A Playful Path to Sustainability: Synthesizing Design Strategies for Children's Environmental Sustainability Learning Through Gameful Interventions.

Raghad Albar
MA Education and Technology alumni, University College London
raghad.albar.22@alumni.ucl.ac.uk

Andrea Gauthier*
UCL Knowledge Lab, University College London
andrea.gauthier@ucl.ac.uk

Asimina Vasalou
UCL Knowledge Lab, University College London
a.vasalou@ucl.ac.uk

ABSTRACT

The climate crisis has created a time of great uncertainty for children and their futures, raising need for new approaches that support children to learn about environmental sustainability (ES) and prepare them for living with climate impacts. Systematic reviews of IDC have highlighted instances of gameful interventions (i.e., game-based learning (GBL), gamification, and game-authoring) that offer meaningful ES learning opportunities, but there is not yet a comprehensive synthesis of how this is achieved. Our paper reports on a systematic review of 39 interventions to interrogate how gameful interventions are designed to foster children's ES learning. Our results contribute four themes: "GBL genres fostering distinct forms of ES understanding", "gamification as a reinforcer to children's sustainable action", "game-authoring allowing children to voice their perspectives to critical audiences", and "transversal skills embedded in gameful interventions". Based on these findings, the paper proposes design implications for future research in gameful interventions and ES.

CCS CONCEPTS

• **Human-centered computing** → Interaction design; Interaction design theory, concepts and paradigms.

KEYWORDS

game-based learning, gamification, game authoring, children, environmental sustainability learning

ACM Reference Format:
Raghad Albar, Andrea Gauthier, and Asimina Vasalou. 2024. A Playful Path to Sustainability: Synthesizing Design Strategies for Children's Environmental Sustainability Learning Through Gameful Interventions.. In *Interaction Design and Children (IDC '24), June 17–20, 2024, Delft, Netherlands.* ACM, New York, NY, USA, 17 pages. https://doi.org/10.1145/3628516.3655797

1 INTRODUCTION

The climate crisis is a pressing global issue that demands urgent attention. The consequences of Earth's changing climate include but are not limited to rising global temperatures, more frequent and extreme weather events (droughts, hurricanes, heatwaves, etc.), and rising sea levels precipitated by the melting of the polar ice caps [36]. The resultant changes to habitats threaten the ecological diversity of the planet, as well as homes and livelihoods worldwide, especially for those most dependent on the natural environment. Children and adolescents, hereafter referred to as 'children' for brevity, are most vulnerable to the effects of climate change because of their underdeveloped physiological defences, the more primitive means by which they engage with their environment, their reliance on adults, and the cumulative effects of the threats they will encounter throughout their lives [86]. UNICEF estimates that half of children globally are at 'extremely high risk' from the hazards and shocks of climate change because of their increased vulnerability and lack of essential services, particularly in the Global South [107]. It is, therefore, a top priority to educate the children of today, who represent the decision-makers of the future, about the effect that human activities have on climate change and the steps that must be taken toward the Environmental Sustainability (ES) of our planet. Education plays an essential role in fostering children's understanding, skills, and participation in ES [62], often requiring children, teachers, and communities to collaborate to resolve environmental problems and issues [13, 104]. Of relevance to child-computer interaction (CCI), such initiatives can be facilitated with digital technology.

Against this context, the present work is informed by Vasalou and Gauthier's [109] recent literature review of CCI research that aimed to capture how digital technologies have been designed to-date to engage children in ES. This review showed that one third of the artefacts developed by CCI researchers were games-based learning (GBL) approaches, in keeping with other research showing that GBL has been a transversal topic in CCI over time [29]. In addition to GBL, these authors identified the emergent application of gamification (GF) and game authoring (GA), highlighting the new opportunities these interventions may afford for children's ES learning, in turn motivating the need to expand our investigation toward *gameful interventions* for children's ES more broadly [109]. While interaction design has long served as a unifying theme in CCI [29], GBL has been often informed by general learning theories [e.g., 4, 5, 9]. In line with this, Vasalou and Gauthier [109] found there was limited application of ES education theories to inform how children's digital technologies were designed, leading them to argue for the need to drive interaction design with relevant domain theories that can serve the distinctive education concerns relevant to ES.

*Corresponding author

IDC '24, June 17–20, 2024, Delft, Netherlands

ACM ISBN 979-8-4007-0442-0/24/06
https://doi.org/10.1145/3628516.3655797

This previous work highlights that CCI designers are well positioned to pivot into the domain ES with their expertise in gameful interventions, yet a critical examination of how gameful interventions can be best designed to support children's learning from an ES perspective is also vital to guide future design efforts. Our paper responds to this challenge through an exploratory research question: *How are GBL, GF, and GA interventions designed to foster children's ES learning?* This is pursued in a systematic literature review of a five-year period yielding a corpus of 39 gameful interventions across 51 research papers. Addressing the theory gap identified by Vasalou and Gauthier [109], we apply ES theories to analyse and critique the design of gameful interventions, whilst also carrying out a "bottom-up" analysis to capture how these past interventions have capitalised on digital game design elements to introduce particular ways of learning. Our research contributes to the literature by elucidating the distinctive ways gameful interventions enhance ES learning, highlighting four future directions for design and research in gameful interventions: (1) building new stewardship identities through authentic game roles explored in game narratives, (2) fostering place-based learning through the game/or game actions situated within the physical world, (3) engendering systems-thinking to simulate or trigger children's thinking of the multi-faceted nature of ES, and (4) leveraging critical approaches to ES learning where games can be used to voice children's concerns, challenge social structures and attitudes.

2 BACKGROUND

2.1 Key issues in children's ES learning

The role of education as a potential catalyst for change in the climate crisis is increasingly recognized, e.g., through raising public awareness/concern and the need to develop skills/capacities necessary to address the crisis [98]. Furthermore, children's ES education can have a multiplier effect, where families and communities adopt habits and behaviours that their children bring home from school [61]. It is also critical that children's voices are heard on these topics that will affect their futures, and that they have an outlet to express their concerns [107]. Below, we delve into the *purpose, place, and practice* of ES education [57], emphasizing that, due to the extensive nature of the subject, our strategy is to thematise key perspectives from ES education literature, drawing out the distinctive set of issues and principles that underpin ES education.

