

Systematic Review

From Engagement to Resilience: A Systematic Review of Game-Based Learning for Environmental Resilience

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Abstract

As Education for environmental resilience increasingly adopts Game-based learning (GBL) to address climate challenges, a critical ambiguity remains regarding how learning outcomes are structured. While games effectively enhance learner engagement, it is unclear whether this affective participation translates into the higher-order competency of sustainable climate resilience. To address this, this study followed PRISMA guidelines to conduct a systematic literature review (SLR) of 175 studies published between 2015 and 2025. We adopted a hierarchical taxonomy to code outcomes, distinguishing between affective precursors (empathy), cognitive foundations (systems thinking), and the ultimate goal of resilience (adaptive action competence). The macro-analysis indicated that although the complexity of game simulations has risen, evaluations often remain arrested at the motivational level due to a disjunction between game affordances and instructional support. Multi-level coding further reveals that specific mechanisms, such as dynamic perturbation, spatio-temporal feedback, and resource trade-offs, provide the structural scaffolding necessary to elevate learning from shallow empathy to cognitive resilience. Based on these findings, we propose the Game–Teacher–Resilience (GTR) Framework, arguing that transformative education requires coupling specific mechanics with pedagogical intervention to bridge the gap between engagement and resilience.

Keywords: environmental resilience; Game-based learning (GBL); system resilience; teacher scaffolding; PRISMA



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1. Introduction

In an era of intensifying climate uncertainty, Education for environmental resilience faces fundamental challenges [1]. Addressing complex global issues cannot rely only on classroom instruction and textbooks, which often makes climate science abstract and disconnected from students' lived realities [2–5]. Education must shift toward developing advanced competencies in sustainability [6,7]. In this study, we define Environmental Resilience not merely as the ability to recover from a shock, but as the capacity of a socio-ecological system, and the learners acting within it, “to absorb disturbance and reorganize” while undergoing change so as to still retain essentially the same function, structure, identity,

and feedbacks [8,9]. Transposing this into educational objectives, we posit resilience as a higher-order competency equivalent to Action Competence Adaptive Capacity [10]. To avoid conceptual conflation, this review employs a hierarchical operational taxonomy to code learning outcomes:

- **Affective Precursors:** Concepts such as empathy, engagement, and motivation, which serve as the entry point for learning but do not constitute resilience itself.
- **Cognitive Foundations:** Concepts such as systems thinking and mental models, which provide the necessary understanding of inter-dependencies.
- **Environmental Resilience (Target Outcome):** The ultimate capability to navigate resource trade-offs, adapt to dynamic perturbations, and execute responsible decisions under uncertainty [11,12].

To address this need, projects such as *Water Ways* have emerged [12–14]. Leveraging the visualization and interactive advantages of high-fidelity 3D simulations, these initiatives aim to bridge the gap between abstract ecological science and embodied cognition, acting as communicative bridges to resolve students, teachers and parents' divergences [15–17]. This offers a potential virtual testing ground for these sustainability competencies, consistent with evidence on the value of game elements in natural science education [18,19].

Despite these technical advancements, reviewing Game-based learning (GBL) studies revealed a critical limitation [20,21]. Studies frequently treat student satisfaction, enjoyment, and technical immersion (often linked to flow) as primary metrics [22,23]; however, the extent to which these indicators translate into sustainable action competence is unclear [24–26].

As our review highlights, current research suggests that without appropriate pedagogical integration, gamified approaches are limited to visual engagement [20,27–29]. Existing games often fail to support the cross-temporal causal reasoning and resource logic central to sustainability science [5,26,30,31]. Achieving UN's sustainability goals requires more than technical realism; it specifically involves exploring how specific game mechanics and teacher scaffolding can be coupled, a process requiring digital transformation in teacher professional development [32], to support the transformation from passive experience to deep systems thinking [33–35].

This study presents a systematic review of GBL for sustainability over the past decade (2015–2025), encompassing diverse implementations from green building to open resource strategies [20,36,37]. Employing a Systematic Literature Review method following PRISMA guidelines, we examine how game mechanics and pedagogical instruction are combined to build student resilience [5,20,38,39]. This study addresses the following three core research questions:

- **RQ1:** How have research focus and methodologies in this field evolved over the past decade?
- **RQ2:** How do game mechanics interact with teacher support? Specifically, how does this interplay determine whether learning outcomes are limited to transient engagement or translate into long-term sustainability competencies?
- **RQ3:** Based on the findings above, how can an integrated framework be constructed to guide the design and pedagogical implementation of future Education for environmental resilience initiatives?

2. Methodology

2.1. Integrated Research Design: From Macro-Trends to Micro-Mechanisms

To bridge the gap between broad bibliometric patterns and specific pedagogical mechanisms, this study employs an explanatory sequential mixed methods design [40]. This approach structures the inquiry into two distinct yet connected phases, creating a “funnel” from the full dataset down to a high-resolution subset.

The process begins with a quantitative macro-analysis of the full corpus ($N = 175$) to identify dominant clusters and statistical trends (Phase 1). These quantitative findings then serve as the filtering criteria to purposively select a representative subset of 36 exemplary studies (referred to hereafter as the “Core 36”). In Phase 2, these core papers undergo qualitative content analysis to explain how the design features identified in the first phase actually function in practice. This sequential structure ensures that the qualitative deep dive is not arbitrary, but directly grounded in the empirical evidence of the broader field.

- **Quantitative Screening:** The initial macro-analysis of 175 studies (see Section 3.1) revealed a structural paradox. While “Teacher Absent” designs are dominant ($n = 103$), they frequently result in shallow outcomes (Motivation Only). However, a concurrent trend showed a significant rise in High-Fidelity 3D or Spatial technologies (VR, AR, 3D Simulations).
- **The Bridging Decision:** This quantitative trend informed the qualitative sampling. To understand how technology might compensate for teacher absence, we did *not* select based on outcomes (which would be circular). Instead, we selected based on technological affordance. Table 1 explicitly documents these bridging decisions, detailing how specific quantitative findings narrowed the focus of the qualitative synthesis. We isolated 36 studies (referred to as the “Core 36”) that utilized High-Fidelity 3D environments to investigate whether spatial mechanics could functionally substitute for human scaffolding.
- **Qualitative Explanation:** Consequently, the qualitative coding (see Section 3.2) focused exclusively on this “Core 36” subset. As illustrated in Figure 1, the inductive coding process on the “Core 36” moved from raw extraction (Data-Driven) to the theoretical GTR Framework (Theory-Driven): we extracted specific mechanical affordances (e.g., Spatio-Temporal Feedback) within these 3D environments to explain why some achieved “Systems Thinking” while others did not.

Table 1. Methodological Integration: How Quantitative Findings Directed Qualitative Sampling.

Phase 1: Quantitative Finding	Bridging Question	Phase 2: Qualitative Decision
Trend: 58.9% of studies are “Teacher Absent” ($n = 103$), often leading to shallow engagement.	Can technology functionally replace the teacher?	Focused coding on “Teacher Absent” papers to isolate system-driven effects.
Pattern: A significant subset utilizes High-Fidelity 3D or Spatial technologies (VR or AR).	What are the unique affordances of 3D space for resilience?	Selection of the Core 36: Sampled strictly based on High-Fidelity 3D capabilities (avoiding outcome-based circularity).
Outcome: Within the 3D subset, outcomes vary from “Empathy” to “Systems Thinking.”	Which specific mechanisms drive deep cognition in 3D?	Mechanism Extraction: Inductive coding of the Core 36 to identify the GTR pillars (DP, STF, RT).

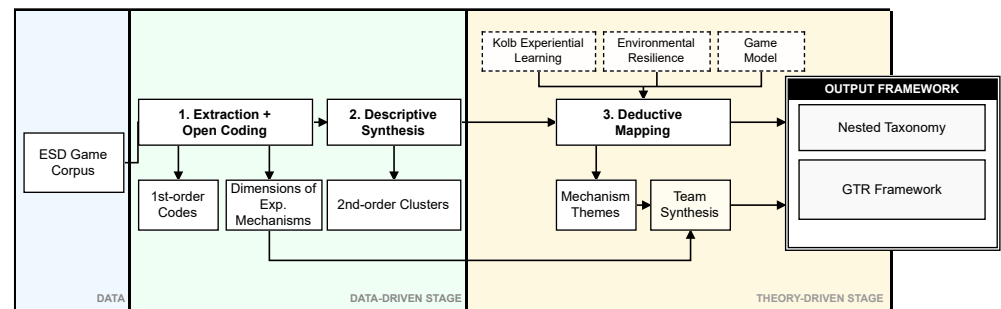


Figure 1. The qualitative synthesis workflow (Phase 2). This process illustrates the inductive coding applied to the "Core 36" studies, transitioning from raw data extraction (Data-Driven) to the construction of the theoretical GTR Framework (Theory-Driven).

2.2. Data Collection and Search Strategy

This study adopted a systematic literature review methodology, following the PRISMA 2020 guidelines to ensure consistent data retrieval [5,41,42]. To examine the intersection of GBL and Education for environmental resilience over the past decade, the search window focused on publications from January 2015 to May 2025 [20]. Regarding PRISMA quality assessment (Items 11 & 18), consistent with the mixed-methods design, we did not employ a binary 'pass or fail' quality appraisal tool (e.g., MMAT). Instead, we evaluated the methodological quality of the included studies based on two core indicators of validity identified in our research questions: (1) the presence of instructional intervention (controls for pedagogical confounding), and (2) the objectivity of measurement instruments (controls for subjective reporting bias). These quality indicators were coded and analyzed as structural variables in the results (see Section 3.3).

2.2.1. Database Selection

Data retrieval was conducted across three primary high-impact databases to ensure interdisciplinary coverage [5,20,38,39]:

- **Scopus:** Selected for its extensive indexing of high-quality literature in education, social sciences, and human–computer interaction [39,42,43]. Searches utilized the TITLE-ABS-KEY field to target terms within titles, abstracts, and keywords [39,42].
- **Web of Science (WoS):** Chosen for its global reach in citation indexing [20,38]. The TS= (Topic) field was employed to ensure search strategy equivalence with Scopus [42].
- **ACM Digital Library:** Included to capture technical and design-oriented proceedings (e.g., CHI, IDC, CHI PLAY) [5,42,43]. Searches combined *Abstract* and *Keyword* fields to maximize metadata coverage [43].

2.2.2. Search Terms and Logic

The search strategy employed Boolean logic to combine keywords across three core dimensions [5,42,43]. While specific syntax varied slightly to accommodate database architectures, the conceptual combinations remained consistent as detailed in Table 2 [5,39].

