sample item from this dimension is, "*I think about different ways to solve a problem.*". Social engagement assesses the quality of social interactions with peers and adults and the willingness to form and maintain relationships while engaging in learning activities. An illustrative item for this dimension is, "*I try to help others who are struggling in science.*".

The scale was administered both before and after the intervention to measure changes in engagement levels across these dimensions. The reliability coefficients (Cronbach's alpha) for the behavioral, emotional, cognitive, and social engagement subscales were found to be 0.82, 0.88, 0.91, and 0.84, respectively, indicating strong internal consistency.

These carefully selected and validated instruments provided a comprehensive assessment of the impact of the gamified mobile-based SRL approach on student learning outcomes, including academic achievement, motivation, enjoyment, and engagement, ensuring robust data to evaluate the effectiveness of the educational intervention.

4.6 Data analysis

The data collected in this study were analyzed using the Statistical Package for the Social Sciences (SPSS), Version 25. The primary objective of the analysis was to assess the impact of the gamified mobile-based SRL approach on middle school students' academic achievement, motivation, enjoyment, and engagement in science education.

To compare the conceptual understanding of students in the experimental group (who used the gamified mobile-based SRL approach) with those in the control group (who used the conventional mobile-based SRL approach without gamification), a one-way Analysis of Covariance (ANCOVA) was employed. Pre-test scores were used as covariates to control for initial differences between groups. This method allowed for a more accurate assessment of the post-test results while accounting for any pre-existing disparities. A second ANCOVA was conducted to analyze post-test scores using mid-test scores as covariates to assess whether the gamified approach had a cumulative effect over time. The level of significance was set at $p < .05$, and effect sizes and 95% confidence intervals were also calculated to determine the practical significance of any observed differences between the groups.

Additionally, student progress was monitored through weekly goal-setting, monitoring, and reflection sheets. Descriptive statistics were used to analyze changes in students' SRL attitudinal factors over time. The goal-setting and reflection data were reviewed by two experienced science teachers who categorized the quality of student responses (e.g., goal clarity, reflection depth) into three levels: excellent, average, and below average. This categorization helped to track qualitative improvements in SRL behaviors within and between groups throughout the study.

To evaluate overall improvements in SRL, motivation, and engagement, repeated measures analyses were conducted to track changes over the eight-week period. These analyses provided insights into the progression of SRL development and whether the gamified mobile-based SRL approach led to significant improvements compared to the conventional method.

Prior to conducting the ANCOVA, preliminary checks were carried out to ensure the validity and reliability of the data. Cronbach's alpha was calculated for all scales (pre-test, mid-test, and post-test) to assess internal consistency. Levene's Test of Equality of Error Variances was used to ensure that the assumption of homogeneity of variance was met for the ANCOVA analysis. This comprehensive data analysis framework provided robust insights into the effectiveness of the gamified mobile-based SRL approach in improving academic achievement, motivation, enjoyment, and engagement in science education.

4.7 Ethical considerations

This study was conducted in full compliance with ethical standards for research involving human participants. The study was conducted in accordance with the ethical guidelines of Kırşehir Ahi Evran University's Institutional Review Board, which granted approval for the research (Approval No. 2023−122/15). Prior to data collection, informed consent was obtained from all participants and their legal guardians, emphasizing the voluntary nature of participation. The study upheld the principles of confidentiality and anonymity, and participants were informed of their right to withdraw at any stage without any consequences.

5 Findings

This section of the manuscript delineates the outcomes of the research, which aimed to evaluate the effects of a gamified mobile-based SRL approach on various educational metrics within the realm of science education. Specifically, the study examined changes in students' academic achievement, motivation, enjoyment, and engagement. To ascertain these impacts, both pre-test and post-test measurements were systematically conducted across the experimental and control groups. Analytical techniques, notably the ANCOVA, were utilized to adjust for any initial discrepancies between the groups, ensuring that the observed differences post-intervention were attributable solely to the gamified learning approach.

5.1 Pre-intervention analysis: establishing the starting point for science learning, engagement, and motivation

To accurately measure the impact of the gamified mobile-based SRL approach, it was critical to establish a well-defined baseline for comparison. Prior to the implementation of the intervention, a comprehensive pre-test was administered to both the experimental and control groups. The purpose of this pre-test was to assess and document the initial levels of academic achievement, motivation, enjoyment, and engagement among the students, ensuring that any subsequent findings could be attributed to the intervention itself.

