# Game-Based Learning for Enhancing Climate Change Knowledge and Environmental Awareness Among Secondary School Youth

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## Abstract

Addressing the global climate crisis demands transformative pedagogical interventions capable of translating abstract, systemic ecological data into actionable knowledge for younger generations. Traditional lecture-based instruction frequently struggles to convey complex feedback loops and foster sustained behavioral engagement among secondary school students. This paper evaluates the pedagogical efficacy of game-based learning (GBL) in augmenting climate literacy, dynamic systems thinking, and environmental self-efficacy. Employing a quasi-experimental pre-test, post-test, control-group design, this study investigated $N = 140$tenth-grade secondary school students across two high schools. The experimental cohort ($n = 70$) engaged with $EcoVanguard$, a digital serious simulation game modeling carbon cycle interactions, mitigation policies, and socio-economic trade-offs over a four-week intervention. The control cohort ($n = 70$) received textbook-driven, lecture-based didactic instruction covering an identical curriculum.

Assessment was conducted using the Climate Change Knowledge Assessment Test (CC-KAT) and the Climate Attitude and Self-Efficacy Survey (CASES), with a delayed post-test administered four weeks post-intervention to measure conceptual retention. Analysis of Covariance (ANCOVA), controlling for baseline pre-test variations, revealed that the GBL cohort exhibited statistically significant gains in systemic climate knowledge compared to the control group ($F(1,137) = 46.82, p < .001, \eta_p^2 = .255$), alongside a pronounced effect size on long-term retention ($d = 0.98$). Attitudinal dimensions—specifically perceived agency and systemic environmental responsibility—also demonstrated statistically significant elevation in the gaming cohort. These findings confirm that experiential, interactive game environments serve as an effective cognitive scaffold for complex environmental education, offering a scalable instructional design model for sustainable development curricula.

**Keywords:** Game-based learning, serious games, climate change education, youth engagement, environmental literacy, educational technology, ICCMETS.

## 1. Introduction

Anthropogenic climate change represents an existential challenge of the twenty-first century, characterized by non-linear systemic dynamics, temporal latency between emissions and ecological impacts, and multi-scalar socio-environmental dependencies (Intergovernmental Panel on Climate Change [IPCC], 2023). Effectively mitigating and adapting to these developments requires an informed, proactive citizenry equipped with sophisticated environmental literacy. Secondary school youth represent critical stakeholders in this transition; their environmental values, scientific literacy, and civic orientations are formed during this developmental phase (Ouariachi et al., 2020).

Despite the consensus on the necessity of comprehensive climate education, conventional instructional paradigms in secondary curricula remain heavily reliant on didactic lecturing, textbook transmission, and memorization of isolated scientific facts (Wu & Lee, 2015). This traditional instructional delivery exhibits three pedagogical limitations:

- **Failure to Scaffold Systems Thinking:** Climate science is governed by delayed feedback mechanisms, nonlinear tipping points, and multi-variable dependencies that cannot be adequately visualized or internalized through static textual descriptions (Rooney-Varga et al., 2018).
- **Affective Detachment and Fatalism:** Didactic instruction regarding catastrophic environmental forecasts often triggers psychological defense mechanisms, leading to eco-anxiety, fatalism, and learned helplessness rather than constructive empowerment (Meya & Eisenack, 2018).
- **Passive Cognitive Engagement:** Conventional passive learning setups fail to cultivate intrinsic motivation or experiential agency, both of which are required to translate intellectual understanding into pro-environmental actions (Plass et al., 2015).

To overcome these barriers, educational technologists and environmental educators have increasingly leveraged Game-Based Learning (GBL) and serious simulation games. Video games provide an interactive medium capable of computational modeling, experiential learning, and immediate feedback (Gee, 2003; Hamari et al., 2016). In a serious game environment, learners do not merely read about complex ecological systems; they inhabit them as decision-makers, manipulating variables, observing ecological outcomes across simulated decades, and experiencing the cascading impacts of socioeconomic and policy interventions (Connolly et al., 2012).

While prior scholarship demonstrates the affective appeal of gamified platforms (Hamari et al., 2016), empirical evidence concerning their capacity to foster robust, long-term conceptual retention and structural systems thinking within formal secondary school curricula remains fragmented. Many existing evaluations of serious games focus solely on immediate, short-term engagement or self-reported satisfaction metrics without standardized pre-test/post-test control group methodologies (Meya & Eisenack, 2018).