Purpose. ES education should encourage a holistic, systems-thinking understanding of sustainability by acknowledging the interconnectivity and interdependence between three pillars: society, economy, and environment [57, 79]. One approach is Education for Sustainable Development (ESD), in which global challenges are contextualised within the Sustainable Development Goals (SDGs) set by the United Nations. ESD aims to support this holistic, systems-thinking approach by integrating socio-cultural and socio-political aspects, including equity, poverty, democracy, and quality of life [110], and strives to harmonise these connections to protect the well-being of both current and future generations [31]. However, one critique is its focus on human "development", which may be interpreted as leeway for prioritising economic growth over environmental preservation and social equity [44]. Other scholars posit that the focus should be placed on understanding issues of social justice that arise from economically-driven human behaviour, e.g., by analysing "who benefits, who pays, and who suffers from human action that is harmful to the environment", to deepen learners' critical environmental literacy and conscious global citizenship [60]. Yet another perspective is the importance of building affective connections with the non-human, natural world. For example, Bonnett [10] argues that the purpose of ES education is not only to ensure our physical survival on this planet, but also for our spiritual survival, by forming an appreciation of how we connect to nature. He explains that humans need to appreciate nature as "self-arising"—that is, as pre-eminently having its own being that we can affect but of which we are not the author—and that this self-arising quality can stimulate us to find wonder in our everyday natural surroundings, which may lead to spiritual growth and foster stewardship and affection toward the natural world [10].

Place. The issue of place was originally concerned with where ES was integrated into the curriculum, e.g., by infusing it across subjects or by developing it as its own interdisciplinary subject [57]. We might also extend the concept of *place* to think about whether learning indeed happens in the classroom at all or if this should happen in informal learning environments (e.g., community centres, homes), which could anchor the learning in everyday living or local, real-world problems, taking pressure off the curriculum [98]. Because tackling ES challenges require collective action and the involvement of diverse stakeholders [13], informal and situated approaches that get children to collaborate with peers, family members, and other community stakeholders can help foster skills that are necessary in the real-world and empower children through agentic, collective action [104]. Furthermore, building on the argument above by Bonnett [10], Lehtonen et al. [50] postulate that people discover their interconnectedness with nature through embodied learning experiences that are situated "in place", i.e., in the real-world context.

Practice. There is increasing recognition that ES education should move away from a purely fact-based knowledge learning to more embedded, skills-based, and action-oriented learning [8, 63, 97]. Bedi & Germein [8] suggest that, to support transformation and change, ES education should implement active, constructivist, social/collaborative, and participatory learning approaches. This contrasts with more traditional approaches to education that focus exclusively on knowledge dissemination and individual achievement, aligning with long-standing arguments to this end [e.g., 97]. Monroe et al. [62] offer a practical framework to think about ES education strategies in both formal and informal learning contexts, identifying four key strategies: *conveying information, building understanding, improving skills,* and *enabling sustainable action* (summarised under Table 1). This raises the question of how ES issues are framed in these approaches and the impact of this framing on children. For instance, when situating learning experiences in real-world sustainable action and skills, the learning can take on an inherently *positive* lens, and children may develop a sense of empowerment and self-efficacy in relation to taking an agentic role [103]. This may also contribute to feelings of constructive hope, which has been identified by scholars as an enabler of pro-environmental action [21, 70, 71]. Contrastingly, other pedagogical approaches focusing on conveying information and building understanding might inadvertently take a predominantly *negative*

Table 1: Monroe et al. [62]'s environmental education learning strategies

Learning strategy	Description	Examples in formal and informal ES education
Convey information	A one-way transmission of factual, conceptual, and procedural knowledge	Textbook, lecture, video, film, and internet resources, information displays with limited interactivity
Build understanding	A two-way exchange of knowledge, aligning with constructivist learning supporting a critical and discursive understanding of ES	Discussion, role play, simulation, case study, experiment, game, constructivist methods, experiential learning, field study, workshop, environmental monitoring, guided tour, guided nature walk
Improve skills	Apply their understanding in the way of practical skills, including active citizenship, communication, and teamwork	Cooperative learning, issue investigation, inquiry learning, citizen science programs, volunteer service, some types of project-based education
Enable sustainable action	A deepening of skills where learners are supported to lead on identifying real-world actions for complex environmental problems	Inquiry-based education, some types of service learning, and other opportunities for learners to define problems, design and select action projects, identify facts, and build skills in problem solving

frame, especially if (as described above under 'Purpose') they aim to build children's understanding of environmental harm as social harm and the economic drivers behind it. Finnegan [21] found that, while both climate hope and anxiety played equal roles in teenagers' participation in climate action, teachers' positive and action-oriented framing was positively correlated with teens' hope for the future.

2.2 Gameful interventions and their application to ES

In this work we aim to explore the use of digital gameful interventions in ES learning by focusing on three approaches: game-based learning (GBL), gamification (GF) and game authoring (GA).

GBL involves integrating pre-defined learning objectives into a game [89], which can be defined as a system wherein "players engage in an artificial conflict, defined by rules, that results in a quantifiable outcome" [85]. "Good" games are touted for their ability to engage players in new identities, give context and meaning to interactions, foster systems-thinking, bolster recovery from failure, and support scaffolded learning experiences [27, 28]. Prensky outlined the six key characteristics of games as having (i) rules, (ii) goals and objectives, (iii) outcomes and feedback, (iv) conflict/competition/challenge/opposition, (v) interaction, and (vi) representation or story [77]. Variations in how these characteristics are expressed in the game design produces different game *genres* (Table 2). Coakley and Garvey [18] argue that simulation, strategy, and adventure "styles" of games may be relevant to ES education specifically. Other relevant genres might include action, puzzle [33], and trivia games [91]. Janakiraman et al.'s [39] non-systematic review of digital games for K-12 ES education highlighted that GBL created a "spirit of inquiry", allowing for testing and exploration of the interconnectedness of multiple factors, visualisation of cause-and-effect, building of empathy toward others, and contextualised learning within simulated real-world problems. However, this review [39] and others [96] did not examine how the specific design of the games supported ES learning, a gap which our work aims to address.

GF contrasts to GBL in "the use of game design elements in non-game contexts" [19], e.g., through defining challenges, awarding points/badges, and tracking progress. Whilst in GBL the game design elements are theorised to cause learning directly, game elements in GF are more likely to affect learning indirectly by altering learners' behaviour or attitudes (e.g., engagement) toward a learning activity (external to the GF) [49]. GF interventions can apply one or combine several of Prensky's game design characteristics. For instance, a review of GF for adults' water and energy conservation found that visualisation of behaviour, particularly in comparison to historical, normative, or social reference values, as well as personalised action recommendations and reminders, virtual and real-world rewards, and social interaction were key elements of effective behaviour-change interventions [1]. Another broad review of gaming interventions for energy conservation found GF interventions specifically to be effective at increasing users' awareness of their energy consumption, even amongst children, with longer-term change in energy-saving habits [64]. Nonetheless, existing systematic reviews have not yet focused on GF for children and the different ways GF is designed to promote ES learning across diverse ES domains.