Correspondingly, the WoS search utilized the TS= field with identical Boolean logic. For the ACM Digital Library, due to input constraints, keywords were distributed across abstract and full-text metadata fields to ensure comprehensive retrieval. All initial records were imported into Zotero for duplicate management.

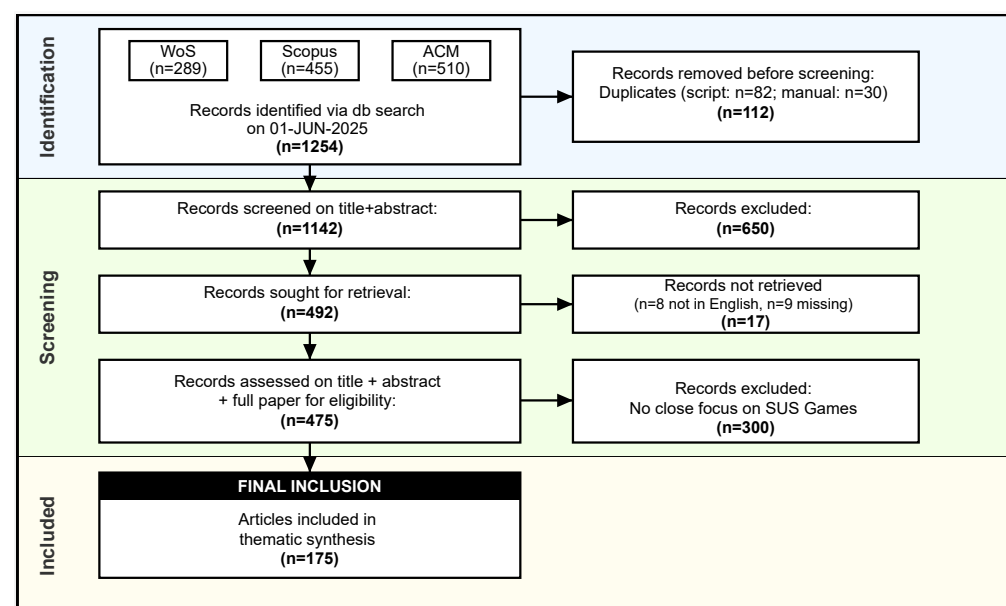
Table 2. Systematic Search Strategy: Conceptual Dimensions and Execution.

(a) Search Strategy Dimensions, Keywords, and Rationale	
Dimension	Keywords and Rationale
Game Dimension	Keywords: <i>“Game-based learning”, “educational game”, “serious game”, gamification.</i> Rationale: Selected to encompass diverse implementations of game-based interventions across different media forms.
Pedagogical Dimension	Keywords: <i>teacher, classroom, pedagogy, instruction.</i> Rationale: Used to isolate studies involving active pedagogical intervention or verifiable classroom scenarios.
Sustainability Dimension	Keywords: <i>sustainab *, “environmental education”, ecology, climate, pro-environmental *.</i> Rationale: Includes both broad sustainability concepts and specific environmental contexts.
(b) The Exact Search Query String Used in Scopus	
Scopus Query String	
TITLE-ABS-KEY((“Game-based learning” OR gamification OR “educational game” OR “serious game”) AND (teacher OR classroom OR pedagogy OR instruction) AND (sustainab * OR “environmental education” OR ecology OR climate))	

Note: The asterisk (*) indicates a wildcard for truncation. Double quotes (“ ”) indicate exact phrase searching. Keywords are italicized for visual distinction. Boolean operators (AND, OR) are used to combine dimensions. Single words (e.g., gamification) and wildcards are unquoted to allow for stemming and variations.

2.2.3. PRISMA Selection Procedure

As illustrated in the PRISMA flow diagram (Figure 2), the initial identification phase yielded a total of 1254 records across the three databases (WoS: 289; Scopus: 455; ACM: 510). Following the removal of 112 duplicates (comprising both script-based and manual cleaning), 1142 records remained for the screening phase. During the primary screening based on titles and abstracts, 650 records were excluded for irrelevance (e.g., non-educational focus or purely theoretical papers). Subsequently, 492 records were sought for retrieval. After assessing full-text eligibility, an additional 300 articles were excluded as they lacked a close focus on Sustainability games. Ultimately, 175 articles met all inclusion criteria and were selected for the final thematic synthesis.

**Figure 2.** PRISMA flow diagram detailing the literature identification, screening, and inclusion process (2015–2025).

2.3. Qualitative Analysis and Coding Protocol

Focusing on these 175 core documents, we adopted a Codebook Thematic Analysis approach [44], integrated with Directed Content Analysis [45] to systematically map the intersection of game mechanics and pedagogical roles. Unlike Reflexive Thematic Analysis which prioritizes purely subjective interpretation, Codebook Thematic Analysis allows for the use of a structured coding frame, essential for the quantitative mapping (e.g., Sankey diagrams) presented in this study, while retaining the qualitative depth required to interpret complex pedagogical interactions.

To address the research questions, this study employed a hybrid analysis approach. Structural variables (Teacher Role, Learning Outcomes) were coded deductively based on the initial PRISMA screening, while pedagogical mechanisms were derived inductively using Affinity Diagramming [46,47]. This process generated a systematic list of snippets containing key pedagogical terms (such as teacher, instructor, facilitator, guidance, or scaffolding) along with the 600 characters immediately preceding and succeeding each keyword occurrence to ensure semantic context. We refer to these context-rich segments as keyword concordances [46]. An illustrative example of such a keyword concordance is presented in Figure 3, which demonstrates how the raw text (left) is translated into interpretative codes (right).

Context	... As the game contains many dimensions... the facilitator should be prepared to distill the most important elements for the students. Findings: Facilitation was also important for ensuring a smooth simulation. Instructors have the overarching perspective... Their ability to identify barriers and opportunities for learning are an asset. The finding that skilled facilitation can lead to improved game play is reinforced... (Source: Snippet from Jedd et al., 2025)	1st order tags	Objectives articulated by professor	Incentive for participation
	Additional assignments / essays		Specific instructions given	
	Facilitator distills elements		Coordinators, referees, guides	
	Identify barriers / opportunities		Ensure a smooth simulation	
		2nd order tags	Instructor as Critical Pedagogical Intervenor	
			Components of Guided Experiential Learning	
			Integrating Objectives with Participation	

Figure 3. Example of a keyword concordance (600 characters before and after the keyword) for “facilitator or facilitation” on the left, and the respective thematic synthesis coding (1st and 2nd order tags) on the right. The red dashed underlines indicate the occurrences of the searched keywords within the text snippet. Source: snippet derived from Jedd et al. [48].

2.3.1. Coding Scheme and Operational Definitions

Following the Directed Content Analysis paradigm, we developed an a priori codebook derived from the initial literature screening. To ensure coding consistency, we established rigorous operational definitions and decision rules for the three primary teacher roles. As detailed in Table 3, these categories were treated as mutually exclusive for the

primary classification, although we acknowledge the practical simultaneity of roles in synchronous settings (see Section 3.2).

Table 3. Operational Definitions and Coding Guidelines for Teacher Roles.

Category	Operational Definition & Coding Guideline	Representative Examples
Gatekeeper	Definition: The instructor acts as a validator or boundary-setter who enforces simulation rules, corrects misconceptions, or defines the limits of possible actions. Guideline: Code as Gatekeeper IF the text explicitly mentions the teacher approving topics, modifying game parameters to constrain students, or intervening to ensure simulation accuracy.	“The teacher defined the boundaries of what is possible within the simulation.” [49] “Instructor approved student topics before game design began.” [50]
Facilitator	Definition: The instructor acts as a mediator who guides post-game reflection (debriefing), manages social conflicts, or bridges game metaphors to reality. Guideline: Code as Facilitator IF the primary intervention involves leading debriefing sessions, managing emotional frustration, or facilitating discussions on real-world transfer.	“Facilitators led a four-phase debriefing to translate emotions into analysis.” [48] “Teacher mediated conflicts between player groups.” [51]
Absent	Definition: The learning process relies primarily on the game system itself, with the teacher absent or present only for logistical support. Guideline: Code as Absent IF the teacher is not mentioned, or is described solely as providing technical support (e.g., fixing hardware) without pedagogical scaffolding.	“Students played the game autonomously in the lab.” [2] “The app provided all instructions; no teacher intervention was recorded.” [16].

2.3.2. Reliability and Rigor: The Negotiated Consensus Approach

Addressing the complexity of pedagogical coding, we prioritized negotiated consensus over statistical inter-rater reliability metrics (e.g., Cohen’s Kappa). In Human–Computer Interaction (HCI) and educational research, statistical metrics often artificially flatten complex, high-inference concepts by forcing coders to agree on superficial features [52,53]. Given that “Teacher Scaffolding” is a nuanced construct dependent on subtle contextual cues, we followed the rigor protocol recommended by McDonald et al. [52] and Valenzuela et al. [54]:

- **Training and Calibration:** All four coders initially coded a random sample of 20 papers (approx. 10% of the corpus). Discrepancies were discussed to refine the operational definitions in Table 4, particularly distinguishing between “technical support” (Absent) and “pedagogical scaffolding” (Facilitator).
- **Independent Coding with Drift Monitoring:** The remaining articles were distributed, with 20% of the dataset ($n = 35$) subjected to double-blind coding to monitor drift.
- **Collaborative Adjudication:** Instead of calculating a binary agreement statistic, all discrepancies in the double-coded set were resolved through collaborative adjudication. For instance, studies exhibiting hybrid teacher roles (e.g., Jedd et al. [48]) were

flagged and discussed by the full team until a consensus on the *primary* pedagogical function was reached. This process ensures that the final categorization reflects a deep contextual understanding rather than superficial keyword matching [55,56].

Table 4. Phases of the Qualitative Analysis and Coding Procedures.

Phase	Process Description	Example or Outcome
Independent Coding [27,30,43,57,58]	Four researchers independently conducted close reading to extract key segments regarding Teacher Behaviors (e.g., guiding) and Game Mechanism Features (e.g., fidelity).	Example: A segment stating “teacher guides students to reflect on trade-offs” was coded as Scaffolding Intervention.
Affinity Diagramming (Open Coding) [30,46,47,59,60]	Merged similar descriptive codes during collaborative workshops.	Example: Grouped specific terms like “flood scenarios,” “drought events,” and “pollution peaks.”
Affinity Diagramming (Axial Coding) [30,46,59,60]	Elevated grouped codes into abstract theoretical dimensions.	Example: The events above were abstracted into dynamic perturbation. This constructed the classification strategies in Result II.
Consensus & Iteration [5,27,38,56,57,61,62]	Held regular meetings to resolve discrepancies by back-tracing to original texts until inter-rater agreement was achieved.	Outcome: This iterative process yielded the “Four Design Clusters” presented in Result I.