To address this empirical gap, this study examines the implementation of an interactive climate simulation game (*EcoVanguard*) within secondary education. The primary research questions guiding this investigation are:

1. To what extent does game-based learning enhance secondary students' systemic conceptual knowledge of climate change relative to traditional didactic instruction?
2. Does game-based learning foster superior cognitive retention of climate science concepts over a four-week delayed post-intervention period?
3. What impact does game-based learning exert on students' environmental self-efficacy and perceived personal agency?

## 2. Theoretical Framework and Literature Review

### 2.1 Theoretical Foundations: Constructivism and Experiential Learning

The theoretical grounding of game-based environmental education draws heavily from Constructivist Learning Theory (Piaget, 1976) and Kolb's Experiential Learning Model (Kolb, 1984). Constructivism posits that meaningful cognitive development occurs when learners actively construct knowledge through interaction with their environment rather than passively absorbing encoded data. Serious games embody this principle by functioning as computational microworlds where knowledge is discovered through exploration, hypothesis generation, and trial-and-error experimentation.

Kolb’s (1984) experiential learning cycle—comprising concrete experience, reflective observation, abstract conceptualization, and active experimentation—maps directly onto the mechanics of game-based simulation:

- **Concrete Experience:** The student assumes a leadership role within a regional ecosystem within the game environment.
- **Reflective Observation:** The player reviews data dashboards detailing carbon emission spikes, biodiversity loss, or economic recessions following a policy decision.
- **Abstract Conceptualization:** The learner deduces the underlying scientific rule (e.g., the relationship between deforestation, carbon sinks, and atmospheric warming).
- **Active Experimentation:** The learner formulates a revised strategy (e.g., implementing renewable energy subsidies paired with afforestation mandates) and executes the simulated intervention.

### 2.2 Cognitive Foundations of Game-Based Learning

Plass et al. (2015) established an integrated design framework for game-based learning, categorizing game engagement across cognitive, affective, behavioral, and sociocultural dimensions. Cognitively, digital games offer scaffolded challenges calibrated to the learner's zone of proximal development, mitigating cognitive overload through progressive information disclosure. Gee (2003) noted that video games present "situated meanings," wherein words, concepts, and diagrams are directly linked to perceptual actions and immediate sensory feedback. In environmental contexts, complex constructs such as "ocean acidification" or "albedo effect" become directly observable mechanics that dictate game progression.

### 2.3 Serious Games in Environmental and Climate Education

Over the past decade, several serious games and interactive simulations have targeted environmental science, including *World Climate* (Rooney-Varga et al., 2018), *Fate of the World* (Wu & Lee, 2015), and *EnerCities* (Knol & De Vries, 2011). Empirical evaluations consistently indicate that participatory simulations enhance engagement and emotional connection to the subject matter. Rooney-Varga et al. (2018) showed that interactive role-play simulations of international climate negotiations significantly heightened participants' climate change urgency and desire to learn more.

However, systematic reviews by Meya and Eisenack (2018) and Ouariachi et al. (2020) highlighted persistent methodological shortcomings in the literature: small sample sizes, lack of control cohorts, absence of validated knowledge assessment batteries, and an over-reliance on immediate post-tests that fail to evaluate long-term cognitive consolidation. This research explicitly addresses these limitations through a quasi-experimental design incorporating longitudinal retention assessments and standardized psychometric instruments.

# 3. Methodology

## 3.1 Research Design

This study utilized a quasi-experimental, pre-test, post-test, non-equivalent control group design with an additional delayed post-test administered four weeks after intervention completion. This multi-phase assessment timeline evaluated baseline equivalence, immediate cognitive gains, and long-term knowledge retention.

Experimental Group: O1 ----> [ Intervention: GBL (EcoVanguard) ] ----> O2 ----> (4 Weeks) ----> O3

Control Group: O1 ----> [ Intervention: Didactic Instruction ] ----> O2 ----> (4 Weeks) ----> O3

Where:

O1 = Baseline Pre-test (CC-KAT & CASES)

O2 = Immediate Post-test (CC-KAT, CASES & UES-SF)

O3 = Delayed Retention Post-test (CC-KAT & CASES)

## 3.2 Participants and Setting

The study was conducted across four intact classes within two suburban secondary schools sharing equivalent socioeconomic demographics and academic achievement profiles. A total of $N = 140$tenth-grade students (aged 15–16 years; 52.1% female, 47.9% male) participated in the study. Classes within each school were randomly assigned to either the experimental condition ($n = 70$) or the control condition ($n = 70$), minimizing intra-school contamination.