Lastly, GA is distinctive in placing children in a design (and sometimes development) role of their own games. Kiili et al. [43] highlight that empowering learners to design and develop games can promote active participation, creativity, and problem-solving skills, thus, skills necessary in the 21st century. Additionally, when tasked with designing games for a younger audience, Pierson and Clark [76] found that students deepened their conceptual understanding about the game topic, leading to rich scientific reasoning with peers. Research with children who collaboratively crafted digital stories about ES found the authoring practice fostered collaboration and communication skills, as well as a means of self-expression [56], which may extend to the practice of GA. The authors found that the openness of the storytelling practice engendered links between social and environmental pillars, and a critical social justice lens [56]. In other work, Burke and Crocker [12] showed that children who crafted 3D exhibits to communicate to others about ocean conservation developed emotional connections with their work,

Table 2: GBL game genres [based on 18, 33, 91].

Game genre	Genre description	Defining mechanics
Action	Featuring game action as a main way to progress within the game	Mechanic requiring hand-eye coordination and reaction time
Adventure	Foregrounding immersive narrative and character development; player explores the game and employs problem-solving to resolve puzzles	Storytelling and role-playing serving motivating the game goal and progression
Simulation	Replicating real-world activities or processes, by mirroring diverse facets of real-life scenarios and featuring visual/behavioural realism	Replicating real-life system and its dynamics, where players can manipulate variables and observe effects of their changes on the system
Strategy	Emphasising core elements of strategic planning, effective decision making and efficient resource evaluation/allocation	Requiring the formulation of a strategic plan to successfully accomplish a predetermined goal
Trivia/Puzzle games	Featuring quizzes and/or simple puzzles that usually test knowledge and basic skills	Incorporating trial-and-error with game feedback

which in turn drove conservation-oriented mindsets, values, and empathy toward the natural world. To the best of our knowledge, there has been no effort yet to synthesise literature on GA and scrutinise its design in relation to children's ES learning.

Whilst gameful interventions show promise in their application to ES and children's learning, limitations have been also raised, particularly in relation to GBL and GF. Focused on GBL, Stanitsas et al.'s [96] review of 77 digital and non-digital games for ESD found that only 32% involved all pillars of sustainability, and therefore failed to foster real systems-thinking, which, as argued under 2.1, is a core purpose of ES education. This was shown by Vasalou and Gauthier [109] whose review also revealed that GBL did not foster interdependence between different domains of sustainability (i.e., how waste, food, energy, etc., are all related), nor express issues of social justice. Additionally, GBL often places learning indoors. Whilst this can be advantageous when the game provides access to domains inaccessible to children (e.g., marine life), this use of GBL can be questionable when applied to domains children can access, such as nature. In this instance, situating the learning inside a digital environment can limit children's direct interactions with nature, which are crucial in the formation of attachments and affective connections [109]. Similar to GBL, GF has been criticised due to its limited focus on systems-thinking. GF has been predominantly designed to address sustainable resource consumption. Centring on resource efficiency and environmental impact, GF design has neglected broader societal implications and economic dimensions associated with shifting consumption practices, whilst offering extrinsic rewards that sometimes contradict the message of sustainable consumption, e.g., receiving coupons that promote further consumption [32]. Other concerns raised include reducing consumption behaviours rather than radically transforming them, failing to implement fantasy/narrative gaming features that might better inspire and engage users, avoiding the use of negative behavioural reinforcement (e.g., punishment, which could facilitate productive failure), and lacking goal-setting features for users [32], yet we note that these critiques have not been meaningfully connected to issues raised in ES literature.

In summary, this paper is motivated by Vasalou and Gauthier's [109] literature review from three flagship CCI venues, showing that 30% of papers on technologies for children's ES had a game focus. As we outline in the next section, the current paper reaches beyond these CCI venues and takes a broader view on gameful interventions, synthesizing literature on GBL, GF, and GA approaches, to guide the design of future gameful initiatives. The research responds to a gap in existing reviews on GBL for children's ES learning which have not identified specific game design themes that promote learning [39, 96], whilst reviews of GF interventions have not focused on children [1, 64], nor have design gaps been contextualised within ES theory [32]. Furthermore, the use of GA in this domain has not yet been considered in past reviews. Motivated by the need to consolidate the design opportunities and limitations of gameful interventions (see Section 2.2), this paper asks, "*How are GBL, GF, and GA interventions designed to foster children's ES learning?*".

3 METHODOLOGY

We conducted a systematic literature review of studies with diverse research designs (quantitative or qualitative) that reported on gameful interventions for children's ES learning. A PRISMA approach [74] was followed to address the research question, with some modifications (e.g., a risk of bias assessment was not conducted, given its inappropriateness to assess the quality of qualitative research). The structured search covered a five-year time span between January 2018 and March 2023. This timeframe was selected to ensure the dataset reflected the most recent developments in gameful interventions and its application to ES, whilst keeping the sample size manageable for in-depth qualitative analysis of the papers' gameful design decisions. A total of 51 papers were identified. This paper corpus was suitable to analyse the papers' content in depth and, whilst yielding a more expansive corpus than past systematic reviews carried out in CCI within focused domain areas [e.g., 20, 35, 109].

Table 3: Search terms for corpus

Target	Search terms
Gameful interventions	"game-based learning" OR "learning game" OR "educational game" OR "serious game" OR "games for learning" OR "computer game" OR "video game" OR "gamifi*"
User group	"pre-school" OR "kindergarten" OR "early childhood education" OR "child*" OR "kid*" OR "pupil" OR "primary school" OR "primary students" OR "primary education" OR "elementary school" OR "elementary student" OR "elementary education" OR "middle school" OR "teen*" OR "secondary school" OR "secondary students" OR "secondary education" OR "high school"
Environmental sustainability	"sustainab*" OR "climate change" OR "climate crisis" OR "climate emergency" OR "climate breakdown" OR "global warming" OR "global heating" OR "greenhouse gas" OR pollution" OR "environmental education" OR "climate science" OR "learning about nature" OR "learning about the environment" OR "ecolog* education" OR "ecolog*" OR "biodiversity" OR "ocean health" OR "oceanography" OR "deforestation" OR "environmental degradation" OR "environmental conservation" OR "nature conservation" OR "conservation of nature" OR "environmentalism" OR "connection to nature" OR "nature-based solutions" OR "stewardship" OR "renewable energy" OR "energy conservation" OR "conserve energy" OR "sav* energy" OR "energy consumption" OR "reduce energy" OR "energy cost" OR "energy efficiency" OR "waste management" OR "recycling" OR "upcycling" OR "up-cycling"

3.1 Eligibility criteria

The inclusion criteria aimed to identify peer-reviewed papers, published in English, that relate to gameful interventions and children's ES. Only studies that focused on children and people younger than 18 were considered. To be included, the study needed to clearly identify a 'digital gameful intervention' as defined under 2.2. In addition, the pedagogical approach had to be centred on stimulating or reinforcing ES learning in children. Studies that considered issues related to ES (e.g., the science of hurricanes), but not the influence of people on the natural world (or their connection to it), were excluded following the same approach reported in Vasalou and Gauthier [109]. Papers that did not specify the design dimensions of the gameful intervention, such as the game mechanics, were also excluded given our aim to analyse the design of each gameful exemplar.