2.4. Sub-Sample Selection: High-Fidelity 3D Exemplars

To address RQ3 regarding the specific affordances of immersive technologies, we extracted a core sub-sample of 36 studies (the “Core 36”). We established a technological inclusion criterion rather than an efficacy-based one to avoid the risk of circularity, where studies are selected based on reported outcomes.

The studies utilized High-Fidelity 3D Simulations or Spatial Environments (including 3D Desktop Simulations, VR, and AR). We excluded 2D casual games, quizzes, and non-digital board games from this specific mechanism analysis. This selection is grounded in the theoretical premise that Environmental Resilience requires unique spatial affordances that 2D media cannot fully provide:

- **Epistemic Visibility (Making the Invisible Visible):** Resilience requires understanding complex, invisible ecological processes (e.g., groundwater flow, carbon cycles). High-fidelity 3D simulations offer unique affordances to render these abstract data into perceptible spatial cues via volumetric rendering and particle systems [63].
- **Bridging Psychological Distance:** Climate change is often perceived as distant and 3D spatial environments leverage embodied cognition and presence to induce a visceral emotional response, bridging the gap between abstract data and personal relevance [64].
- **Safe Experimentation (The Sandbox):** Resilience is an action competence. 3D physics engines provide a safe “sandbox” for simulating non-linear dynamic perturbations

(e.g., flood dynamics) without real-world risk, allowing learners to experiment with trade-offs in a situated context [65].

3. Results I: Research Trends and Gaps

This section presents a synthesized analysis of the selected 175 empirical studies. We begin by examining the temporal and descriptive distributions to understand the field's trajectory, followed by a critical analysis of the divergence between pedagogical design and actual effectiveness.

3.1. Descriptive Analysis of the Selected Corpus

To contextualize the current state of empirical evidence, we analyzed the temporal distribution of the 175 studies that met our inclusion criteria. As illustrated in Figure 4, the volume of eligible research included in this review shows a significant upward trajectory.

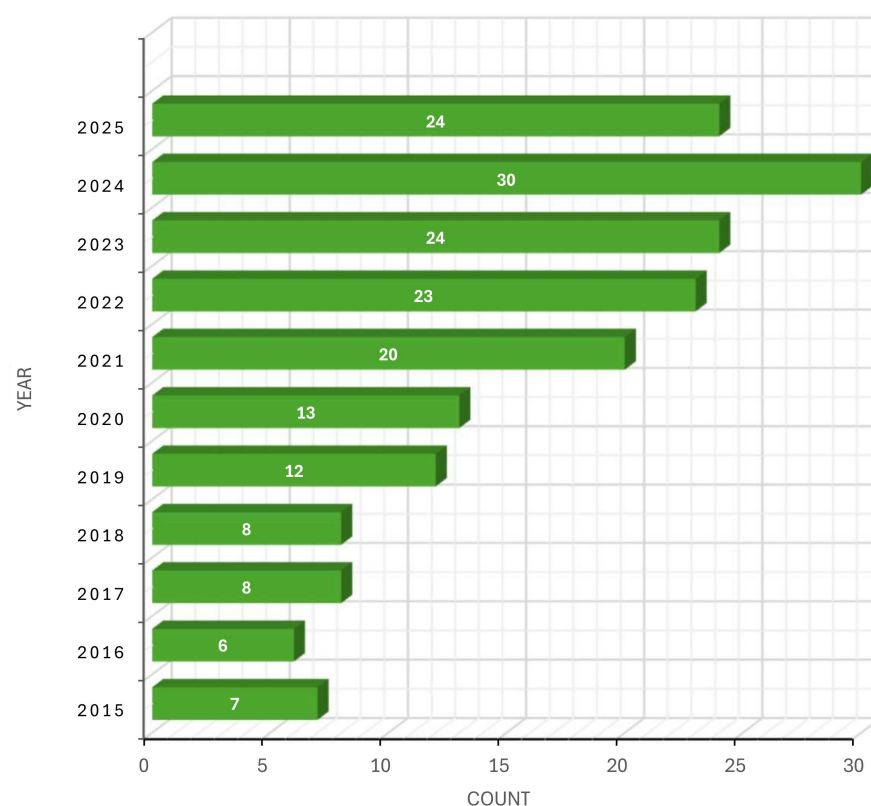


Figure 4. Distribution of the 175 included studies by year of publication. The increasing number of selected papers post-2020 indicates a growing density of empirical work meeting the review's quality and relevance criteria.

The data reveals a distinct intensification in high-relevance scholarship. Between 2015 and 2019, fewer studies (averaging 8 per year) met the rigorous inclusion criteria for empirical validation and game-based intervention. However, a sharp inflection point appears in the 2020–2021 period. This surge culminates in 2024, which accounts for 30 included studies, which is a nearly fourfold increase compared to the start of the decade.

This trend suggests that the field is not only expanding in volume but also in maturity, producing a higher density of empirical studies capable of passing strict screening protocols. The diversification of design approaches observed within this growing corpus necessitates a structured typology. Consequently, we categorized the selected studies into four distinct design clusters to better understand how these emerging technologies are being applied.

3.2. Overview: The Divergence of Pedagogy and Design

Based on the inductive analysis of the 175 empirical studies, and responding to the design diversity noted above, we classified the corpus into four distinct design clusters. As detailed in Table 5, these categories range from high-fidelity visualizations aimed at emotional resonance to complex simulations fostering systems thinking.

Table 5. The Four Design Clusters of Game-based Environmental Learning.

Cluster Category	Key Attribute	Definition & Focus
Systems Thinking & Simulation [1,26,31,48,66–71]	Model Fidelity	Focuses on the precise simulation of variables (e.g., water flow, carbon cycles) to test students' ability to understand complex causal relationships.
Teacher-Integrated [24,28,30,50,56,60,72–75]	Scaffolding	Games deployed as part of a formal curriculum where the instructor plays a primary role in facilitating the learning process.
Sustainability-Oriented [5,14,29,76–82]	Goal Alignment	Projects designed to address targets within the UN Sustainable Goals and specific issues like flood control.
Mechanics & Empathy [3,51,54,55,66,67,83–88]	Affective Engagement	Utilizes visual and narrative affordances to evoke emotional resonance with nature, typically employed in autonomous, learner-led settings.

The empirical robustness of these clusters is underpinned by a significant diversity in target populations and technological media within the analyzed corpus. Regarding demographics, applications span from early childhood and primary education [89–92] to specialized vocational training for law students and rural communities [19,93–96]. Thematically, while climate crisis mitigation remains central [97–102], the scope extends to broader social competencies and general environmental awareness [103–110]. Technologically, the landscape has evolved beyond simple desktop simulations to include diverse immersive formats such as Location-Based AR [111–115], VR environments [116–122], and hybrid escape room experiences [50,123–126], illustrating the versatile implementation of these design clusters across the field.

The spatiotemporal distribution of these clusters, visualized in Figure 5, reveals that the field has not evolved through a simple linear progression but rather exhibits a distinct divergence between pedagogy and design. A structural analysis of the diagonal axis demarcates a clear boundary between Instructor-Involved and Learner-Led domains [46].

On one side of this divide, particularly in the upper-right quadrant post-2020, there has been explosive growth in Mechanics and Empathy-oriented designs (Orange). This trend suggests that while current autonomous game designs excel at delivering affective immersion, the transition to structural resilience often benefits from further scaffolding support.

Conversely, the lower-left quadrant shows that Systems Thinking (Light Blue) remains firmly anchored below the dashed line, highly coinciding with Teacher-Integrated instruction (Dark Blue).

This spatial separation underscores a critical design opportunity: while high-fidelity simulations provide powerful visual mental models (Upper-Right), the translation of this engagement into high-order cognition has historically relied on the explicit scaffolding provided by instructors (Lower-Left). Consequently, the education for environmental resilience cluster involves a dual support structure (Green nodes in Figure 4). This finding

implies that future designs must not only aim to synergize with human instruction but also to embed these cognitive guiding tasks directly into game mechanics, effectively integrating the pedagogical role into the technology itself.