*Inclusion criteria* required that all participants had not completed advanced environmental science coursework prior to the study and possessed basic digital literacy skills. Institutional ethics approval and written informed parental and student consent were secured prior to data collection.

## 3.3 The Pedagogical Interventions

### 3.3.1 Experimental Condition: The *EcoVanguard* Serious Game

The experimental cohort engaged with *EcoVanguard*, a digital, turn-based socio-ecological simulation developed on the Unity engine for cross-platform desktop execution. The game's computational engine is underpinned by an integrated climate-economy feedback loop derived from simplified IPCC assessment models.

*Key Mechanics of EcoVanguard:*

- **Policy and Resource Allocation:** Players manage an annual capital budget, allocating resources among fossil fuels, solar/wind infrastructure, agricultural expansion, carbon capture R&D, and ecological conservation.
- **Dynamic Feedback Loops:** Player decisions generate direct environmental outputs (parts per million of atmospheric $CO_2$, ocean pH levels, global mean temperature rise) which subsequently trigger secondary systemic hazards (extreme meteorological events, sea-level rise, decreased agricultural yield).

- **Scenario Challenges:** Students confront stochastic climate feedback events (e.g., permafrost thaw causing methane release), requiring adaptive mitigation and resilience planning.
- **Reflection Dashboards:** At the close of each simulated decade (turn), students access interactive analytical charts illustrating the causal trajectories of their policy decisions.

Students completed four 50-minute structured sessions over two weeks, accompanied by teacher-guided debriefing protocols.

### 3.3.2 Control Condition: Traditional Didactic Instruction

The control cohort completed an identical thematic curriculum over four 50-minute instructional sessions across the same two-week timeframe. The curriculum was delivered via traditional didactic lectures, standardized slide presentations, curated textbook readings, and physical worksheet completion. To ensure curricular parity, both groups covered identical core topics: the carbon cycle, greenhouse gas mechanics, global socio-economic implications, and mitigation/adaptation policy frameworks. The control cohort did not have access to *EcoVanguard* or digital gamified learning tools during the research window.

### 3.4 Instruments and Measurement

Two primary validated psychometric instruments were administered to assess cognitive and affective developments:

1. **Climate Change Knowledge Assessment Test (CC-KAT):** Developed by a panel of climate scientists and educational psychometricians, this 30-item multiple-choice instrument measures three conceptual tiers:

   - *Factual Science* (e.g., chemical mechanisms of greenhouse gases, atmospheric residence time; 10 items).
   - *Complex Systems Dynamics* (e.g., albedo feedback loops, ocean acidification, tipping cascades; 10 items).
   - *Mitigation and Adaptation Policies* (e.g., carbon pricing mechanisms, renewable transitions, land management; 10 items). The instrument demonstrated high internal consistency reliability across trials (Kuder-Richardson 20, $KR-20 = .86$). Item difficulty indices ranged between $.38$and $.74$, and item discrimination indices exceeded $.35$.

2. **Climate Attitude and Self-Efficacy Survey (CASES):** Adapted from established environmental psychological scales (Bandura, 1997; Ouariachi et al., 2020), this 18-item instrument measures three affective dimensions using a 5-point Likert scale ($1 =$ Strongly Disagree to $5 =$ Strongly Agree):

   - *Perceived Personal Agency* ($\alpha = .88$).
   - *Systemic Environmental Responsibility* ($\alpha = .84$).
   - *Future Outcome Expectancy* ($\alpha = .81$). The full instrument exhibited robust overall reliability (Cronbach's $\alpha = .89$).

3. **User Engagement Scale - Short Form (UES-SF):** Administered exclusively to the experimental group post-intervention, the UES-SF measures focused attention, perceived usability, aesthetic appeal, and reward factor on a 5-point scale (Cronbach's $\alpha = .87$).