3.2 Search method

A search was conducted using Scopus, ProQuest, the ACM Digital Library, and Web of Science. The use of Scopus and the ACM Digital library ensured that papers published at IDC and IJCCI were identified, while also broadening the reach to other venues that may attract CCI researchers. To formulate the search phrases, three search targets were designed reflecting the technology (gameful interventions), user group (pre-schoolers to young people) and ES (defined broadly and using keywords identified in the ES and digital technology review by Vasalou and Gauthier [109]). Table 3 summarises the search terms used.

3.3 Selection process

The selection process is visualised in Figure 1. We downloaded 736 abstracts from the databases using the above search terms. After removing duplicates and ineligible items, there were a total of 321 abstracts. Next, the titles and abstracts were screened for eligibility based on whether they were in English, appeared to represent a gameful intervention for children, and focused on climate change/sustainability. All abstracts were screened by the first author with the second authors screening 50% of the items in a fully-crossed design (κ =0.73, p<.001); 126 abstracts were retained. This was followed by the first two authors reading each full article to confirm eligibility in a fully-crossed design (κ =0.85, p<.001), where any ambiguous cases were discussed. 51 papers matched the criteria for inclusion in the corpus. Papers were excluded if (i) the full-text was not in English, (ii) the intervention was not GBL, GF, or GA, (iii) the gameful component was not digital/technological [e.g., physical or imaginary games 26, 30], (iv) the gameful intervention did not facilitate children's learning climate change/sustainability as a human-driven issue [e.g., 40, 93], (v) the gameful component was used to assess knowledge/skills rather than foster ES learning [e.g., 24], or (vi) if there was simply not enough description of the approach [e.g., 34, 54]. From the 51 papers included, 12 represented a prototype already in the corpus, and thus 39 unique gameful interventions are reported, an issue which we reflect in our analytic approach.

3.4 Analytic approach

An analysis was performed on each of the 39 gameful interventions, rather than on each of the 51 papers, so that those with multiple publications were not over-represented. As such, we use the interventions' names in our results and discussion. Intervention names demarcated with an asterisk (*) are ones where an intervention name was not specified in the paper, so we named it ourselves based on the paper title/relevant themes.

A coding framework was devised to characterise the corpus and capture trends regarding the context of the research. Following previous CCI literature reviews [20, 35, 109, 113] several codes were used. These included: the geographical area of the research, the target age group, and their education level. This information was determined from the abstract, introduction, and methodology sections. Information was also collected about the domain each gameful intervention addressed, which was inductively thematised

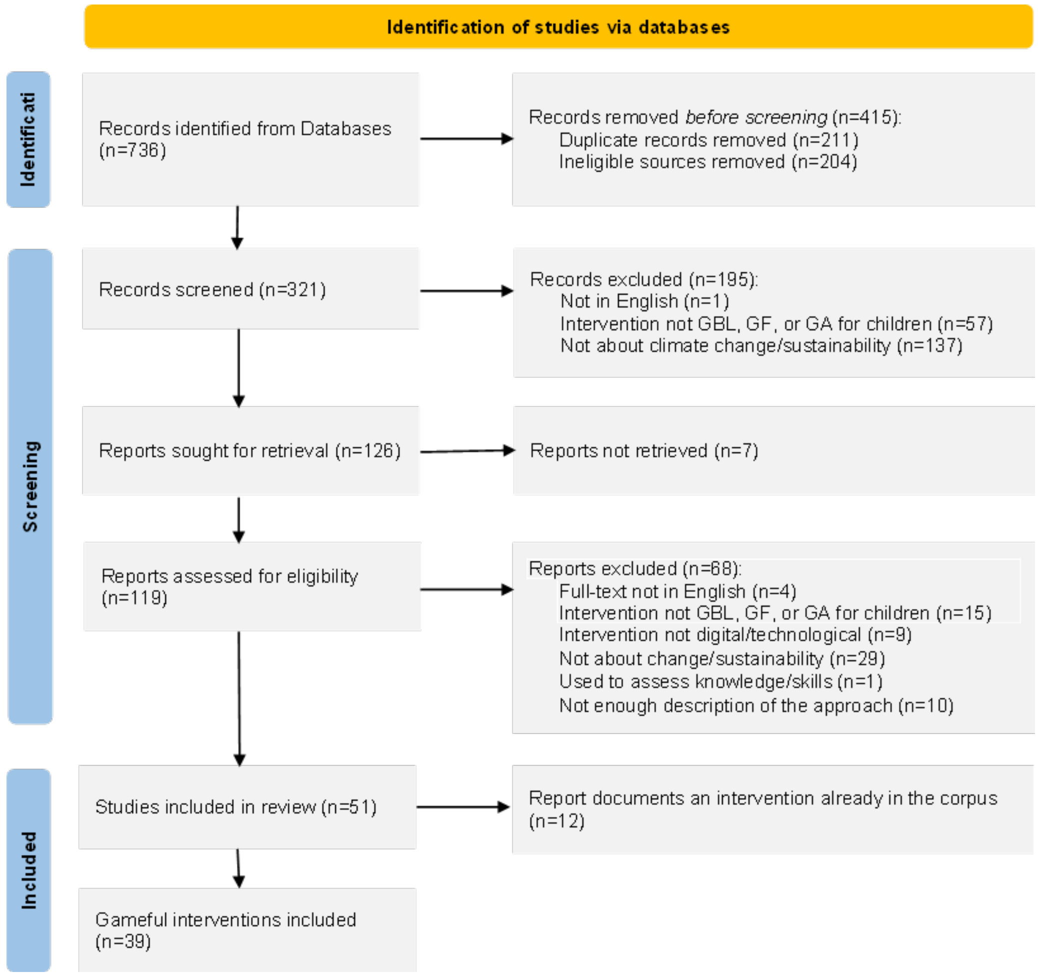

Figure 1: PRISMA selection flow diagram [74].

to develop a code book of seven domains: waste, nature conservation, sustainable development, energy and water conservation, transportation, and everyday activities and practices. Furthermore, in line with the gameful lens taken in the paper, each article was deductively coded to reflect its focus on game-based learning (GBL), gamification (GF), and/or games authoring (GA), allowing for a frequency analysis.