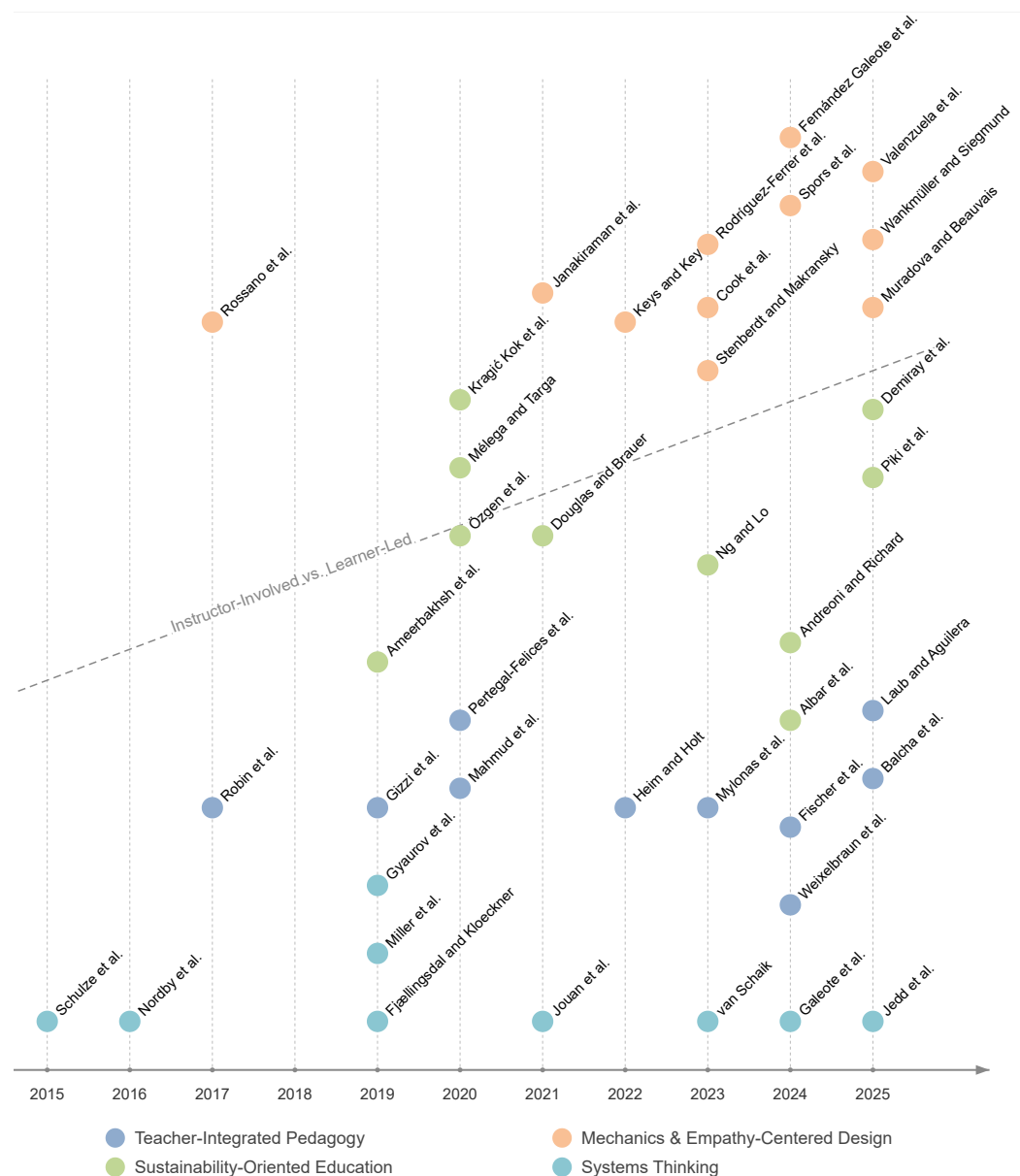


Figure 5. The evolution of research themes and pedagogical positioning in representative exemplars selected from the full corpus ($N = 175$). Note: To visualize the distinct characteristics of the four design clusters (see Table 5), this chart plots key representative studies selected from the complete dataset. The dashed diagonal line distinguishes between Instructor-Involved (lower-right) and Learner-Led (upper-left) domains. Designs above the line rely on specific game affordances to function as algorithmic pedagogical agents, whereas clusters below the line typically require human facilitation. (Sources cited in figure: [1,3,5,14,24,26,28–31,48,50,51,54–56,60,66–88])

3.3. Evidence Flow Analysis: From Design Intent to Implementation Gaps

Figure 6 visualizes the full chain of evidence, mapping the trajectory from Design Clusters to Teacher Roles, Learning Outcomes, and Measurement Types. The aggregate flow in the Teacher Role column (177 instances) marginally exceeds the total number of unique studies ($N = 175$). This reflects the hybrid nature of synchronous simulations,

where two specific studies [48,49] necessitated dual coding for simultaneously fulfilling both Gatekeeper and Facilitator functions.

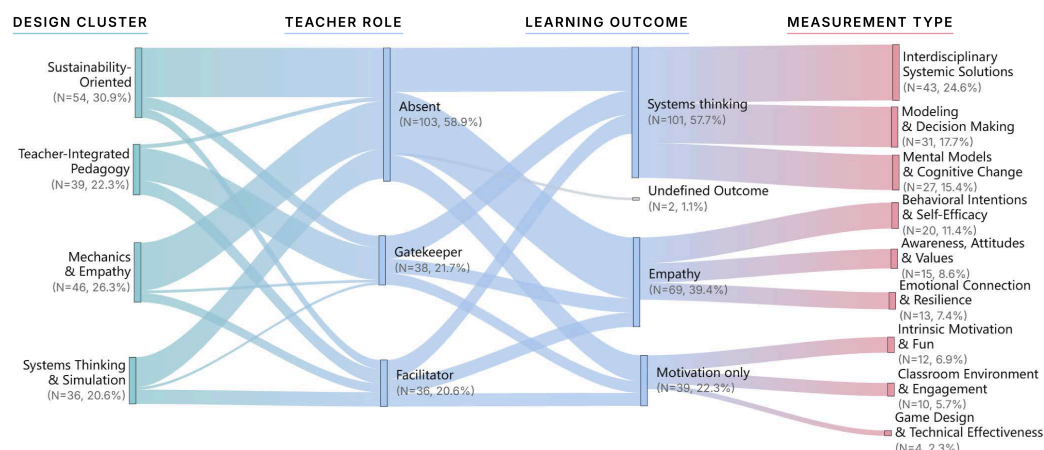


Figure 6. Evidence Flow Sankey Diagram. Note: The diagram illustrates the flow of 175 empirical studies. The width of the bands is proportional to the number of studies.

3.3.1. Design Clusters and Implementation Modes

The leftmost column reveals how design intent influences implementation strategies. The data indicates a strong correlation between specific design clusters and the presence of human scaffolding. The “Mechanics & Empathy” cluster ($n = 46, 26.3\%$) and the “Sustainability-Oriented” cluster ($n = 54, 30.9\%$) predominantly flow into the Teacher Absent node, indicating that these designs are largely deployed as autonomous learning tools. In contrast, the “Teacher-Integrated Pedagogy” ($n = 39, 22.3\%$) and “Systems Thinking & Simulation” ($n = 36, 20.6\%$) clusters are more frequently distributed across the Gatekeeper and Facilitator roles. This distribution suggests that designs focusing on complex simulations or formal curricular integration typically necessitate human mediation to function as intended.

3.3.2. The Distribution of Teacher Roles

The central node highlights the dominance of the Teacher Absent format ($n = 103, 58.9\%$), suggesting that over half of the empirical studies rely on automated pedagogical agents. However, the data reveals distinct outcome patterns across the three roles. The Teacher Absent category exhibits the widest dispersion in outcomes; while it contributes the largest absolute number to Systems Thinking ($n = 34$), it is simultaneously the primary source for Empathy ($n = 47$) and Motivation Only ($n = 20$). Conversely, the Gatekeeper role ($n = 38$) demonstrates a higher conversion rate toward cognitive outcomes, with nearly half of its associated studies ($47.4\%, n = 18$) mapping explicitly to Systems Thinking. Distinct from both, the Facilitator role ($n = 36, 20.6\%$) shows a balanced distribution, supporting Systems Thinking while maintaining a significant connection to Empathy outcomes, indicating that active facilitation is often used to bridge cognitive understanding with emotional engagement.

3.3.3. The Prevalence of Systems Thinking

Regarding learning outcomes (Column 3), Systems Thinking has emerged as the dominant reported category ($n = 101, 57.7\%$), surpassing Empathy ($n = 69, 39.4\%$) and Motivation Only ($n = 39, 22.3\%$). The data shows that Systems Thinking is not exclusive to simulation games but is reported across all four design clusters. However, the validity of this widespread outcome must be contextualized by the measurement instruments used to verify it, as detailed in the final column.

3.3.4. Stratification of Measurement Types

The rightmost column (“Measurement Type”) provides a granular breakdown of the instruments used to verify these outcomes, revealing a three-tiered distribution based on methodological rigor.

The first tier comprises performance-based measures ($n = 74$), which utilize objective data to assess competence. This category includes Interdisciplinary Systemic Solutions ($n = 43$, 24.6%), typically evaluated through standardized rubrics applied to student-generated artifacts and project deliverables, and Modeling & Decision Making ($n = 31$, 17.7%), which predominantly relies on in-game telemetry, simulation logs, and algorithmic performance metrics to track user actions directly.

The second tier focuses on the structural organization of knowledge, represented by the 27 studies (15.4%) measuring Mental Models & Cognitive Change. Unlike simple recall tests, these studies employ structural assessment tools, such as concept maps and Causal Loop Diagrams, to visualize the complexity of learners’ internal understanding.

Finally, the third tier, covering approximately 42% of the corpus, relies on perception-based and affective indicators. This segment aggregates Behavioral Intentions ($n = 20$), Awareness ($n = 15$), Emotional Connection ($n = 13$), Intrinsic Motivation ($n = 12$), and Classroom Environment ($n = 10$). These constructs are primarily assessed via self-reported Likert-scale questionnaires and semi-structured interviews. This stratification highlights that while the field largely reports Systems Thinking as an outcome, a significant portion of the evidence base depends on self-reported perceptions rather than objectively verified performance.

3.4. Heatmap Analysis: The Contradiction of Quantity and Quality

To measure the impact of teacher absence, we generated a Heatmap Analysis (Figure 7) cross-analyzing the distribution density of teacher roles versus learning outcomes. To ensure the validity of this correlation, this specific analysis focuses exclusively on determinate pedagogical results. Consequently, the two studies previously identified as “Undefined Outcome” (see Figure 6) were excluded from the “Absent” category, resulting in a refined sample of ($n = 101$) for this condition.

The highest density appeared at the intersection of Teacher Absent or Empathy ($n = 47$). This suggests that in the large sample without teacher intervention ($n = 101$), nearly half (46.5%) of the studies stopped at affective experience. This indicates that independent game mechanisms are highly effective at evoking feelings; however, reported outcomes often remain confined to the affective level, failing to document the transition from emotion to critical reflection. This trend is potentially compounded by the reliance on perception-based measurements rather than objective performance metrics. This limitation is not confined to empathy; it mirrors a structural inefficiency in fostering high-order capabilities. As detailed below, identifying this pattern requires distinguishing between absolute frequency and proportional success regarding Systems Thinking:

- **Surface Data:** The Teacher Absent group contributed the highest number of Systems Thinking studies ($n = 34$), far higher than the Gatekeeper group ($n = 18$).
- **Deep Data (Conversion Rate):** However, once base size differences are accounted for, the efficiency gap becomes immediate. Under Teacher Absence, only 33.6% ($34/101$) of studies successfully achieved systems thinking goals. In contrast, when the teacher intervened as a Gatekeeper, this conversion rate jumped to 47.4% ($18/38$); as a Facilitator, it maintained 41.7% ($15/36$).

This efficiency gap of approximately 14 percentage points (47.4% vs. 33.6%) statistically illustrates the catalytic role of the teacher. Current empirical data indicate that teacher guidance is a critical variable ensuring the transformation of learning from shallow moti-

vation to deep system complexities. Future mechanism design must achieve conversion efficiencies comparable to those of human teachers to be effective in teacher-less scenarios.