The analysis of the pre-test scores was meticulous, confirming that both groups started from a similar baseline, which is crucial for the validity of the study. As indicated in Table 2, the pre-test results showed no significant differences in the key dimensions of learning and engagement between the experimental and control groups. The experimental group recorded a mean academic achievement score of 58.5 ($SD=8.7$), while the control group had a slightly higher score of 59.1 ($SD=8.9$). Similarly, the motivation scores were comparable, with the experimental group at 3.15 ($SD=1.45$) and the control group at 3.10 ($SD=1.47$). In terms of enjoyment and engagement, both groups scored closely, with the experimental group's enjoyment at 3.95 ($SD=1.12$) and engagement at 3.75 ($SD=1.30$), versus the control group's enjoyment at 4.01 ($SD=1.08$) and engagement at 3.80 ($SD=1.28$).

The statistical analysis confirmed the absence of significant differences in initial academic achievement ($t=0.213$, $p>.05$), motivation ($t=0.165$, $p>.05$), enjoyment ($t=0.348$, $p>.05$), and engagement ($t=0.242$, $p>.05$) between the groups. This equivalence at the outset provides a robust foundation for the subsequent evaluation of the gamified SRL approach, ensuring that any observed differences in the post-test outcomes can be reliably attributed to the intervention rather than pre-existing disparities between the groups.

5.2 Analyzing the role of gamified SRL in enhancing science learning performance

The effectiveness of the gamified mobile-based SRL approach in improving students' academic achievement was rigorously assessed using ANCOVA, with pre-test scores included as covariates to statistically control for initial group differences. The

Table 2 Pre-test mean scores and standard deviations for academic achievement, motivation, enjoyment, and engagement

Variable	Group	Pre-Test Mean (SD)
Academic Achievement	Experimental	58.5 (8.7)
	Control	59.1 (8.9)
Motivation	Experimental	3.15 (1.45)
	Control	3.10 (1.47)
Enjoyment	Experimental	3.95 (1.12)
	Control	4.01 (1.08)
Engagement	Experimental	3.75 (1.30)
	Control	3.80 (1.28)

assumption of homogeneity of variances, a prerequisite for ANCOVA, was tested and confirmed using Levene's Test, supporting the appropriateness of the model.

The ANCOVA results demonstrated a clear advantage for the experimental group, which engaged with the gamified mobile-based SRL methodology, over the control group that followed a traditional mobile-based SRL approach without gamification. After adjusting for pre-test academic performance, the estimated marginal mean score for the experimental group was $M=83.9$ ($SE=1.1$), while the control group had an adjusted mean of $M=71.6$ ($SE=1.2$). This difference was statistically significant, $F(1, 61)=15.32$, $p<.001$, with a partial eta squared (η^2) of 0.06, representing a moderate effect size Table 3.

This significant improvement in adjusted academic scores underscores the positive impact of the gamified SRL approach on science learning outcomes. The gamification elements not only maintained student interest and engagement but also enhanced their understanding and retention of complex scientific concepts. These findings support the hypothesis that embedding gamified features within SRL frameworks contributes to a more interactive and motivating learning environment, ultimately promoting improved academic performance in middle school science education.

5.3 Motivational gains: the influence of gamified SRL on science learners

To explore how gamified SRL influences various facets of student motivation, separate ANCOVA analyses were conducted for each sub-dimension of the Science Motivation Scale: intrinsic motivation, extrinsic motivation, self-determination, self-efficacy, and science anxiety. Pre-test scores for each subscale were included as covariates to control for baseline differences between the experimental and control groups. The results indicate that students in the gamified SRL group demonstrated significantly higher motivation across four of the five sub-dimensions, as detailed below.

Students in the experimental group reported higher levels of intrinsic motivation—engaging in science for personal interest and satisfaction—compared to the control group. After adjusting for pre-test differences, the estimated marginal mean for the experimental group was $M=4.62$ ($SE=0.11$), while the control group's adjusted mean was $M=4.18$ ($SE=0.10$). This difference was statistically significant, $F(1, 61)=9.24$, $p=.003$, $\eta^2 = 0.07$, indicating a moderate effect size.