To address the RQ, a **deductive coding scheme** was developed to categorise (i) game genre and (ii) ES education strategy. Whilst the latter was applied to the whole corpus, the game genre was used to code papers in the corpus that reported on GBL only. For the game genres codebook, we drew on previous research, which has proposed three game "styles" previously applied to ES [18]: simulation, strategy, and adventure games. Additionally, parts of Heintz & Law's [33] game classification was used to extend the classification to action and puzzle games. Finally, due to their relevance to educational contexts [91], trivia was bundled under the puzzle genre, as they both test players' knowledge but in different ways (i.e., text vs graphic). In total, six genres were coded as reported in Table 2. For the ES education approach, a codebook was devised based on Monroe et al.'s [62] framework which focuses on the education strategies used to foster environmental knowledge and behaviours. In their own review of ES education, this past work identified four themes of education strategies currently used in formal and informal ES, as previously outlined in Table 1 (1) conveying information, (2) building understanding, (3) improving skills, and (4) enabling sustainable actions. This deductive coding was used to identify trends in the application of ES education strategies to gameful interventions, which in the case of GBL was carried out on the game genres.

In addition to this deductive coding, a descriptive summary of each gameful intervention was created to evidence the codes. We used these descriptions in a **bottom-up inductive analysis** to explore how specific dimensions/features of gameful interventions advanced the ES education strategies, looking out in particular for key education foci, as raised under Section 2. The inductive analysis resulted in four themes which structure the results: game-genres build ES understanding in distinctive ways in GBL, gamified action builds understanding, game-authoring builds understanding

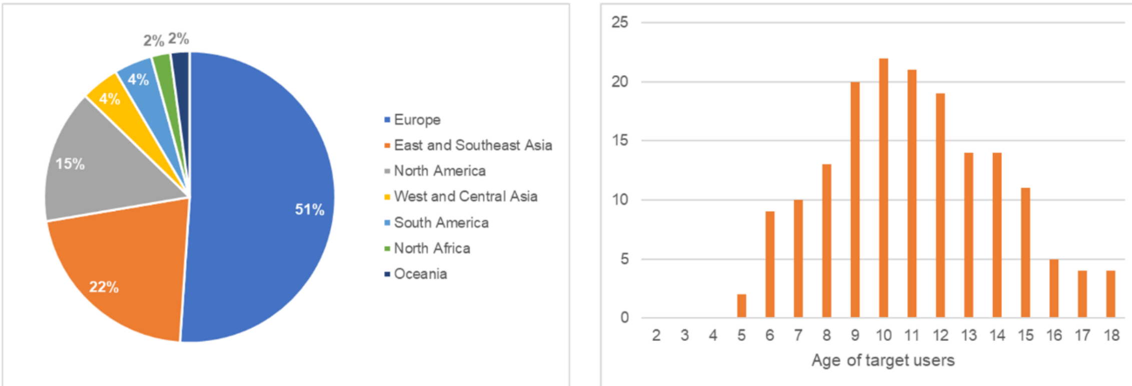

Figure 2: Geographic distribution of gameful intervention by world region (left) and distribution of interventions by age of target audience (right). Note: Interventions may be represented more than once if they target multiple ages and/or were designed/implemented in multiple different countries.

through self-expression and communication, and gameful interventions promote social and domain-specific skills.

To ensure rigour and manage subjectivity, both deductive and inductive analyses were performed collaboratively between the co-authors, in line with past work [109], guided by the interpretive lens of the analysis. This involved regular meetings to work on the analysis in tandem and discussing ambiguous cases.

4 RESULTS

4.1 Description of paper corpus

Of the 39 gameful interventions, 30 incorporated game-based learning (GBL), seven incorporated gamification (GF), and five incorporated game-authoring (GA). Some interventions used more than one approach and thus two combined GBL and GF, and one combined GBL and GA. To exemplify, *enCOMPASS* [22, 23] linked an AR-enhanced trivia game (GBL) to a gamified energy-tracking app (GF), and *PerfectVille* [47] was a simulation game (GBL) that also allowed players to reauthor its rules (GA). A full list of interventions and their descriptions can be found in the Appendix.

The majority of interventions were designed and implemented in the Global North (n=28) with fewer in the Global South (n=12). Specifically, interventions came from Europe (n=24), East and Southeast Asia (n=10), and North America (n=7), whereas fewer came from West and Central Asia (n=2), South America (n=2), North Africa (n=1), and Oceania (n=1) (Figure 2 left). Note that the totals add in excess of 39 as some interventions were studied internationally, e.g., *EcoChampion* was designed in Morocco, Argentina, and Germany [95], and the *GAIA Challenge* was developed between Italy, Greece, and Sweden [65–67, 73, 105, 106]. Figure 2 (right) displays the distribution of gameful interventions by the age of target users. This indicates a focus on upper-primary and lower-secondary school age groups in gameful interventions for ES. Thus, children younger than eight and older teenagers over 15 have received less attention echoing findings from previous review papers [109, 113].

The gameful interventions targeted different domains of human activity impacting ES (see Figure 3). Some targeted discrete domains (waste, nature, energy, transport, water), whilst others looked at domains more holistically (sustainable development, everyday activities/practices, general themes). **Waste** was the largest discrete category (n=14), including how plastic waste ends up in the oceans/water ways and its impacts on marine biodiversity (n=8), proper recycling/sorting of waste (n=5), upcycling of waste (n=1), and littering (n=1). **Nature** conservation was targeted by four (n=4) interventions, focusing on the conservation of biodiversity in terrestrial plants and animals. **Energy** was the focus of four (n=4) interventions, in terms of energy conservation (n=3) and understanding renewable energy sources (n=1). Additionally, low-carbon modes of **transportation** (n=3) and **conservation of water** in domestic settings (n=2) also featured as discrete domains. Taking a more holistic perspective, **sustainable development** was another area of focus (n=5), highlighting the multi-domain nature of sustainability and allowing children to explore urbanisation and how cities can develop in sustainable ways (n=3), how algae might be used in diverse ways in the future for sustainable development (n=1), and the sustainable development goals (n=1). Also highlighting the multi-domain nature of sustainability were interventions that focused on **everyday activities and practices** (n=4) related to energy/water conservation, consumerism, food choices/waste, and transportation. Finally, five (n=5) interventions covered themes related to sustainability in more **general** ways that did not tie the topic down to specific domains or everyday practices e.g., man-made pollution or climate change.