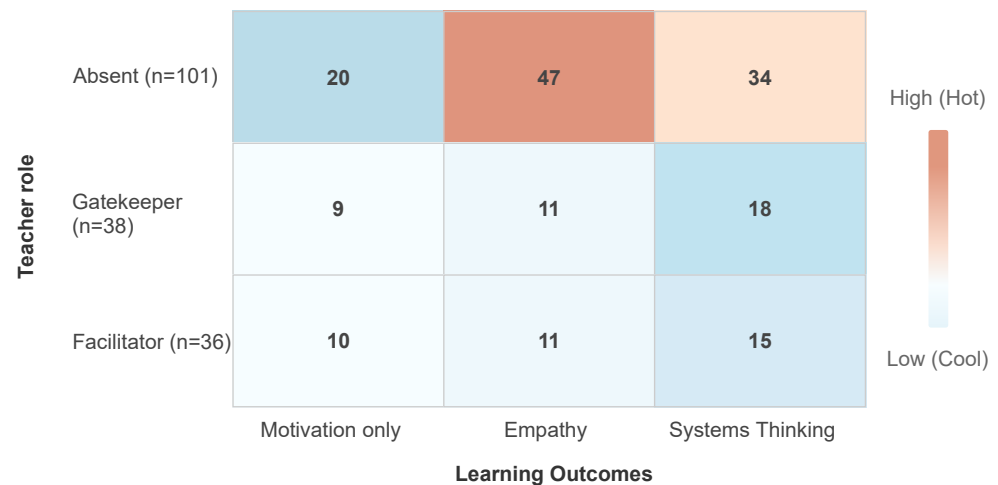


Figure 7. Teacher Roles vs. Learning Outcomes (Validated Data). Note: Data points classified as “Undefined Outcome” ($n = 2$) were excluded from this visualization to ensure the precision of the density distribution.

4. Results II: Building 3D Environmental Resilience Mechanisms

While Result I revealed the structural disjunction typically caused by teacher absence, the qualitative synthesis of 175 papers suggests an alternative perspective: specific game mechanics can successfully substitute for human scaffolding. To understand how game mechanics may compensate for the teacher’s absence, we analyzed the mechanics of the “Core 36” studies that utilized high-fidelity 3D environments. By correlating these mechanism-based affordances with higher-order learning outcomes, we identified three core dimensions that form the 3D Environmental Resilience Framework:

- **Dynamic Perturbation (DP):** Mechanics that introduce sudden systemic shocks to disrupt static mental models.
- **Spatio-Temporal Feedback (STF):** Mechanics for visualizations that bridge the gap between action and distant consequences.
- **Resource Trade-Offs (RT):** Mechanics of constraints that force decision-making under scarcity.

Collectively, these mechanics function as “Gatekeeper” role. Unlike passive entertainment, they act as a pedagogical filter, screening out lower-level game experience and forcing learners to confront cognitive bottlenecks to build deep competence. Table 6 summarizes valid definitions and functions.

Table 6. Core Dimensions of 3D Environmental Resilience Mechanisms.

Dimension	Mechanism Name	Definition and Pedagogical Function
Cognitive	Dynamic Perturbation (DP) [11,26,49,127,128]	Introduces unpredictable, uncontrollable events (e.g., stochastic shocks or catastrophes) to disrupt stable states [11,26,49,127,128], forcing a cognitive shift from rote optimization to iterative adaptation in ill-defined problem spaces [3,48,68,127], simulating the systemic pressure and reflection of Socratic questioning [11,129].

Table 6. *Cont.*

Dimension	Mechanism Name	Definition and Pedagogical Function
Epistemological	Spatio-Temporal Feedback (STF) [11,14,130,131]	Renders invisible ecological data as perceptible spatial cues over time [11,14,130], acting as a visual scaffold to lower the cognitive threshold for abstract concepts [3,34,67,129].
Social	Resource Trade-Offs (RT) [11,48,49,77,129]	Assigns conflicting goals regarding limited resources [11,48,49,129], simulating socio-political complexity and forcing negotiation [4,48,49,77,132,133].

4.1. Dynamic Perturbation (DP)

Standard educational games often follow a linear tutorial–challenge structure [26]. However, this deterministic design contradicts the nature of sustainability challenges, which are wicked problems characterized by deep interconnectivity [11,49,55,70]. Linear pedagogy fails to prepare competencies for real-world Uncertainties [1,26]. To rupture this misconception, studies achieving high scores in Systems Thinking primarily adopted the Dynamic Perturbation (DP) mechanism [26,31,128]. This involves injecting nonlinear, stochastic shocks (such as flash floods, random crop failures, or fluctuating prices [68,127,128]) directly into the game loop. Unlike static quizzes, DP forces players to shift from optimization (executing a perfect plan in a stable state) to adaptation (surviving in a shifting state) [11,48,127,128]. Evidence from Gizzi et al. and Janakiraman et al. shows that random events prevent rote memorization and force continuous monitoring of variables [11,55,75]. This algorithmically driven unpredictability effectively simulates the cognitive load of Socratic questioning [11,129], implicitly asking: “What will you do if the boundary conditions suddenly change?”

4.2. Spatio-Temporal Feedback (STF)

One of the main challenges of games for environmental resilience is the invisibility of ecological processes like groundwater pollution or carbon accumulation [129,130,134]. In traditional teaching, teachers explain these abstract concepts. In 36 core games, Spatio-Temporal Feedback (STF) assumes this explanatory role [16,135]. This mechanism uses 3D shaders and particle systems to render invisible data as perceptible environmental cues, breaking cognitive inertia [68,136,137]. Pedagogically, STF acts as a Visual Scaffold verified by recent green system evaluations [73,115,138]. By translating abstract spreadsheet numbers into spatial reality (e.g., water turning green), it significantly lowers the cognitive threshold [31,34,68,130]. The review shows that games utilizing terrain modification features or pollution diffusion visualization are superior to text interfaces in cultivating Systems Thinking [55,71]. This immediate feedback loop, recently enhanced by GenAI-driven affectivity, allows students to implicitly understand causal relationships without explicit verbal instruction [55,73,139].

4.3. Resource Trade-Offs (RT)

Resilience is not just ecological but also socio-political [5,11,125,140]. The analysis confirms that Resource Trade-Offs (RT) are key for simulating social complexity and organizational interdependencies [49,141,142]. This involves assigning conflicting goals regarding limited resources to different players, ranging from profit-seeking farmers versus conservation-seeking ecologists to manufacturing life-cycle decisions and e-waste man-

agement [132,143,144]. Pedagogically, RT simulates the Gatekeeper function by creating Constructive Friction [11,49,77]. It prevents perfect solutions, forcing players to negotiate regarding land use or disaster response and accept imperfect compromises, which is a hallmark of Systems Thinking [145–147]. The heat map analysis (Result I) indicated that teacher absence usually leads to shallow empathy [55,72,148]. However, the sub-sample that achieved Systems Thinking despite teacher absence almost all included multi-agent resource trade-offs [70,125]. This suggests that resource conflict mechanisms act as a proxy for teacher-led debate, driving students toward deeper synthetic thinking [49,135].

4.4. Synthesis: A Taxonomy of 3D Environmental Resilience Mechanisms

To visually present the screening logic and feature distribution of the 36 foundational papers underpinning the 3D Framework, a Feature Co-occurrence Matrix was constructed [5,20,21,43]. This matrix classifies the selected studies by platform type, including Desktop Simulations [14,17,25,34,54,55,62,68,71,74,76,85,128,129,148–154], Immersive Systems [11,16,66,67,83,130,155–158], and Mixed Modes [49,69,159], and maps their specific performance across three dimensions: Game Mechanics (green), Teacher Support (dark green), and Learning Outcomes (pink) [49,148,150,160–162].

First, there is a distinct sparsity of teacher support [20,24]. The teacher support column is predominantly gray, with only 8 papers containing explicit teacher intervention, confirming that the core sample consists mainly of studies with low human intervention [20]. Second, a mechanism-outcome substitution effect is observable [55,86,153]. Despite the absence of teachers, studies integrating strong mechanics, indicated by dense green blocks, consistently demonstrated high-order learning outcomes, indicated by dense pink blocks [55,153]. The specific cases annotated in the figure provide empirical grounds for subsequent mechanism extraction [20,42]. For instance, desktop simulation cases such as Janakiraman et al. [55] and Taillandier et al. [49] achieved Systems Thinking through significant dynamic perturbation and resource trade-offs, even in the absence of an instructor. Immersive systems like Torreggiani et al. [152] utilized trade-off mechanisms in VR environments to enhance the willingness for resilience action without external assistance. Mixed-mode cases, such as Miller et al. [69], demonstrated the synergistic effects of multi-dimensional mechanisms. This visual evidence suggests that the digital mechanics in these studies assumed the function of pedagogical agents [17,55,82]. A compensation effect is evident in rows lacking teacher support; whenever dynamic perturbation and resource trade-offs are activated, the studies tend to report the acquisition of Systems Thinking [11,49,55].

Furthermore, multidimensional synergy plays a critical role, as the effect of a single mechanism is often less significant than combined mechanisms [11,77]. The matrix reveals that studies possessing both spatio-temporal feedback and trade-off mechanisms have a higher success rate in achieving the highest-order goal of action competence or resilience [11,49,129]. Based on the qualitative coding of these specific success cases, we summarize the three core mechanism dimensions below [49,152].

Figure 8 presents the final Taxonomy of 3D Environmental Resilience Mechanisms [11,26,42]. This framework unpacks the mechanisms of effective game design into nine Base Dimensions (e.g., Temporal, Spatial, Allocative), as defined in the legend [11,136]. Distinct from generic gamification classifications, this taxonomy highlights a combinatorial logic: highly effective mechanisms are often generated through the Intersection of multiple dimensions rather than single elements [2,11,35]. For instance, combining Informational Augmentation (I) with Stochasticity (R) generates dashboards that reveal the impact of random hazard events [14,25,26]. These mechanisms are clus-

tered into three pillars, each addressing a specific pedagogical barrier identified in the literature [42,123,163]:

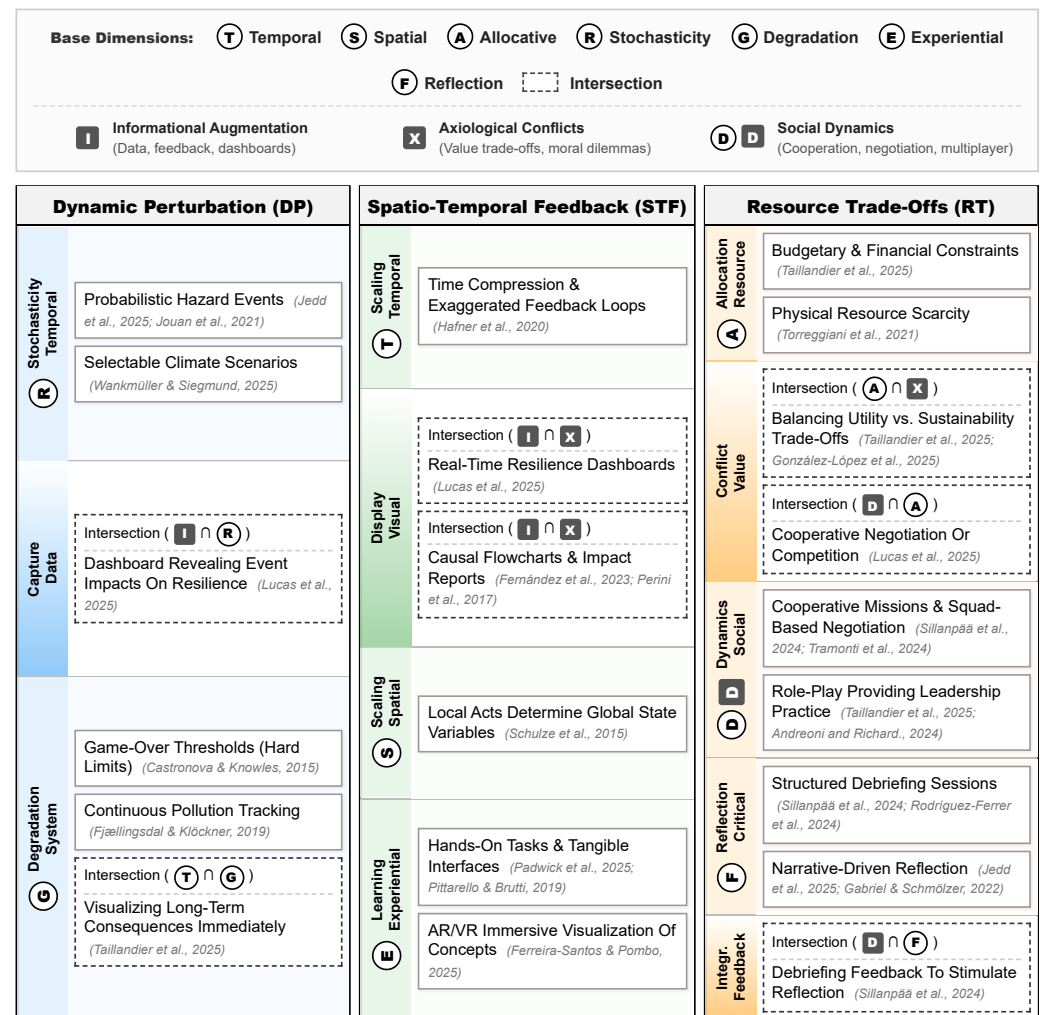


Figure 8. Taxonomy of 3D Environmental Resilience Mechanisms. Note: The diagram categorizes mechanisms into three pillars: Dynamic Perturbation, Spatio-Temporal Feedback, and Resource Trade-offs. Symbols denote base dimensions (circles) and augmenting factors (squares). Dashed boxes illustrate combinatorial intersections where dimensions fuse to generate specific pedagogical tools. Representative empirical studies referenced in the figure include: Dynamic Perturbation mechanisms [3,31,48,49,68,145,164]; Spatio-Temporal Feedback interfaces [7,71,133–135,145,151,165]; and Resource Trade-offs dynamics [35,49,51,77,108,127,141,145,152].

1. **Dynamic Perturbation (DP):** Focuses on the unpredictability of nature [1,11,25,26]. By introducing stochastic shocks (e.g., carbon policy uncertainties, invisible costs) and Wicked Problems [164,166], these mechanisms shift the focus from static optimization to adaptive resilience strategies, addressing learning bottlenecks through disruptive strategies [136,167,168].
2. **Spatio-Temporal Feedback (STF):** Focuses on the Invisibility of processes [130,134]. Through Time Compression (T) and Systemic Fidelity, these designs act as cognitive scaffolding, rendering abstract long-term data into immediate, perceptible cues [11,34,73,76].
3. **Resource Trade-Offs (RT):** Focuses on the complexity of decisions [11,49,129]. These mechanics simulate socio-political complexities by embedding allocative constraints and value conflicts into adaptive platforms [7,48,77], thereby driving students to develop key competencies in sustainability through negotiation and compromise [6,169].

4.5. Comparative Analysis of Design Mechanisms and Scale

To rigorously examine how spatial scale influences game design decisions, we conducted a comparative feature mapping. From the total corpus of 175 studies, we isolated a sub-sample of 86 primary empirical studies that exhibited distinct spatial design characteristics. The remaining 89 articles were excluded from this specific comparative analysis as they were either non-empirical (e.g., systematic reviews, theoretical frameworks), lacked specific spatial definitions (e.g., generic gamification quizzes without spatial descriptors), or encompassed mixed scales without a dominant focus as visualized in Figure 9.

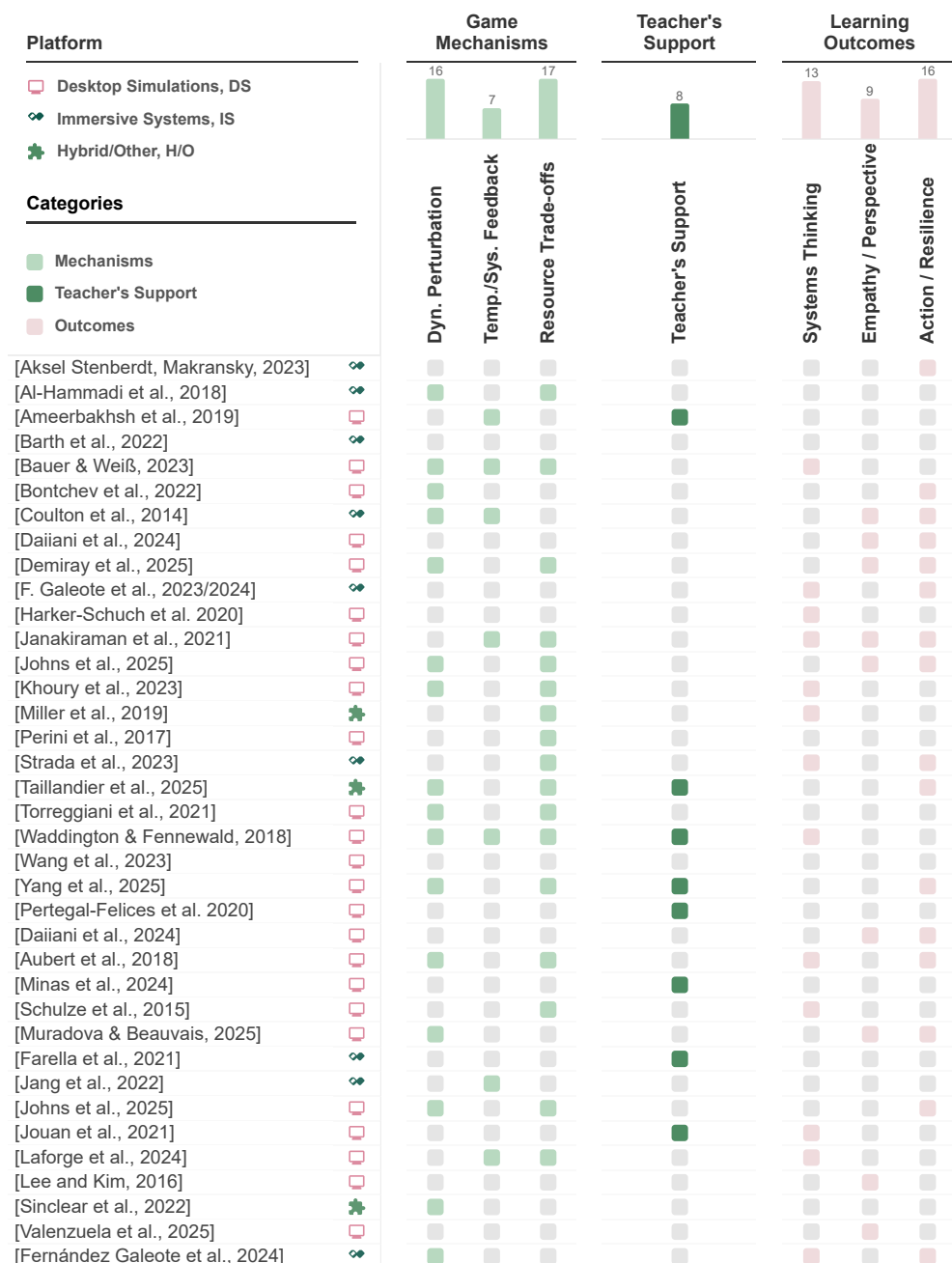


Figure 9. Feature Co-occurrence Matrix showing the interrelationships among platform types, game mechanics, teacher support, and learning outcomes in the core sample ($n = 36$). Note. Studies are categorized by platform: DS (Desktop Simulations), IS (Immersive Systems), and H/O (Hybrid/Other). Columns display specific design mechanisms, teacher support presence,

and learning outcomes. Colored cells denote the confirmed presence of a variable, while gray cells indicate absence. Numerical headers indicate the total frequency of each attribute within the dataset. (Sources: [11,14,16,17,25,34,49,54,55,62,66–69,71,74,76,83,85,128–130,148–161]).

The final dataset ($N = 86$) was categorized into two distinct spatial scales:

- **Global-Based ($n = 41$):** Games that position the player as a macro-manager of planetary or city-wide systems. For example, Janakiraman et al. [55] describe their design as allowing students to play *EnerCities* to “balance environmental health, happiness of citizens, and resource depletion,” effectively simulating a planetary boundary model.
- **Local-Based ($n = 45$):** Games that embed learning in specific physical environments or communities. For instance, Strada et al. [11] define their approach as an Augmented Reality based urban development game designed to “promote player awareness... in urban space,” directly linking digital content to specific geographic coordinates.

As visualized in Figure 10, distinct dichotomies emerged across cognitive mechanisms, technological mediation, and pedagogical impacts.

Group	Cognitive Mechanism		Technological Mediation		Student Impact	
	Abstraction & Macro-Policy	Ecological Restoration	High-Fidelity / Digital Twin	AR / Location-Based Services	Systems Thinking	Place-based Competence
Global (n=41)	95.1% (n=39)	4.9% (n=2)	87.8% (n=36)	4.9% (n=2)	80.5% (n=33)	19.5% (n=8)
Local (n=45)	28.9% (n=13)	71.1% (n=32)	44.4% (n=20)	44.4% (n=20)	28.9% (n=13)	71.1% (n=32)
Relative Frequency: 0–20% 21–40% 41–60% 61–80% 81–100%						

Figure 10. Heatmap analysis of design mechanisms and student outcomes across spatial scales ($N = 86$). Note: The matrix reveals a fundamental divergence: Global games ($n = 41$) rely on Abstraction (95.1%) and High-Fidelity (87.8%) to teach Systems Thinking. In contrast, Local games ($n = 45$) utilize Ecological Restoration (71.1%) and a hybrid of AR/High-Fidelity (44.4% each) to foster Action Competence. The “Missing Middle” is evident in the low Systems Thinking scores (28.9%) for Local games.

