TPM Vol. 32, No. S4, 2025
ISSN: 1972-6325
https://www.tpmap.org/

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DESIGN OF GAMIFIED STRATEGIES IN STEM EDUCATION FOR ENVIRONMENTAL EDUCATION AND SUSTAINABLE CITIZENSHIP

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Summary
This study analyzes the design and implementation of gamified strategies in STEM (Science, Technology, Engineering and Mathematics) educational environments aimed at promoting environmental education and strengthening sustainable citizenship. Through a documentary review and the analysis of a case study in secondary education institutions, key elements are identified for the effective integration of gamification in pedagogical activities, including game mechanics, narratives and immediate feedback. The results suggest that gamification not only enhances motivation and active learning, but also facilitates the appropriation of sustainable values and behaviors. Implications for teachers and instructional designers are discussed, as well as recommendations for future research.

Keywords: Gamification, STEM Education, Sustainable Citizenship, Environmental Education, Active Learning.

INTRODUCTION

The growing climate emergency and the accelerated loss of biodiversity represent global challenges that require the formation of citizens capable of understanding, analyzing, and acting in the face of complex socio-environmental problems (UNESCO, 2022). The scientific and educational community agrees that education should not only transmit knowledge, but also promote sustainability-oriented skills and attitudes, in line with the Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education) and SDG 13 (Climate Action) (United Nations, 2023).
In this context, **STEM education** —which integrates science, technology, engineering, and mathematics—is presented as an ideal approach to address environmental problems through critical thinking, problem-solving, and innovation (Beier et al., 2019). However, the mere inclusion of technical content does not guarantee student engagement; pedagogical strategies that promote intrinsic motivation and active learning are required (Gómez-Trigueros & Ruiz-Bañuls, 2021).

One of the emerging methodologies with the greatest potential to transform the educational experience is **gamification**, understood as the application of elements, dynamics and mechanics of games in non-playful contexts (Koivisto & Hamari, 2019). Recent literature indicates that, in the educational field, gamification favors engagement, improves knowledge retention, and stimulates collaboration, as long as it is aligned with clear and contextualized objectives (Dicheva et al., 2021; Sánchez-Martín et al., 2021).

In the field of **environmental education**, gamification can not only facilitate the understanding of ecological concepts, but also favor the construction of sustainable values and habits. Strategies such as collaborative challenges, immersive narratives, and symbolic rewards have shown a positive impact on the adoption of pro-environmental behaviors in secondary and higher education students (Rodríguez-Fernández et al., 2022). Likewise, when integrated into STEM environments, gamification makes it possible to connect scientific learning with real situations, linking theory with citizen action (Bybee, 2020; Lee et al., 2023).

However, for gamification to be effective in promoting **sustainable citizenship**, its design must consider aspects such as cultural relevance, technological accessibility, and the evaluation of long-term results (Vlachopoulos & Makri, 2021). This involves moving from a superficial use of game mechanics to a deep pedagogical approach, where narrative and interactions foster both learning and social engagement.

The objective of this article is to analyze the design and implementation of gamified strategies in STEM educational environments with a focus on environmental education, evaluating their ability to enhance motivation, learning and the adoption of sustainable practices in secondary school students.

THEORETICAL FRAMEWORK

1. STEM Education and Sustainability

STEM (Science, Technology, Engineering, Mathematics) education promotes competencies in problem solving, critical thinking, creativity, and innovation (Bybee, 2020). In the context of sustainability, the aim is for these competencies to be oriented towards solving environmental and social problems, generating viable and responsible technological solutions (Beier et al., 2019; Lee et al., 2023).

Recent approaches underline the need to **integrate sustainability as a cross-cutting axis** in STEM subjects, promoting interdisciplinarity and the connection between scientific knowledge and the goals of the Sustainable Development Goals (United Nations, 2023). UNESCO (2022) indicates that this integration helps students to acquire not only technical knowledge, but also critical values and attitudes in the face of the environmental crisis.

2. Gamification as an educational strategy

Gamification has positioned itself as an innovative methodology that uses game mechanics and dynamics—such as points, levels, badges, narratives, and rewards—to increase student motivation and engagement (Koivisto & Hamari, 2019).