In applying Monroe's framework of ES education strategies (Table 4), we found that all three gameful approaches conveyed information. Inspecting the remaining education strategies, GBL was typically designed to prioritise building understanding, with a more limited focus on improving skills and enabling sustainable action. GF and GA also reflected a focus on building understanding. However, whereas GF interventions prioritised enabling sustainable action, with some focus on skills development, GA interventions were most focused on skills improvement (with understanding as a

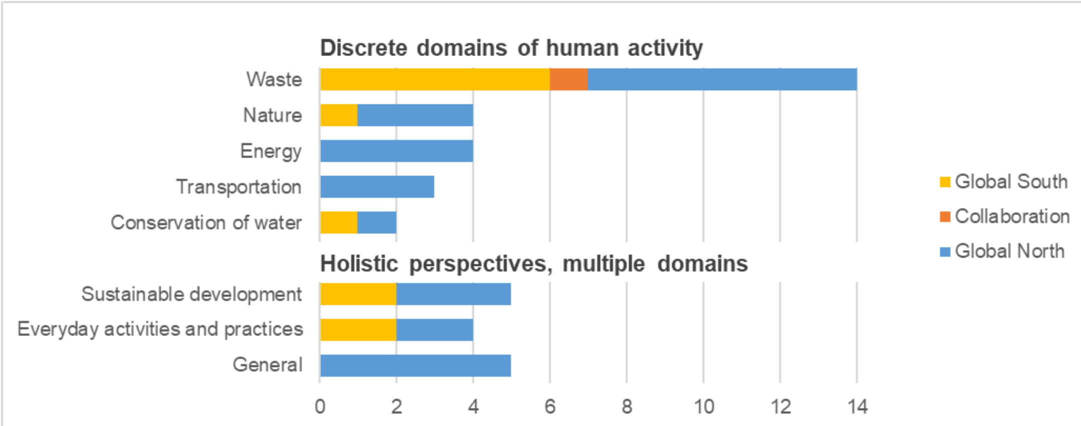

Figure 3: Domains of human activity targeted impacting ES that were targeting by gameful interventions, with global region indicated.

Table 4: Crosstabulation of gameful interventions by Monroe et al. [62]'s ES education strategies.

	Conveys information	Builds understanding	Improves skills	Enables sustainable action
GBL (30)	30 (100%)	28 (93.3%)	7 (23.3%)	2 (6.7%)
GF (7)	7 (100%)	5 (71.4%)	3 (42.9%)	7 (100%)
GA (5)	5 (100%)	5 (100%)	5 (100%)	0 (0%)
TOTAL (39)	39 (100%)	35 (89.7%)	13 (33.3%)	7 (17.9%)

GBL = game-based learning; GF = gamification; GA = game-authoring. Some approaches combine GBL/GF/GA, so add up to >39.

Table 5: Cross-tabulation of game genres appearing in the GBL interventions. Cells in black are single-genre games.

	Action	Adventure	Simulation	Trivia/Puzzle	Strategy
Action	6	2	1	2	0
Adventure	2	4	2	1	0
Simulation	1	2	2	1	2
Trivia/Puzzle	2	1	1	4	0
Strategy	0	0	2	0	1
TOTAL	11	9	8	8	3

prerequisite) but did not enable sustainable action. In the following sections, we elaborate on these patterns, illustrating through examples how each gameful intervention accomplished these education strategies.

4.2 Game-genres build *ES understanding* in distinctive ways in GBL

Table 5 displays the frequency of game genres used across the 30 GBL interventions. The table indicates an equal balance between adventure, simulation, and trivia/puzzle games, with action games being the most frequent and strategy games employed the least. It also illustrates that some genres were combined within the same game, but, for brevity, in the description that follows, we consider only one such combination (simulation + strategy) owing to the strengthened opportunities for ES understanding this combination offered. Additionally, Figure 4 demonstrates the distribution of GBL game genres by age of target users, demonstrating that certain genres tended to be used with primary school-aged children (e.g., action, trivia/puzzle), whereas others were used more with secondary school-aged children (e.g., simulation, strategy). Adventure games straddled upper primary- and lower secondary-aged children.

The **action** (n=11; [2, 6, 7, 38, 51–53, 55, 84, 94, 95, 111]) genre was the most prominent in the corpus. Action games promoted building understanding of ES concepts through trial-and-error in simple tasks and puzzles, where chances of making a productive error were enhanced by the need for hand-eye coordination and reaction time indicative of the action genre. It is also notable that all focused on the domain of waste sorting. For example, *HydroHero* [6] is an infinite-runner style game where the player runs beside a canal and must collect items that shouldn't be there, such as trash and harmful plant species, whilst avoiding obstacles and

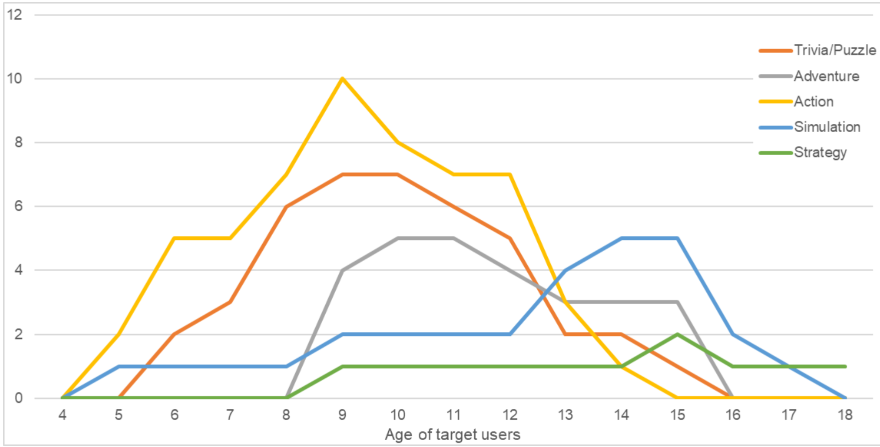

Figure 4: Frequency of GBL genres by age of target users.

gaining velocity as they progress. Thus, in action games, the action, rather than the narrative, was the driving mechanic for building understanding.