4.5.1. Cognitive Mechanisms: The Managerial Gaze vs. Situated Connection

The analysis reveals a stark contrast in the cognitive roles assigned to players. To validate this observation, a Pearson’s Chi-square test of independence was conducted. The results confirmed a statistically significant association between spatial scale and cognitive mechanism ($\chi^2(1, N = 86) = 39.82, p < 0.001$), with all expected cell frequencies exceeding 5, satisfying the test assumptions.

- **Global-Based Games:** The vast majority of global games ($n = 39, 95.1\%$) employ Abstraction and Macro-Policy mechanisms. As noted by Castronova and Knowles [164], these designs allow players to “see the whole board,” positioning them as administrators managing resources through charts and abstract variables. This fosters a “managerial gaze,” where sustainability is treated as a resource optimization puzzle.
- **Local-Based Games:** Conversely, local games predominantly utilize Ecological Restoration and Reconnection mechanisms ($n = 32, 71.1\%$). These designs position players as embedded actors. For example, Newsome [170] describes the player’s role not as managing data, but as engaging in tangible activities like “collecting insects” to create “actionable items outside of gameplay.”

While global games excel at simplifying complexity, they risk creating an epistemic distance between the player and the environment. Local games bridge this gap but often lack the macro-level strategic layer found in global simulations.

4.5.2. Technological Mediation: Monolithic vs. Hybrid Approaches

Technological choices show a significant divergence in platform reliance. Global interventions are almost exclusively dominated by High-Fidelity or Digital Twin technologies ($n = 36$, 87.8%), with only a marginal 4.9% ($n = 2$) utilizing AR or location-based features. This suggests that global sustainability topics are currently treated as “placeless” problems best solved on a screen. In contrast, local games exhibit a balanced technological split. While 44.4% ($n = 20$) utilize AR or Location-Based Services to overlay digital information onto the physical world, an equal proportion (44.4%, $n = 20$) relies on High-Fidelity screen-based representations. The presence of 44.4% screen-based games in local contexts suggests that designers often struggle to implement complex simulations in AR. Most local screen-based games are simple information kiosks or narratives, lacking the sophisticated system modeling seen in global games. This points to a technological opportunity: developing “Situated Simulations” that combine the system depth of global games with the location-awareness of local AR.

4.5.3. Student Impact: Understanding Systems vs. Taking Action

The design choices above directly cascade into divergent learning outcomes. Global games prove highly effective at fostering Systems Thinking ($n = 33$, 80.5%), helping students understand complex causal loops such as the relationship between CO₂ emissions and sea levels. However, this cognitive gain rarely translates into immediate behavioral intent, with only 19.5% of studies reporting Action Competence. Conversely, Local games excel at building Place-based Action Competence ($n = 32$, 71.1%). By engaging with familiar environments, students demonstrate a higher willingness to take specific actions like recycling or energy saving. Yet, these interventions often lack the “big picture” understanding of how these local actions mitigate global climate change, as evidenced by the low prevalence of Systems Thinking outcomes (28.9%) in this category.

4.5.4. Synthesis: The Missing Middle

In summary, the field is currently bifurcated. Global games produce “knowledgeable observers” who understand the system but feel detached from it, while Local games produce “engaged activists” who care about their community but may miss the systemic interconnectedness. The data suggests a critical need for cross-scale design frameworks, games that can start with local, tangible action and scale up to global, systemic understanding, bridging the gap between acting locally and thinking globally.

5. Discussion

5.1. The Impact of Teacher Guidance and the Limits of Digital Nativism

RQ2 asked about the interactive relationship between game mechanics and teacher guidance [11,55,72]. Our heat map analysis highlights a risk: teacher absence leads to a drop in the Systems Thinking conversion rate by approximately 14 percentage points [48,72,148]. This result challenges the view of digital nativism in the field of games for environmental resilience, which assumes that younger learners naturally acquire complex concepts through independent interaction with digital tools [26,72,80]. Data shows that in an unintrusive state, rich media environments guided students into a flow experience [6,31,171]. While this experience evokes empathy, it often masks critical reflection on deep structural issues [16,55,61]. Games lacking a Gatekeeper role often become superficial, and students

experience negative affect within simulated disasters but cannot solve problems through trade-offs in terms of action [48,49,148]. However, bringing back the teacher faces substantial pragmatic hurdles. Recent studies highlight that high-maintenance inquiry scenarios often lack feasibility in standard classrooms [172], and long-term deployment of complex environments like Minecraft encounters significant logistical barriers [173], leading to fluctuating levels of teacher acceptance [174]. Therefore, given these structural bottlenecks, we argue that the game system itself must assume the responsibility of automated pedagogical agents [17,26,55].

5.2. Mechanics as Scaffolding: The Emergence of Automated Pedagogical Agents

Addressing RQ3, based on the taxonomy in Result II, we found that successful games for environmental resilience provide a functional compensation in the absence of human instruction [11,17,55]. The core logic of studies accomplishing Systems Thinking without teachers lies in using specific composite mechanisms to emulate the cognitive scaffolding typically provided by teachers [17,33]. Dynamic perturbation simulates the cognitive pressure of Socratic questioning [55,129]. Teachers often break students' fixed mindsets through hypothetical questions [48,173]. In studies like Janakiraman et al., algorithm-generated stochastic shocks force students to face prediction failures, a process that can be enhanced by knowledge-based automatic question generation systems [11,55,68,175]. This cognitive dissonance, triggered by mechanisms, produces a reflective effect equivalent to teacher questioning [148]. Additionally, these game mechanics act as a digital proxy for classroom debate [48,129]. Grounded in Social Constructivist Learning theory, which posits that knowledge is produced in social negotiation [72], multi-agent resource conflict mechanisms compel players to negotiate the tension between self-interest and collective survival [12,31]. The friction embedded in this mechanism simulates conflicting viewpoints in classroom debates, prompting students to transform from one-way knowledge receivers to negotiators of system complexity [11,49].

To elevate these automated agents from functional substitutes to effective "future paradigms," design must address the Technology Acceptance Model (TAM) and personalization [176]. Mechanisms should not be monolithic but tailored to learner personality traits and styles [177,178], and perform cultural adaptation based on models like Hofstede to align with local values [179]. Furthermore, to mitigate anxiety in high-immersion VR settings [23] and ensure inclusivity for marginalized groups [180], user participation in development is essential [181]. Finally, ensuring the long-term sustainability of these agents requires economic strategies for Open Educational Resources [37] and designs that maintain engagement for Gen-Z beyond the novelty effect [18,22,182]. However, it is crucial to clarify that these mechanisms function primarily as cognitive scaffolds rather than holistic replacements. While algorithms can effectively trigger critical reflection through feedback loops, they cannot fully replicate the socio-emotional support, moral role-modeling, and adaptive empathy that human educators provide. Therefore, the GTR (Game–Teacher–Resilience) Framework advocates for these mechanisms not to oust teachers, but to serve as robust assistive systems that ensure deep learning continues even when 1-on-1 human guidance is logistically impossible.

5.3. The Mechanism of Restoration and the Local Simulation Gap

A critical insight from Figure 10 is the technological split in Local-based games. While 44.4% of local studies utilize High-Fidelity screens, our qualitative analysis reveals a qualitative gap: unlike the complex systemic simulations found in Global games (87.8%), local screen-based games often function as simple narratives or information kiosks. Simultaneously, AR approaches (44.4%) excel at connection but often lack simulation depth.

This suggests that the local context is currently under-explored regarding high-fidelity systemic modeling. We propose applying the rigorous simulation mechanics of Global games to local environments, creating situated simulations. This approach derives unique value from the local context: it restores the visibility of hidden natural processes (such as groundwater flow or local carbon cycles) which are often obscured in students' daily lives. Unlike the detached perspective of Global games, this approach reconnects people, place, and nature. Consequently, it has the potential to empower learners to devise tangible, place-based solutions while bridging the gap in systems thinking within local contexts.

5.4. Limitations and Future Directions

While this systematic review identifies a structural correlation between specific game mechanisms and resilience outcomes, three critical limitations regarding causal inference, sample selection, and measurement validity must be acknowledged to contextualize the findings.

5.4.1. Inference of Mechanism Substitution

The thematic synthesis suggests that mechanisms like Dynamic Perturbation can simulate Socratic questioning by inducing constructive friction. However, this conclusion is derived from an inductive analysis of co-occurrences rather than controlled experimentation. We cannot rule out the influence of confounding variables, such as learners' intrinsic motivation or prior gaming literacy, which might enable them to succeed in "Teacher-Absent" settings regardless of the mechanisms used [17,55,129]. It remains undetermined whether fully automated mechanisms can achieve efficacy equivalent to human instruction in areas requiring complex value guidance and emotional scaffolding [20,85,134]. Therefore, the GTR Framework should be viewed as a theoretical model. Future research urgently requires rigorous experimental designs (e.g., Randomized Controlled Trials) to quantitatively isolate the instructional effectiveness of these affordances from learner characteristics [20,162].

5.4.2. Technological Selection Bias

To address RQ3, this review applied a strict inclusion criterion focusing on High-Fidelity 3D and Spatial environments (the "Core 36"). While this was necessary to analyze spatial affordances, it inherently excludes the potential of low-fidelity, text-based, or 2D narrative games, which may foster resilience through different cognitive pathways (e.g., narrative transportation) rather than spatial immersion. Consequently, our findings regarding "Spatio-Temporal Feedback" are specifically applicable to immersive environments and should not be generalized to all forms of GBL. Future reviews should examine how low-tech interventions might achieve similar outcomes with lower implementation costs.

5.4.3. Measurement Validity and Reporting Bias

A methodological limitation pervades the analyzed corpus: the dominance of self-reported data over objective behavioral metrics. As indicated in our Heatmap Analysis, high "Action Competence" scores often reflect students' perceived willingness to act rather than verified behavioral changes, potentially inflating the success rate of Global Games due to social desirability bias. Furthermore, due to the significant heterogeneity of game designs, statistical methods for detecting publication bias (e.g., funnel plots) were not applicable [42]. To mitigate this, we employed investigator triangulation and cross-verification within the 36 core subset to ensure qualitative reliability. Nevertheless, the "Attitude-Behavior Gap" remains a critical blind spot; future studies must prioritize longitudinal behavioral logs over immediate post-game surveys to validate true resilience.

6. The Game–Teacher–Resilience Framework

Current practices often fall into a disconnected state where game design relies overly on visual-centric fidelity and lacks teacher intervention [20,42,121]. Learners easily slide into a passive flow experience [133,138,162]. While this enhances engagement and shallow empathy, it is inherently low-friction and leads to outcomes stalling at mere awareness arousal, a trajectory visualized as Path 1 in Figure 11.