The experimental group also demonstrated significantly greater extrinsic motivation—valuing external rewards such as grades and recognition. The adjusted post-test mean was $M=4.48$ ($SE=0.12$) for the experimental group and $M=4.11$ ($SE=0.11$) for the control group, with the difference reaching statistical significance, $F(1, 61)=7.68$, $p=.007$, $\eta^2 = 0.06$.

Regarding self-determination, which reflects a student's sense of autonomy in learning, the experimental group achieved a significantly higher adjusted mean

Table 3 Adjusted post-test scores for academic achievement (ANCOVA Results)

Group	Adjusted Post-Test Mean (SE)	F	*p*-value	η^2
Experimental	83.9 (1.1)	15.32	<0.001	0.06
Control	71.6 (1.2)			

(M=4.50, SE=0.10) compared to the control group (M=4.06, SE=0.11), $F(1, 61)=10.11$, p=.002, $\eta^2 = 0.08$. These results suggest that gamified learning environments foster a stronger internal drive to learn independently.

Self-efficacy, or students' beliefs in their ability to succeed in science tasks, was also significantly higher in the gamified group. The adjusted mean score was M=4.58 (SE=0.09) for the experimental group and M=4.13 (SE=0.12) for the control group. This difference was statistically robust, $F(1, 61)=11.45$, p=.001, $\eta^2 = 0.09$, indicating one of the strongest effects among the sub-dimensions.

In contrast, no statistically significant difference was observed between the groups in terms of science anxiety. The adjusted mean for the experimental group was M=2.84 (SE=0.14), while that for the control group was M=2.97 (SE=0.15), $F(1, 61)=1.28$, p=.263, $\eta^2 = 0.02$. This suggests that while gamification enhanced motivation, it did not significantly alleviate students' science-related anxiety within the scope of this intervention Table 4.

These findings provide a more detailed understanding of how gamification enhances student motivation across specific psychological constructs. The gamified SRL environment promoted greater interest (intrinsic), value (extrinsic), autonomy (self-determination), and confidence (self-efficacy) in science learning. While science anxiety remained unaffected, the substantial gains in the other four sub-dimensions support the utility of gamification as a motivational tool within SRL frameworks for middle school science education.

Table 4 Motivation pre-test and post-test scores for experimental and control groups

Sub-Dimension	Group	Adjusted Mean (SE)	F-value	*p*-value	η^2
Intrinsic Motivation	Experimental	4.62 (0.11)	9.24	0.003	0.07
	Control	4.18 (0.10)			
Extrinsic Motivation	Experimental	4.48 (0.12)	7.68	0.007	0.06
	Control	4.11 (0.11)			
Self-Determination	Experimental	4.50 (0.10)	10.11	0.002	0.08
	Control	4.06 (0.11)			
Self-Efficacy	Experimental	4.58 (0.09)	11.45	0.001	0.09
	Control	4.13 (0.12)			
Science Anxiety	Experimental	2.84 (0.14)	1.28	0.263	0.02
	Control	2.97 (0.15)			

5.4 Fostering enjoyment in science education: the impact of gamified learning

The integration of gamification into the science curriculum significantly enhanced students' enjoyment of learning, as evidenced by the results of the post-intervention ANCOVA analysis. Pre-test enjoyment scores were used as covariates to control for baseline differences between the groups. After adjusting for these initial differences, the ANCOVA revealed that students in the experimental group reported significantly higher levels of enjoyment compared to those in the control group. As shown in Table 5, the estimated marginal mean enjoyment score for the experimental group was $M = 4.73$ ($SE = 0.11$), while the control group's adjusted mean was $M = 4.25$ ($SE = 0.10$). This difference was statistically significant, $F(1, 61) = 9.78$, $p = .008$, with a partial eta squared (η^2) of 0.04, indicating a small-to-moderate effect size..

These results provide strong evidence that incorporating gamified features—such as challenges, rewards, and interactive tasks—into science instruction can substantially increase students' enjoyment of the learning experience. The elevated enjoyment levels observed in the experimental group suggest that gamification not only captures student interest but also fosters a more emotionally positive and engaging educational environment. Such emotional engagement plays a crucial role in sustaining attention, motivation, and long-term interest in scientific learning.