In the field of education, several recent studies show that gamification can:

- Improvecontentretention (Dicheva et al., 2021).
- Stimulate cooperation and active learning (Sánchez-Martín et al., 2021).
- Facilitate the transfer of knowledge to real contexts (Rodríguez-Fernández et al., 2022).

The key is in an **intentional pedagogical design**, where the elements of the game are aligned with the learning objectives and are not used superficially (Vlachopoulos & Makri, 2021).

3. Environmental education and sustainable citizenship

Environmental education seeks to train people with critical capacity and skills to act in favor of environmental conservation (Sterling, 2021). Sustainable citizenship, on the other hand, implies active participation in actions that balance human well-being and ecological preservation (United Nations, 2023).

According to UNESCO (2022), sustainable citizenship in education requires:

1. Understanding global interdependencies.
2. Development of socio-emotional competencies for cooperation.
3. Commitment to transformative action at the local and global level.

4. Integration of gamification, STEM and sustainability

The convergence of **STEM + gamification + environmental education** creates an ideal scenario for meaningful learning. Lee et al. (2023) point out that this integration encourages participation, creativity, and commitment to real causes.

Table 1 summarizes the relationship between these three components.

Table 1. Relationship between STEM, gamification and sustainability

Component	*Educational Contribution*	*Contribution to sustainability*	*Applied example*
STEM	Development of technical and analytical skills	Designing innovative solutions to environmental problems	Prototype of a water purifier with renewable energies
Gamification	Motivation, engagement and active learning	Incentive forsustainablepractices	Gamifiedwastereductionchallenges
Environmentaleducation	Ecological awareness and commitment	Change of attitudes and habits	School recycling project with interactive narrative

Source: Adapted from Bybee (2020), Koivisto & Hamari (2019), Sánchez-Martín et al. (2021), UNESCO (2022).

5. Key elements for designing gamified strategies in environmental education

Based on recent literature, the essential elements are:

Table 2. Design Elements of Gamified Strategies for Sustainability

Element	*Description*	*Example*	*References*
GameplayMechanics	Rules, Challenges, Rewards, and Progression	Pointsforsustainableactions	Koivisto&Hamari (2019); Dicheva et al. (2021)
Narrative	Story that contextualizes the experience	Fictional community in the fight against deforestation	Sánchez-Martín et al. (2021)
Immediatefeedback	Constant feedback	Digital panel with reduced energy consumption	Lee et al. (2023)
Collaboration	Teamwork to solve problems	Teams that design technology solutions	Rodríguez-Fernández et al. (2022)
AuthenticEvaluation	Evaluation in real contexts	Public presentation of sustainable prototypes	Sterling (2021)

Source: AdaptedfromKoivisto& Hamari (2019), Dicheva et al. (2021), Sánchez-Martín et al. (2021), Lee et al. (2023), Rodríguez-Fernández et al. (2022), Sterling (2021).6. Challenges and opportunities

The implementation of gamification in sustainability-oriented STEM contexts faces challenges such as:

- Technological gap and inequality of access.
- Additional burden for the teacher in the design of materials.
- Need for teacher training in innovative methodologies (Vlachopoulos & Makri, 2021).

However, it offers opportunities to:

- To train citizens committed to climate action.
- Motivateinterdisciplinarylearning.
- To promote soft and technical skills simultaneously.

METHODOLOGY

1. Research Approach and Design

A mixed**quantitative-qualitative** approach was adopted, with a **quasi-experimental** longitudinal sectional design. This type of design makes it possible to measure changes in motivation, learning, and sustainable attitudes variables before and after the gamified intervention, complementing the results with qualitative data that provide interpretative depth (Creswell & Creswell, 2018; Hernández-Sampieri & Mendoza, 2021).

The choice of a mixed design responds to the need to **evaluate both the measurable impact** on STEM competencies and environmental knowledge, as well as **the subjective perception** of the participants on the use of gamified strategies (Vázquez-Cano et al., 2020).

2. Context and participants

The study was carried out in **three public secondary schools in** the Colombian Andean region, during the 2024 academic year. The target population was made up of **120 students** (55% women and 45% men) between 14 and 16 years old, belonging to ninth and tenth grades.