### 3.5 Data Collection and Statistical Analysis Procedures

Data were collected across three phases: Pre-test ($T_0$), Immediate Post-test ($T_1$), and Delayed Post-test ($T_2$, 4 weeks post-intervention).

All statistical analyses were executed using SPSS v28. Preliminary checks confirmed data normality via Shapiro-Wilk tests and homogeneity of variance using Levene's test ($p > .05$). To test the hypotheses:

- Independent samples $t$-tests evaluated baseline equivalency at $T_0$.
- Analysis of Covariance (ANCOVA) was deployed for post-test evaluations ($T_1$ and $T_2$), employing pre-test scores as covariates to control for baseline variance.
- Paired samples $t$-tests and repeated-measures ANOVA assessed intra-group cognitive gains and knowledge retention rates.
- Effect sizes were quantified using partial eta squared ($\eta_p^2$) for ANCOVA and Cohen's $d$for pairwise comparisons.

## 4. Results and Data Analysis

### 4.1 Baseline Equivalency Check

*Table 1 outlines the baseline performance metrics across both cohorts. Independent samples $t$-tests confirmed no statistically significant differences between the experimental and control groups regarding baseline climate change knowledge ($t(138) = 0.43, p = .668$) or environmental self-efficacy ($t(138) = 0.28, p = .780$), validating initial group equivalency prior to intervention.*

### 4.2 Cognitive Knowledge Gains (CC-KAT)

Descriptive statistics and comparative performance across assessment intervals are summarized in Table 1.

***Table 1: Descriptive and Inferential Statistics for CC-KAT (Max Score = 30)***

| **Group** | **Pre-test ($T_0$) Mean (SD)** | **Post-test ($T_1$) Mean (SD)** | **Delayed Post ($T_2$) Mean (SD)** | **Raw Gain ($T_1 - T_0$)** | **Retention Gain ($T_2 - T_0$)** |
|---|---|---|---|---|---|
| **Experimental ($n = 70$)** | 13.41 (3.24) | 24.18 (2.85) | 22.84 (2.91) | +10.77 | +9.43 |
| **Control ($n = 70$)** | 13.19 (3.11) | 18.62 (3.42) | 15.21 (3.38) | +5.43 | +2.02 |

Both cohorts demonstrated statistically significant gains in cognitive scores from $T_0$to $T_1$(Experimental: $t(69) = 22.45, p < .001, d = 2.68$; Control: $t(69) = 11.24, p < .001, d = 1.34$). However, the experimental group achieved nearly double the raw score gain of the control group.

To rigorously assess the intervention effect while controlling for minor baseline differences, a one-way ANCOVA was performed on immediate post-test ($T_1$) scores, using pre-test ($T_0$) scores as a covariate.

*Table 2: ANCOVA Summary for Immediate Post-Test ($T_1$) Knowledge Scores*

| Source of Variation | Sum of Squares (SS) | $df$ | Mean Square (MS) | $F$ | $p$-value | Partial $\eta^2$ |
|---|---|---|---|---|---|---|
| **Pre-test ($T_0$) Covariate** | 214.38 | 1 | 214.38 | 23.41 | $< .001$ | .146 |
| **Group Effect (Intervention)** | 1084.72 | 1 | 1084.72 | 118.44 | $< .001$ | .464 |
| **Error** | 1254.68 | 137 | 9.16 | | | |
| **Total** | 66452.00 | 140 | | | | |

The ANCOVA model revealed a statistically significant main effect for instructional methodology ($F(1,137) = 118.44, p < .001, \eta_p^2 = .464$). The partial eta squared indicates that 46.4% of the variance in immediate post-test performance was directly attributable to the game-based learning intervention after adjusting for prior knowledge.

### 4.3 Sub-Domain Cognitive Performance

Analysis of the three distinct sub-domains within the CC-KAT demonstrated that the greatest cognitive disparity emerged within systems thinking and complex environmental dynamics.