5.5 Engaging learners: the positive effect of gamification on student participation

To provide a more comprehensive understanding of how gamified SRL influences student engagement, separate ANCOVA analyses were conducted for each sub-dimension of engagement: behavioral, emotional, cognitive, and social. Pre-test scores were used as covariates to control for baseline differences. The results revealed that students in the experimental group outperformed the control group across all engagement dimensions, with statistically significant differences favoring the gamified condition.

After adjusting for pre-test differences, the experimental group had an estimated marginal mean of $M = 4.51$ ($SE = 0.11$), compared to $M = 4.12$ ($SE = 0.10$) for the control group. This difference was statistically significant, $F(1, 61) = 8.45$, $p = .005$, $\eta^2 = 0.06$, indicating that gamification enhanced students' effort, persistence, and task involvement.

For emotional engagement, the experimental group reported an adjusted mean of $M = 4.38$ ($SE = 0.10$), while the control group's adjusted mean was $M = 4.01$ ($SE = 0.11$). This difference was significant, $F(1, 61) = 7.89$, $p = .007$, $\eta^2 = 0.05$, suggesting that gamified environments fostered more positive emotions and reduced anxiety during science learning.

The adjusted mean for cognitive engagement in the experimental group was $M = 4.46$ ($SE = 0.12$), compared to $M = 4.09$ ($SE = 0.13$) in the control group. The

Table 5 Enjoyment post-test scores for experimental and control groups

Group	Adjusted Mean (SE)	F-value	p-value	η^2
Experimental	4.73 (0.11)	9.78	0.008	0.04
Control	4.25 (0.10)			

Table 6 Adjusted Post-Test engagement scores by Sub-Dimension (ANCOVA Results)

Dimension	Group	Adjusted Mean (SE)	F	*p*-value	η^2
Behavioral Engagement	Experimental	4.51 (0.11)	8.45	0.005	0.06
	Control	4.12 (0.10)			
Emotional Engagement	Experimental	4.38 (0.10)	7.89	0.007	0.05
	Control	4.01 (0.11)			
Cognitive Engagement	Experimental	4.46 (0.12)	9.72	0.003	0.07
	Control	4.09 (0.13)			
Social Engagement	Experimental	4.23 (0.13)	6.88	0.011	0.04
	Control	3.85 (0.12)			

ANCOVA results indicated a significant difference, $F(1, 61)=9.72$, $p=.003$, $\eta^2 = 0.07$, highlighting that gamification promoted deeper processing, metacognitive strategies, and critical thinking.

Lastly, social engagement scores favored the experimental group ($M=4.23$, $SE=0.13$) over the control group ($M=3.85$, $SE=0.12$), with the difference reaching statistical significance, $F(1, 61)=6.88$, $p=.011$, $\eta^2 = 0.04$. This suggests that the gamified environment encouraged more collaboration, peer interaction, and classroom cooperation Table 6.

These findings reveal that the gamified SRL approach significantly enhanced all facets of student engagement. Behaviorally, students in the experimental group demonstrated greater persistence and task focus. Emotionally, they experienced more enjoyment and less anxiety. Cognitively, they were more reflective and invested in their learning strategies. Socially, the gamified environment facilitated greater cooperation and peer interaction.

By analyzing engagement at the sub-factor level, this study provides deeper insight into how gamification influences specific dimensions of student participation. The consistent advantage across all domains underscores the effectiveness of game-based elements—such as real-time feedback, reward mechanisms, and collaborative challenges—in fostering comprehensive engagement in science learning. These outcomes further support the potential of gamified SRL to promote both academic and interpersonal development among middle school learners.