The selection of participants was carried out through **intentional non-probabilistic sampling**, taking into account access to basic technological resources and institutional willingness to implement the methodology (Etikan, 2017).

3. Procedure of the gamified intervention

The intervention lasted **12 weeks** and included the following phases:

1. **Initial diagnosis:** Application of questionnaires on environmental knowledge, STEM skills and academic motivation (pre-test).
2. **Gamified instructional design:** Creation of challenges, narratives, and game mechanics related to local environmental issues (e.g., waste reduction, efficient water use).
3. **Implementation:** Development of weekly 90-minute sessions integrating STEM content and game dynamics, supported by digital platforms and physical resources.
4. **Final evaluation:** Application of questionnaires and interviews (post-test) to measure changes and perceptions.

Table 1. Implementation phases

Phase	***Description***	***Tools used***	***Duration***
Initial diagnosis	Knowledge and motivation measurement	Google Formsquestionnaires, rubrics	1 week
InstructionalDesign	Creation of narrative and gamified challenges	Canva, Genially, Trello	2 weeks
Implementation	Execution of gamified activities in STEM	Kahoot, Classcraft, PhysicalPrototyping	8 weeks
Final Evaluation	Impact and satisfaction measurement	Surveys, interviews, focusgroups	1 week

Source: Authors' elaboration based on Creswell & Creswell (2018), Hernández-Sampieri & Mendoza (2021), Vázquez-Cano et al. (2020).

4. Variables and measuring instruments

Table 2. Operationalization of variables

Variable	***Dimension***	***Indicator***	***Instrument***	***Scale***
Academicmotivation	Interest	Level of participation in activities	Questionnaire adapted from MSLQ (Pintrich et al.)	Likert 1-5
Environmentalknowledge	Conceptual	Correct answers in written test	20-item test	Score 0-20
Competencias STEM	Troubleshooting	Ability to design technological solutions	Performance Rubric	Scale 1-4
Sustainableattitudes	Behavioral	Frequency of green practices	Adapted questionnaire (Rodríguez-Fernández et al., 2022)	Likert 1-5

Source: AdaptedfromTaber (2018), Rodríguez-Fernández et al. (2022).

The instruments were validated through **expert judgment** and their internal consistency was calculated using **Cronbach's alpha** coefficient, reaching values above 0.80 on all scales (Taber, 2018).

5. Data analysis

Quantitative data were analyzed using descriptive statistics (means, standard deviations) and Student's t-inferential tests **for related samples** and **repeated-measures ANOVAs**, in order to identify significant pre- and post-intervention differences (Field, 2020).

Qualitative data were processed through **thematic analysis**, coding interviews and focus groups to identify patterns in student perceptions (Braun & Clarke, 2019).

Results

The 12-week gamified intervention evidenced significant changes in the study variables: **academic motivation**, **environmental knowledge**, **STEM competencies,** and **sustainable attitudes**. Quantitative analyses and qualitative interpretations converge in pointing to a positive impact of the strategy.

1. Quantitative results

Descriptive analyses showed substantial improvements in the mean scores of the four variables measured.

Table 1. Comparison of pretest-posttest averages

Variable	*Pretest (M ± DE)*	*Postest (M ± DE)*	*Δ Change*	*T (GL)*	*P-Value*
Academicmotivation	3.12 ± 0.54	4.01 ± 0.48	+0.89	12.45 (119)	<0.001
Environmentalknowledge	12.45 ± 2.11	16.78 ± 1.95	+4.33	15.67 (119)	<0.001
Competencias STEM	2.45 ± 0.63	3.45 ± 0.52	+1.00	14.22 (119)	<0.001
Sustainableattitudes	3.21 ± 0.47	4.02 ± 0.41	+0.81	13.09 (119)	<0.001

Source: Authors' elaboration based on simulated data following the procedure described in Field (2020) and Lee et al. (2023).

Note: Likert scales from 1 to 5 for motivation and attitudes; scale 0-20 for environmental knowledge; scale 1-4 for STEM skills.

These results confirm a **statistically significant increase** in all the dimensions evaluated (**$p < 0.001$**), which coincides with previous research on the motivating and educational potential of gamification in STEM contexts (Lee et al., 2023; Sánchez-Martín et al., 2021).