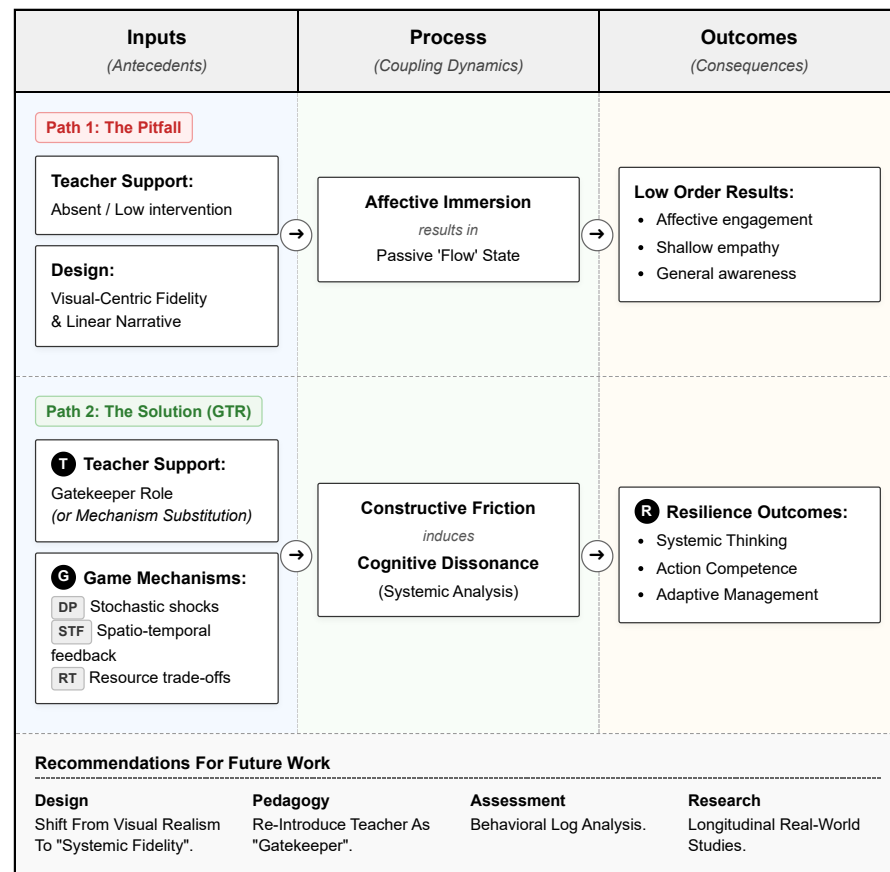


Figure 11. The Process Dynamics of the GTR (Game–Teacher–Resilience) Framework. The diagram synthesizes the study's findings by contrasting the trajectory of unsupported visual fidelity (Path 1) against the proposed model of constructive friction (Path 2) that integrates teacher gating with specific game mechanisms to achieve resilience outcomes.

Path 2 highlights that achieving resilience requires a fundamental shift from seamless usability to Constructive Friction. Unlike the passive 'flow' in Path 1, the system here proactively induces Cognitive Dissonance. By deliberately withholding immediate progress until complex system logic is resolved, the game forces a cognitive transition from passive reception to active, analytical problem-solving.

It is in this deep interaction that learning outcomes can ascend from perceptual empathy to rational Systems Thinking and action competence [7,21,183]. Future games for environmental resilience should prioritize a shift from visual realism to systemic fidelity [46]. This structural validity requires embedding dynamic perturbations [48], such as ecosystem stochasticity, and socio-political complexities [129] directly into game rules. To visually synthesize the structural stability of these elements, Figure 12 defines the core topology of the framework [20,42].

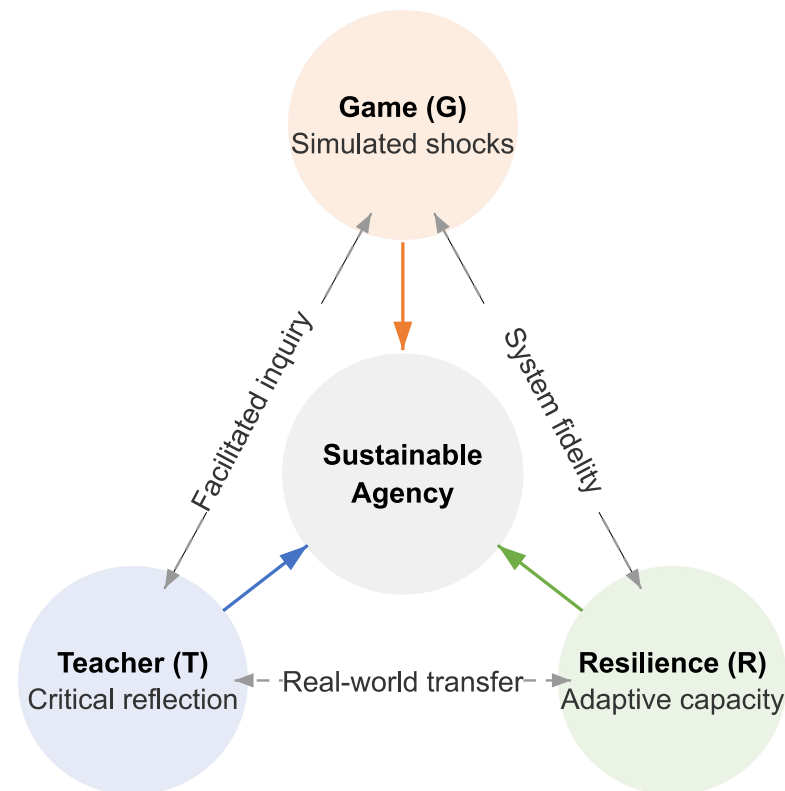


Figure 12. The Structural Topology of the GTR (Game–Teacher–Resilience) Framework. The diagram illustrates how the triadic synergy between game mechanics, teacher facilitation, and resilience attributes converges to foster sustainable agency.

6.1. Operational Use Cases of GTR Implementation

To bridge the gap between abstract simulation and real-world action competence, the GTR Framework provides a flexible architecture that adapts to educational resources. Based on the inductive synthesis of 36 core studies, we delineate two distinct operational modes. In both scenarios, the GTR Framework functions as the central pedagogical logic, ensuring that systemic fidelity and constructive friction prevent the learning process from degrading into passive entertainment.

6.1.1. Mode A: Synchronous Classroom (Teacher as GTR Facilitator)

In this mode, the GTR Framework repositions the teacher from a knowledge transmitter to a Social Negotiation Architect. The game provides the raw data of complex problem-solving, while the teacher executes the critical function of social negotiation.

First, successful implementations leverage the teacher to introduce external constraints that the algorithm cannot fully simulate. For instance, Castronova and Knowles demonstrated how instructors manually introduced policy loopholes during gameplay [164], while Taillandier et al. utilized a Town Council debate format managed by the teacher [49]. These interventions force students to defend their decisions against conflicting stakeholder goals, ensuring they navigate ethical and economic trade-offs rather than simply optimizing a game score.

Second, the transition from game experience to mental models requires structured reflection. Padwick et al. illustrate the Heavy Facilitator role, where teachers anchor in-game disasters (like wildfires) to local realities [135]. Similarly, Jedd et al. validated a three-phase debriefing protocol (Emotion-Analysis-Transfer) [48]. In these cases, the teacher acts as the critical bridge, translating the emotional frustration of wicked problems into rational resilience strategies.

6.1.2. Mode B: Asynchronous Self-Learning (System as GTR Gatekeeper)

In contexts where human facilitation is absent, the GTR Framework embeds pedagogical scaffolding directly into the game mechanics, transforming the system into an Algorithmic Gatekeeper. Here, the game logic itself assumes the responsibility of monitoring competence development.

The core tenet is utilizing blocking mechanisms to prevent shallow trial and error. Wang et al. implemented a Two-Tier testing strategy that pauses game progression until learners correct their misconceptions [34], while Janakiraman et al. designed systems that trigger simulated ecosystem collapse upon failure [55]. These designs embody the GTR principle of constructive friction: the system refuses to provide a flow state until the learner demonstrates genuine systemic thinking.

Furthermore, to replace verbal guidance, the framework relies on spatio-temporal feedback to make abstract data perceptible. Schaper et al. utilized Augmented Reality (AR) to overlay waste sorting instructions onto physical reality [184], acting as a visual scaffold that lowers user cognitive load. Likewise, Sá et al. mapped complex consumption choices directly to a Life Bar (Ecological Footprint) [123]. These mechanisms ensure that even without a teacher, the logic of Action-Consequence connectivity is preserved through embodied cognition and immediate visualization.

7. Conclusions

This systematic review of 175 empirical studies (2015–2025) examines the efficacy of GBL in Education for environmental resilience. Our analysis found an Affective Skew in the field: while modern educational games successfully induce learner engagement and transient empathy through visual fidelity, they often fail to cultivate high-order Systemic Thinking and action competence in the absence of instructional scaffolding [11,55,82,132]. To address this disconnect, this study constructs the GTR (Game–Teacher–Resilience) Framework, which delineates two distinct developmental trajectories for sustainability education [11,20,42].

First, Path 1 (The Pitfall) demonstrates that designs relying excessively on visual-centric fidelity and linear narratives tend to trap learners in a state of Passive Flow [27,46,121]. While this generates emotional resonance, it does not provide enough cognitive load for deep structural learning [34,83,85]. Second, Path 2 (The Solution) proposes that resilience emerges only when creating Constructive Friction through specific Mechanism–Scaffolding Coupling [11,17,55]. Our findings identify three core mechanisms—Dynamic Perturbation (DP), Spatio-Temporal Feedback (STF), and Resource Trade-offs (RT)—that substitute or complement teacher guidance by inducing cognitive dissonance, thereby forcing a shift from passive observation to active systems analysis [11,55,83].

The transition from engagement to resilience requires a fundamental paradigmatic shift [6,7,38]. First, in terms of Design, future initiatives must move beyond Visual Realism toward Systemic Fidelity, ensuring that game rules hard-code the unpredictability and socio-political complexity of real-world ecosystems [1,11,46,48]. Second, regarding Pedagogy, the assumption of digital nativism should be reconsidered; the teacher (or mechanism substitution) must be reintroduced as a Gatekeeper to frame moral value trade-offs [72,80,148]. Finally, for Assessment, the field must evolve from relying on subjective self-reports to objective Behavioral Log Analysis to accurately verify the acquisition of adaptive management capabilities [20,25,153]. In conclusion, transformative UN's sustainability goals cannot rest on the technological affordances of games alone [6,20,38]. It requires the synergistic topology of rigorous game mechanics and active pedagogical intervention to cultivate learners capable of navigating the challenges of climate change [11,17,135].

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