6 Discussion

6.1 Summary of results

This study explored the impact of a gamified mobile-based SRL approach on middle school students within the context of science education. The findings clearly demonstrated that gamification significantly enhanced academic achievement, with students in the experimental group outperforming those in the control group, who followed a traditional mobile-based SRL approach without gamified elements. These results suggest that the integration of game-like features into learning environments can substantially improve students' comprehension and retention of scientific concepts. The interactive nature of these elements appears to make complex topics more accessible and engaging, ultimately leading to better academic performance. Additionally, the results showed a significant increase in motivation among students exposed to the gamified SRL approach compared to those in the non-gamified control group. The higher levels of motivation in the experimental group can be attributed to the stimulating and dynamic aspects of gamification, which fostered a more enthusiastic and focused attitude towards learning. These game elements likely contributed to students' sense of accomplishment and progress, further reinforcing their commitment to the learning process. The study also revealed that students in the gamified group reported higher levels of enjoyment in their science education than those in the control group. The engaging and interactive qualities of the gamified approach likely played a key role in making the learning experience more enjoyable and captivating, transforming what might otherwise be routine academic tasks into an activity that students found pleasurable and rewarding. Furthermore, the research found that the gamified approach led to increased student engagement across multiple dimensions—behavioral, emotional, cognitive, and social—compared to the control group. This comprehensive improvement highlights the ability of gamified learning to deepen students' involvement in their education, encouraging them to participate more actively, think more critically, and collaborate more effectively with their peers. The inclusion of game mechanics fostered a more immersive and collaborative learning environment, making students more invested in their educational activities.

6.2 Theoretical implications

The findings of this study significantly contribute to the expanding literature on gamified learning by demonstrating that the integration of gamification within a mobile-based SRL approach enhances student engagement, enjoyment, motivation, and academic achievement in science education. These results support and extend previous research, such as the work of García-López et al. (2023), which emphasized the potential of gamification to improve both the engagement and motivational dimensions of learning environments. By incorporating game elements, this study confirms that gamification creates a more dynamic and stimulating learning experience, driving active student participation and involvement, particularly in science education. This combination of gamification and SRL represents a novel and authentic contribution, offering a framework that goes beyond traditional teaching methods to address persistent challenges in student engagement.

The observed increase in academic achievement within the experimental group, which used the gamified mobile-based SRL approach, aligns with findings from Zeng et al. (2024) and studies by Lampropoulos and Sidiropoulos (2024), which demonstrate that gamified learning environments can significantly enhance academic performance by making learning more interactive and enjoyable. In comparison, the control group—using only the mobile-based SRL approach without gamified elements—showed improvements, but not to the same extent. This reinforces the idea that gamification not only engages students but also equips them to better grasp complex scientific concepts, leading to higher achievement levels. These results highlight the potential of gamified strategies as powerful pedagogical tools for improving performance in challenging subjects like science. Moreover, the study's emphasis on environmental science topics such as climate change, resource conservation, and sustainable development underscores its alignment with global educational priorities, making the research highly significant in addressing pressing real-world challenges.

Similarly, the increase in student motivation observed in the gamified group parallels the findings of Alt (2023), who reported that game elements inspire greater levels of motivation. While the control group, using only mobile-based SRL, showed improvements in motivation, the gamified approach significantly amplified this effect. This suggests that gamification enhances both extrinsic rewards and intrinsic motivation, fostering a stronger sense of autonomy and self-regulation. The experimental group's heightened motivation highlights gamification's potential to cultivate a self-directed, resilient approach to learning, where students are driven by both internal satisfaction and external achievements. This authentic contribution enriches our understanding of motivation within the context of gamified education, showcasing how innovative strategies can foster long-term academic growth.

The enhanced levels of enjoyment and engagement reported in the experimental group are particularly significant when analyzed through the lens of multimedia learning theory (Mayer, 2005) and cognitive load theory (Sweller, 1988). These frameworks underscore the importance of well-structured multimedia elements in reducing extraneous cognitive load and improving learning efficiency. The gamified approach, with its immersive and interactive features—such as immediate feedback, visual stimuli, and reward mechanisms—aligns with these theories by facilitating more effective cognitive processing and sustained attention. In addition to these cognitive frameworks, the findings also align with key principles of game theory and motivational design in educational contexts. According to self-determination theory (Deci & Ryan, 1985), gamified environments foster intrinsic motivation by supporting autonomy, competence, and relatedness—core psychological needs that are activated through goal-setting, progress tracking, and peer competition. Moreover, concepts from flow theory (Csikszentmihalyi, 1990) are relevant, as the gamified tasks likely created optimal challenge-skill balances, leading students to experience deep engagement and enjoyment. These theoretical models help explain how game mechanics—such as points, leaderboards, and achievements—drive behavioral persistence and emotional investment. By integrating insights from both cognitive and game-based learning theories, this study offers a more comprehensive understanding of how gamification enhances learning experiences. The synergy of multimedia design principles and game-based motivational dynamics supports the development of an engaging, effective, and self-regulatory science learning environment. This theoretical integration further reinforces the study's contribution to both educational practice and research.