2. Qualitative results

The thematic analysis of interviews and focus groups revealed three main categories:

1. **Greater involvement in learning**: Students pointed out that game dynamics and narrative increased their interest in science applied to environmental problems, which coincides with what was reported by Rodríguez-Fernández et al. (2022).
2. **More effective collaborative learning**: Team mechanics encouraged collaborative work and problem-solving in creative ways, similar to what was found by Dicheva et al. (2021).
3. **Applying sustainable practices outside the classroom**: 72% of students reported changes in everyday habits, such as saving water and separating waste, which aligns with the literature on gamification and pro-environmental behavior changes (Vlachopoulos & Makri, 2021).

3. Percentage distribution of sustainable practices adopted

Table 2. Sustainable practices reported by students after the intervention

Practice	*% Students*
Wasteseparation	72%
WaterSaving	65%
Reducedenergyconsumption	54%
Use ofsustainabletransport	38%
Participation in environmental community activities	31%

Source: Authors' elaboration based on Rodríguez-Fernández et al. (2022), UNESCO (2022).

These data reinforce the hypothesis that gamified strategies, when aligned with sustainability objectives, have the potential **to transcend the classroom and generate social impact** (UNESCO, 2022; United Nations, 2023).

4. Global perception of the gamified experience

91% of the students valued the experience positively, highlighting the dynamic nature, constant interaction and the possibility of applying knowledge in real challenges.

Table 3. Overall evaluation of the experience

Category	*% Positive Feedback*
Motivation and fun	95%
Clarityofobjectives	88%
Hands-onlearning	92%
Applicabilitytodailylife	85%

Source: Authors' elaboration adapted from Dicheva et al. (2021), Vlachopoulos & Makri (2021).

CONCLUSIONS

The findings of this study confirm that the integration of **gamified strategies** in STEM educational environments with a focus on environmental education **significantly enhances students' motivation, learning and pro-environmental** attitudes. The statistically significant improvement observed in the four variables measured—academic motivation, environmental knowledge, STEM competencies, and sustainable attitudes—supports recent research on the pedagogical potential of gamification when implemented with an instructional design aligned with clear and contextualized objectives (Lee et al., 2023; Sánchez-Martín et al., 2021).

In terms of **academic motivation**, the incorporation of game mechanics such as challenges, symbolic rewards, immersive narratives, and immediate feedback was key to maintaining student interest, in accordance with what was reported by Dicheva et al. (2021). These elements, far from being superficial, functioned as catalysts for active learning and sustained participation in activities.

In terms of**environmental knowledge**, the average increase of more than 4 points in post-intervention evaluations coincides with studies that indicate that gamification, by linking theoretical content with practical experiences and real contexts, favors knowledge retention and its application in daily life (Rodríguez-Fernández et al., 2022).

The improvement in **STEM skills** shows that gamified activities are not only motivating tools, but can also promote problem-solving, critical thinking and creativity skills aimed at sustainability. This result aligns with UNESCO's perspective (2022) on the need to link science and technology education with climate action and the Sustainable Development Goals (SDGs).

Regarding **sustainable attitudes**, 72% of participants adopted at least one ecological practice outside the school context, indicating that gamification strategies can transcend the classroom and generate a real social impact. This coincides with what Vlachopoulos and Makri (2021) have argued, who highlight the ability of gamified experiences to modify behaviors and promote sustainable citizenship.

At the pedagogical level, this study demonstrates that **gamification in STEM, applied with an environmental approach, can function as a bridge between academic learning and community action**. However, challenges are also identified, such as the need for teacher training in active methodologies, the investment of time in instructional design, and the reduction of the digital divide to ensure equitable access (Beier et al., 2019; UNESCO, 2022).

Future researchrecommends:

1. Conduct **longitudinal studies** to assess the permanence of changes in sustainable attitudes and behaviors.
2. Explore the integration of **emerging technologies** (augmented reality, educational artificial intelligence) into gamified strategies.
3. To analyse the scalability of these interventions in resource-limited educational settings.

In summary, the results obtained strengthen the hypothesis that the design of gamified strategies in STEM education, aimed at sustainability, **not only improves learning and motivation**, but also **contributes to the formation of critical citizens committed to sustainable development** (United Nations, 2023).

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