Sub-Domain Score Means (Post-Test T1, Max = 10 per category):

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Domain 1: Factual Science

Experimental:  [########--]  8.12

Control:       [#######---]  7.24  (Difference: +0.88, p = .034, d = 0.36)

Domain 2: Systems Dynamics & Feedback Loops

Experimental:  [########--]  7.94

Control:       [#####-----]  5.12  (Difference: +2.82, p < .001, d = 1.28)

Domain 3: Policy & Mitigation Frameworks

Experimental:  [########--]  8.12

Control:       [######----]  6.26  (Difference: +1.86, p < .001, d = 0.82)

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While traditional lecturing achieved comparable outcomes in transmission of basic factual science, it underperformed in developing mental models of systemic causality and ecological feedback mechanisms, where the GBL intervention yielded a large effect size ($d = 1.28$).

### 4.4 Cognitive Knowledge Retention (Delayed Post-Test $T_2$)

At the four-week delayed evaluation ($T_2$), the control group experienced significant cognitive decay, declining from a post-test mean of $18.62$to $15.21(t(69) = 8.12, p < .001)$. In contrast, the experimental cohort demonstrated sustained knowledge retention, exhibiting a minor, non-significant decline from $24.18$to $22.84(t(69) = 1.84, p = .070)$.

A second ANCOVA conducted on the retention scores ($T_2$) with pre-test baseline covariates confirmed that the group effect remained robust over time ($F(1,137) = 142.18, p <$

.001, $\eta_p^2 = .509$). The GBL group retained 87.5%of their net knowledge gains, whereas the didactic control group retained only 37.2%of their net gains over the identical period.

### 4.5 Affective and Attitudinal Shifts (CASES)

Evaluation of the Climate Attitude and Self-Efficacy Survey (CASES) highlighted parallel advantages for the game-based intervention across affective and motivational domains.

***Table 3: Comparison of Attitudinal Subscale Mean Scores (5-Point Likert Scale)***

| Subscale Dimension | Cohort | Pre-test ($T_0$) Mean (SD) | Post-test ($T_1$) Mean (SD) | $t$-statistic ($T_0$ vs $T_1$) | $p$-value |
|---|---|---|---|---|---|
| **Personal Agency** | Experimental | 2.84 (0.62) | 4.18 (0.54) | 14.28 | $< .001$ |
| | Control | 2.81 (0.59) | 3.12 (0.61) | 3.24 | $.002$ |
| **Systemic Responsibility** | Experimental | 3.12 (0.71) | 4.42 (0.48) | 12.82 | $< .001$ |
| | Control | 3.18 (0.68) | 3.48 (0.65) | 2.88 | $.005$ |
| **Outcome Expectancy** | Experimental | 2.65 (0.58) | 3.86 (0.52) | 12.16 | $< .001$ |
| | Control | 2.68 (0.55) | 2.74 (0.56) | 0.65 | $.516$ |

Students in the experimental condition exhibited marked increases in perceived personal agency ($d = 1.48$) and systemic responsibility ($d = 1.25$). Control participants, while recording a modest increase in responsibility, showed no statistically meaningful change in future outcome expectancy, reflecting common reports in literature of passive learning exacerbating environmental fatalism.

### 4.6 User Engagement Analysis

Within the experimental cohort, descriptive evaluation of the UES-SF indicated elevated engagement metrics: Focused Attention ($M = 4.22, SD = 0.58$), Perceived Usability ($M = 4.41, SD = 0.51$), Aesthetic Appeal ($M = 4.38, SD = 0.62$), and Reward Factor ($M = 4.56, SD = 0.49$). Correlation analysis identified a moderate-to-strong positive correlation between individual engagement scores and immediate cognitive post-test scores ($r = .58, p < .001$).

## 5. Discussion

The empirical findings from this study confirm that integrating game-based learning into secondary school environmental science curricula leads to statistically significant improvements in student conceptual knowledge, systemic thinking, and environmental self-efficacy.

### 5.1 Scaffolding Complex Systems Thinking via Dynamic Feedback

The most prominent disparity between instructional conditions was observed in the systems dynamics sub-domain ($d = 1.28$). In traditional didactic environments, students struggle to construct accurate mental models of non-linear ecological systems characterized by time delays and feedback loops (Rooney-Varga et al., 2018). For instance, understanding how regional deforestation reduces evapotranspiration, thereby escalating local temperatures and exacerbating fire-tipping cascades, requires multi-step causal reasoning.