Contrastingly, narrative and/or game world exploration were integral to games classified under the **adventure** genre (n=9; [38, 69, 82, 88, 90, 94, 100, 101, 112]), by enabling the player to take on new identities, where puzzles or quests were incorporated in the game narrative. For example, in *For People and Planet* [82], the player engages in a series of stories about everyday life in the Philippines, reflecting how the community encourages sustainability and climate resilience. The main character interacts with people in his everyday life (e.g., grandmother), whilst learning about different environmental issues and adaptation strategies through narrative. The narrative is interspersed with puzzle mini-games associated with the everyday activities (e.g., food preparation and food waste disposal) in the narrative, to build players' understanding of sustainable practice/resilience.

Simulation games (n=8; [3, 7, 41, 47, 68, 78, 88, 100]) tended to emphasise systems-thinking through two dimensions: (i) the three pillars of sustainability (environmental, social, economic) and (ii) the multi-domain nature of ES as detailed under 4.1. Evidencing both dimensions, in *M-Enercities* [3], players discuss and decide collaboratively how best to develop a virtual sustainable city across several domains (e.g., transport, energy), whilst negotiating personal values related to balancing economic gains with environmental and social wellbeing. In contrast, other simulation games focused on a single domain and fewer pillars. For instance, *Simulation GeoGame FVsimulation* [88] focused on biodiversity from the lens of environmental and economic pillars without a recognition of the social pillar. In this game, the players inherit a forest and must manage lumber as a resource whilst protecting the wildcat's habitat, simulating variables associated with the wildcat population, biodiversity of the habitat, amount of timber/revenue, based on decisions made in the game. These decisions are location-based, requiring the player to explore a real-world forest, which situates their understanding in the real world.

Trivia and puzzle games (n=8; [14–16, 22, 23, 25, 72, 75, 78, 87, 92, 111, 112]) facilitated building understanding mostly through trial-and-error, similar to the same kinds of trial-and-error tasks and puzzles as found in action and adventure games (e.g., *Contact from the Future* [75], *Climate4Kids* [25], *PeppeRecycle* [14–16]), except that they lacked the narrative-driven exploration and hand-eye coordination of these other genres. In addition to trial-and-error, and similar to the simulation games, some trivia games motivated the development of systems-thinking through text-based multiple-choice scenarios. For example, in *2020 Energy* [72], players answered questions about everyday scenarios (e.g., buying the most energy efficient products, choosing sustainable clothing) wherein they could choose the answer that was most sustainable. Intended to increase players' understanding of the systemic consequences of their actions, choices were either equitable (social, economic), liveable (social, environmental), bearable (economic, environmental), or sustainable (social, environmental, economic).

Games adopting aspects of the **strategy** genre were less frequent overall (n=3; [37, 47, 68]). The only 'pure' strategy game was *Plastic Stream* [37], a 'tower-defence' style strategy game, where players are faced with waves of flowing plastic that must be collected by boats of specific colours and nets (that catch items that the boats miss) to prevent these items ending up in the sea. Players strategically place their inventory of boats upstream before and during the wave. Nonetheless, in this game, it is noted that the strategy as a gaming mechanic (positioning of defence mechanisms) is weakly connected to the learning outcome (plastic in the ocean is harmful). Combining the strategy and simulation genre, the remaining two games connect the strategy and learning outcomes more directly, with the strategy element adding a layer of complexity to the type of systems-thinking that the simulation engenders. In *PerfectVille* [47], for example, a strategy-simulation game, players are given only 10 moves in which to make value-driven choices about their urban lifestyle, which determines their fate. This necessitates that they think systemically—and strategically—about how their actions impact social and economic well-being, planning several moves ahead.

Table 6 summarises these findings showing how the game mechanics and game design elements elicited ES understanding (right

Table 6: How GBL genres helped players build understanding

Genre	Builds understanding about. . .	Builds understanding by/through. . .
Action	• Right/wrong knowledge, behaviours, and actions • Largely categorisation type domains (e.g., waste sorting/recycling)	• Trial-and-error tasks/quests with feedback; productive failure enhanced by need for hand-eye coordination
Adventure	• Sustainability-related identities, social and environmental impacts of climate change	• Narrative-driven exploration of open worlds, talking with NPCs, narrative-related tasks/quests
Simulation	• Systems-thinking about the multi-domain and interconnected nature of sustainability	• Simulating cause-and-effect between multiple variables related to three pillars of sustainability • Location-based real-world scenarios/activities
Trivia/Puzzle	• Right/wrong knowledge, behaviours, and actions	• Trial-and-error puzzles/quizzes with feedback
Strategy	• Right/wrong actions to improve sustainability/mitigate climate change	• Limited number of moves/choices requires players to think ahead about cause-and-effect of actions

column), whilst illustrating the different ways understanding was enabled within each game genre (left column).

4.3 Gamified action builds understanding

GF interventions were targeted across primary and secondary school-aged children. In contrast to GBL and GA, whose design overall didn't promote children to take sustainable action, an examination of the seven GF interventions in the corpus shows that they were all designed to enable sustainable action and build understanding [17, 22, 23, 58, 65, 66, 73, 83, 87, 102, 105, 106]. More specifically, building understanding was made possible through GF enabling children to take situated actions, making these two education strategies inextricably linked (Table 7). For some GF interventions, the link between understanding and action was made possible by **converting un/sustainable actions into some form of digital currency, or reward**. For example, two GF interventions on sustainable transportation (*Kids-Go-Green* [58] and *Sustainable Mobility App** [83]) calculate digital miles from the real-world distances that children travel via different modes of transportation. The number of digital miles children are awarded depends on the mode of transportation used (i.e., walking/cycling earns more miles than taking the bus, which earns more miles than taking a car over the same distance), advancing the players toward a virtual end goal/destination to collect more miles. Other GF interventions **use eco-feedback to visualise variations in the use of resources** in households (*enCOMPASS* [22, 23]) or schools/classrooms (*GAIA* [65–67, 73, 105, 106]), prompting children through challenges/quests to adjust their conservation actions and see this reflected in their resource use over time. Thus, in these GF designs, the process of interpreting the eco-feedback to inform a sustainable action became the primary mechanism for building understanding of resource use.

There were three interventions that, while their GF elements enabled sustainable action in the short-term, raised questions in how they built meaningful understanding [17, 87, 102]. These required children to complete one or more one-off sustainable actions without offering a mechanism for children to reflect on the impacts of these actions. For example, the *Environmental Citizenship Token App** [102] gamifies a series of one-off ES activities, where the child completes real-world missions related to four ES themes: reusing and recycling, water consumption, ecosystem services, transportation, and food consumption. The child either times their actions (e.g., how many minutes in shower) or counts their output on that task (e.g., number of plants planted) recording it in the app as proof-of-completion. Based on this, the child is rewarded with digital and physical badges. Whilst ES information is clearly displayed in the app and its tasks encourage children to engage in sustainable actions, because these actions are simply marked as completed—without further evaluation or reflection—it is not clear that the child would build a deeper understanding of why they are performing these actions or how to do them well. Contrastingly, if sensor data were used to demonstrate the impact of that action, or if comparisons were made to a baseline or goal, this may have bolstered self-reflection and deeper understanding.