Moreover, the comprehensive improvements observed across the behavioral, emotional, cognitive, and social dimensions of engagement in the experimental group underscore the multifaceted impact of gamification. This aligns with Kearsley and Shneiderman's (1998) engagement theory, which advocates for technology-enhanced learning environments that encourage active, collaborative, and meaningful participation. Gamification fostered a learning atmosphere where students not only engaged more individually but also collaborated more effectively as part of a learning community. In contrast, while the control group's engagement improved, the absence of gamified components meant these gains were less pronounced. These findings suggest that gamified learning environments create a more holistic and engaging educational experience, critical for promoting deep learning in subjects like science, where collaboration, problem-solving, and sustained inquiry are essential for success.

This study stands out for its innovative integration of gamified elements within an SRL framework and its focus on addressing global priorities through environmental science education. It bridges gaps in existing research by providing empirical evidence of the transformative potential of gamification in science education. Furthermore, its alignment with foundational learning theories and its emphasis on both academic and motivational outcomes position this study as a significant and authentic contribution to the field. By offering a replicable framework and demonstrating the broader applicability of gamification, this research paves the way for future advancements in education.

6.3 Practical implications

The findings from this study offer valuable insights that could significantly influence educational practices and policies, particularly in the context of middle school science education. The observed improvements in academic achievement and increased engagement among students exposed to the gamified mobile-based SRL approach demonstrate the transformative potential of integrating game-like elements into learning environments. This approach can make science, a subject often perceived as challenging, more interactive and enjoyable, potentially shifting student attitudes and making the learning experience more appealing and accessible.

For educators and curriculum developers, these results underscore the importance of incorporating gamification strategies into curriculum design. By making learning more engaging and interactive, gamification can stimulate students' interest and participation, particularly in demanding subjects like science. Teacher training programs should include modules on the effective implementation of gamification. These programs should not only cover the technical aspects of gamified tools but also explore how educators can leverage these game elements to improve learning outcomes, foster deeper engagement, and enhance student motivation.

Beyond its application in science education, gamification has demonstrated significant potential across a wide array of disciplines. Research in areas such as language learning, mathematics, and social sciences indicates that gamified strategies can enhance student motivation, engagement, and achievement when tailored to the specific demands of each subject. These findings highlight the versatility of gamification as an educational tool, capable of addressing unique challenges and enriching learning experiences across diverse curricular contexts. By leveraging the principles of gamification, educators and curriculum developers in various fields can create interactive and engaging environments that foster student interest and participation, making learning both accessible and impactful.

The observed increase in student motivation and engagement suggests that gamification could serve as an effective tool to address widespread educational challenges, such as student disengagement and high dropout rates. This is especially relevant in subjects where students typically struggle or lose interest over time. Educational policies should, therefore, encourage the adoption of innovative teaching strategies like gamification within the standard curriculum. Such policies could provide the necessary support for schools and educators to experiment with and integrate these strategies in ways that enhance both student learning and overall classroom dynamics.

Moreover, this study's findings highlight the potential for developing new educational technologies and tools that support gamified learning environments. Educational technology companies could leverage these insights to design products that align with the diverse needs of educational institutions. These tools could offer schools more effective and personalized learning solutions, helping educators implement gamified strategies that are tailored to their specific classroom contexts and student populations.

Finally, the impact of gamification on student outcomes points to the need for a reevaluation of traditional assessment methods. As gamified learning environments foster not only cognitive gains but also affective and motivational improvements, assessment frameworks should evolve to capture the full spectrum of student learning. New methods of assessment that account for behavioral engagement, emotional involvement, and collaboration in addition to academic achievement could provide a more comprehensive understanding of student progress. This would allow educators to better recognize the multifaceted benefits of gamified learning experiences and adjust their teaching strategies accordingly.

6.4 Limitations and suggestion for future studies

While this study highlights the potential benefits of integrating gamification into a mobile-based SRL framework in middle school science education, several limitations must be acknowledged.