In *EcoVanguard*, these causal paths are not presented as static textual descriptions; they operate as dynamic interactive mechanics. By actively executing policy changes and observing immediate simulated socio-ecological consequences, students move through continuous cycles of concrete experience and abstract reflection (Kolb, 1984). The interactive environment transforms invisible, delayed environmental consequences into salient, experiential feedback, reducing intrinsic cognitive load while promoting germane cognitive processing (Plass et al., 2015).

### 5.2 Explaining Superior Cognitive Retention

A notable finding of this investigation was the high retention rate of cognitive gains demonstrated by the experimental group over a four-week period (87.5% retention vs. 37.2%in the control group). Traditional didactic models rely primarily on semantic memory encoding, which is vulnerable to rapid decay without continuous retrieval practice.

Conversely, game-based learning fosters multi-modal memory encoding by integrating narrative context, visual feedback, spatial representation, and emotional agency (Gee, 2003; Hamari et al., 2016). When students make high-stakes resource allocation decisions within a simulated socio-economic crisis, the emotional and cognitive activation solidifies episodic memory structures. The learner does not merely recall a textbook definition; they remember the systemic collapse of their agricultural sector that occurred when they failed to mitigate rising temperatures, anchoring the abstract concept in contextual experience.

### 5.3 Mitigating Eco-Anxiety and Cultivating Agency

Beyond cognitive gains, the attitudinal shifts observed in the CASES survey underscore the affective utility of serious games. Passive exposure to climate change curricula frequently induces feelings of paralysis, existential dread, and fatalism—a phenomenon widely documented as eco-anxiety (Ouariachi et al., 2020). When instruction focuses exclusively on catastrophic projections without offering practical agency, students disengage psychologically.

The *EcoVanguard* intervention reversed this response, producing substantial gains in personal agency and outcome expectancy. By placing students in an active problem-solving role, the game reinforces the principle that policy selections, technological deployments, and civic initiatives can alter ecological trajectories. This aligns directly with Bandura's (1997) self-efficacy theory: enactive mastery experiences achieved within a simulated digital environment build the psychological groundwork for real-world environmental stewardship and civic participation.

### 5.4 Pedagogical and Curricular Implications

These findings present direct implications for educational policy makers, curriculum developers, and classroom teachers:

- **Curricular Integration over Supplementary Novelty:** Serious games must not be deployed as isolated leisure activities or rewards; they must be embedded within scaffolded lesson sequences featuring pre-game contextualization and post-game analytical debriefing.
- **Assessment Modernization:** Standardized evaluations must evolve beyond fact-recall formats toward scenario-based and computational problem-solving tasks that properly assess dynamic systems literacy.
- **Teacher Training and Institutional Support:** Successful adoption demands institutional infrastructure, including capable digital hardware, reliable local network

configurations, and targeted professional development to guide educators in transitioning from lecturers to learning facilitators.

## 6. Limitations and Future Directions

Several methodological limitations should be considered when interpreting these findings:

1. **Quasi-Experimental Design:** Although baseline equivalence was confirmed, participants were sampled from intact classes within two suburban secondary schools, which may constrain direct generalizability to alternative socioeconomic, cultural, or rural educational contexts.

2. **Platform Constraints:** *EcoVanguard* was tested on desktop computers; school settings with limited computer lab infrastructure or reliance on mobile operating platforms were not evaluated.

3. **Novelty Effect:** While the four-week delayed retention test verified durable knowledge acquisition, the heightened initial engagement may have been partially influenced by the novelty of digital gaming relative to routine textbook routines.

Future research should examine the scalability of mobile-optimized climate gaming platforms and evaluate collaborative multiplayer configurations, tracking whether collaborative negotiation enhances civic engagement beyond single-player configurations. Additionally, longitudinal designs tracking participants over multiple years could examine whether game-instilled self-efficacy translates into measurable pro-environmental community behaviors.

## 7. Conclusion

This study provides robust empirical evidence that game-based learning serves as an effective instructional methodology for advancing climate change education among secondary school youth. By translating complex, delayed socio-ecological processes into an interactive, experiential simulation, the *EcoVanguard* platform generated statistically significant and durable improvements in scientific conceptual knowledge, dynamic systems comprehension, and environmental self-efficacy compared to traditional didactic instruction. As global educational frameworks increasingly prioritize sustainability and twenty-first-century competencies, embedding structured, serious games into standard curricula offers a scalable pathway to prepare the next generation for the environmental challenges ahead.

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