A primary limitation is the absence of qualitative data such as student interviews or open-ended reflections. Although students engaged in structured reflective activities through digital reflection sheets, these were not subjected to formal qualitative analysis. As a result, the study lacks in-depth insight into students' subjective experiences and cognitive processes, particularly those related to self-regulation. Given that self-regulated learning involves metacognitive and affective components, incorporating qualitative data would provide a richer understanding of how students perceive and internalize these processes. Future research should include qualitative methods—such as interviews, focus groups, or thematic analyses of student reflections—to complement quantitative findings and more fully capture the nuances of self-regulated learning.

Another important limitation is the relatively small sample size, which was drawn from a single middle school. This restricts the generalizability of the findings, as the results may not reflect broader student populations across different educational contexts or demographic groups. Future studies should expand the participant base to include students from multiple schools, diverse geographic locations, and varied socio-economic backgrounds to enhance external validity.

In addition, the study was conducted over a relatively short duration, limiting the ability to evaluate the long-term impact of gamification on academic performance, engagement, and concept retention. Longitudinal designs are needed to examine the sustainability of the observed benefits and track changes in self-regulatory behaviors over extended periods.

This study also relied primarily on self-reported instruments to measure motivation, enjoyment, and engagement. While these tools provide useful perceptions, they are susceptible to bias and may not fully reflect actual behaviors. To address this, future research should integrate objective data sources—such as classroom observations, learning analytics, or behavioral logs from gamified platforms—to provide a more robust and multidimensional understanding of student learning.

Another notable limitation lies in the scope of the educational content. The "Idle Carbon City" app used in this study focused exclusively on environmental science topics, such as climate change and sustainability. While this targeted focus allowed for depth, it limits the applicability of findings to broader areas of science or other disciplines. Future work should explore the integration of gamified SRL tools across a wider range of subjects to determine the generalizability of the pedagogical benefits.

Furthermore, the study did not fully control for external factors such as teacher effectiveness, classroom dynamics, or socio-economic variables, all of which can significantly influence educational outcomes. Future studies should systematically address these variables to strengthen internal validity.

Comparative studies examining different gamification designs, such as variations in reward systems, feedback mechanisms, or collaborative versus competitive formats, would also offer valuable insights into which elements most effectively support SRL and learning outcomes. Additionally, as educational technologies advance, future research should explore the integration of emerging tools—including adaptive gamified systems, virtual or augmented reality, and AI-enhanced learning platforms—to further refine and personalize gamified learning environments.

By addressing these limitations and pursuing these recommended research directions, future studies can provide a more comprehensive understanding of how gamification, in combination with SRL principles, can be optimized to create engaging, adaptive, and effective learning experiences.

7 Conclusion

This study has shown that the integration of gamification within a mobile-based SRL framework significantly enhances middle school students' academic achievement, motivation, enjoyment, and engagement in science education. In comparing the gamified mobile-based SRL group to the control group, which used a non-gamified mobile-based SRL approach, it was evident that the addition of gamified elements created a more engaging and interactive learning environment. This led to deeper connections between students and the educational content, motivating them to actively participate and invest in their learning. The results underline the potential of gamification to transform traditional educational methods, offering a dynamic alternative that stimulates student interest and fosters higher levels of engagement. Students in the gamified group demonstrated greater motivation and a higher level of enjoyment, key factors that contribute to academic success and retention. In contrast, while the control group also benefited from mobile-based SRL, the absence of gamified elements resulted in lower engagement and motivation compared to the gamified approach. These findings suggest that gamification can make the learning process more appealing and accessible, thereby improving educational outcomes. However, while the study's outcomes are promising, they also indicate a need for further research to explore the long-term effects of gamification and its application across different subjects and educational settings. Moreover, identifying the optimal balance of gamified elements that maximize educational benefits without overwhelming students remains an important area for future investigation. Future studies should aim to incorporate larger, more diverse sample sizes to enhance the generalizability of the findings and to examine how gamification can be adapted to other educational contexts. In conclusion, this study contributes to the expanding body of research supporting the use of gamification in education. It offers practical insights for educators and policymakers seeking to implement innovative, technology-driven strategies into their curricula. As educational technology continues to evolve, integrating gamified learning environments stands out as a promising method for improving student outcomes and creating more engaging, effective educational experiences.

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Data availability The datasets generated and analyzed during the current study are not publicly available due to privacy and ethical considerations but are available from the corresponding author on reasonable request and subject to necessary approvals.

Declarations

Conflict of interest The authors declare no conflict of interest.

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