Table 7: How gamification helped students build understanding through action

Builds understanding about…	Builds understanding by/through…
• The impact of un/sustainable actions	• Conversion of real-world actions into digital currency • Quests prompt reflection on eco-feedback visualizing resource use and impact of interventions
• Actions that are/are not sustainable	• Rewards, badges for completing sustainable actions

4.4 Game-authoring builds understanding through self-expression and communication

GA interventions targeted mainly upper primary and secondary school-aged children. Compared to GBL and GF interventions, where ES was represented through pre-authored content and mechanics, the five GA interventions in the paper corpus were all designed to **encourage children's perspectives and expressions of ES** [11, 45, 47, 48, 80]. Children expressed both their ES-related knowledge and concerns when authoring the games. At the same time, they developed their collaboration, design, and development skills during orchestrated group work, an issue we will return to in 4.5. Yet, it is noted that a common challenge researchers faced was on how to best scaffold children to lead on the game design and development process. This was addressed through a range of strategies, including the inclusion of researchers who coded the games [11], or creating a half-baked game the children went on to adapt [47]. In one such intervention (*PerfectVille* [47]), students had to modify the rules and parameters of an existing simulation game in line with their ES values. In some instances, however, it was unclear how well the game design activity was scaffolded, as the gaming mechanics designed by the children were not always well connected to the learning outcomes, e.g., making a character jump to catch methane coming out of cows or pollution coming out of chimney stacks (e.g., *Building Systems from Scratch GA workshop** [80]). In line with their constructionist underpinnings, the game artefacts created by the children suggested a communicative purpose, and two of the papers [11, 45] reported explicitly engineering this by inviting other children and adults to play them. Examining the games children authored is thus valuable both in gauging their ES understanding and the communicative strategies they used to build future players' understanding of ES.

To this end, it was observed that children's framing of the problem took a negative lens, using provocation and driving empathy toward non-human characters. For instance, in the *Design with Feeling GA Workshop** [11], older children created embodied participatory simulation games for younger ones to learn about plastic pollution and its impact on marine ecosystems. The games produced were embodied multiplayer action games, where players used their bodies to control the characters. In one game designed, players were either Red Polluters (throwing rubbish into a river) or Green Cleaners (picking up the rubbish and putting it bins), competing against each other. In another game, each player controlled a fish who swam around eating (what they thought was) food. In later levels, the players discover that it wasn't food but plastic, and the players were poisoning themselves whilst trying to stay alive. A similar theme might be seen in *Wolf Live!* [45], where one of the mini-games authored involved having a wolf cross a busy motorway without being hit. Similarly, in *Design for Impact GA Workshop** [48], the authored game had different endings, one of which involved the world "imploding due to the destruction of all the plants, trees, and animals". In contrast, the framing was more positive and action-oriented within other child-authored games, demonstrating to future target audiences what children could do in response to the climate crisis. In one such game, where the player was prompted to clean up marine ecosystems [11], the child designers indicated that they didn't want their players to feel hopeless and alone. Similar approaches were observed in a couple of games created in the *Building Systems from Scratch GA workshop** [80] where children took more action-oriented lenses, e.g., a game of planting trees, properly recycling materials, and choosing specific plants to sequester more carbon.

4.5 Gameful interventions promote social and domain-specific skills

Turning our attention to whether the three gameful interventions engendered skills, Table 4 shows that they varied across the three approaches from 23% for GBL, 43% for GF and 100% in GA. **Collaboration and communication skills** were engendered across all three intervention types, though there were differences in how this was achieved. Within GBL, some games were designed to be played in a group and centred on solving an ES-related problem (e.g., *Minecraft camp* [41], *Simulation GeoGame FVsimulation* [88]), with several involving the negotiation of different values (e.g., economically/socially-driven vs environmentally-driven values) before making shared decisions toward sustainable development of a game-world (e.g., *M-Enercities* [3], *Climate Adaptation Game* [68], *PerfectVille* [47]). The same approach was taken in GA. However, communication skills were not only mobilised by the child team whilst designing the game, but also in communicating the ES problem to an anticipated future audience. GF prompted collaboration,

Table 8: How gameful interventions promote social and domain-specific skills

Improves ES skills related to. . .	Improves ES skills by/through. . .
• Collaboration and communication	• Negotiation of values toward shared decision-making between peers (GBL, GF, GA) and between children and other stakeholders (GBL, GF)
	• Design to communicate and express ES to external audiences (GA) • Competitive elements (e.g., leaderboards) to prompt reflection on skills and actions (GF)
• ES domains	• Tasks requiring application of skills to children's real-world environment (GBL, GF), e.g., through location-based game tasks, computer-vision, environmental monitoring

too, such as in the case of *enCOMPASS* [22, 23], where communication and negotiation between parents and children was necessary, given that the adults have access to eco-feedback in a gamified app, and the children are introduced to energy conservation through associated AR trivia-based GBL activities that feed back into the gamified app. In contrast to GBL and GA, three GF made use of competition, which acted as a catalyst to draw attention to eco-feedback and sustaining actions. For instance, in *GAIA*, leaderboard displays were used to facilitate competition between classes and schools particularly in relation to tracking energy consumption [65–67, 73].

Two of the three gameful interventions, GBL (n=2) and GF (n=3), were designed to advance **domain-specific skills**. This was achieved in GBL by situating the learning in the environment, connecting what children learned to its context and making skills transferability possible. For instance, in *Simulation GeoGame FVsimulation* [88], players conduct location-based tasks in a real-world forest that simulates the experience of collecting real scientific data about the wildcat population. Similarly, in *PeppeRecycle* [14–16, 84], a robot uses computer vision to recognize real-world trash items *from* the classroom, and children have to categorize these *in* the classroom by selecting the correct bin through the robot-tablet interface. In this way, waste sorting skills exercised through the game can be directly transferred to behaviours in the classroom. If *PeppeRecycle* had also prompted the children to put these items in a real-world bin, the game would have also 'enabled sustainable action', suggesting a missed opportunity. In the case of GF, domain-specific skills centred on resource monitoring and constructing sensors for resource monitoring (*GAIA* [65–67, 73, 105, 106], *enCOMPASS* [22, 23]), as well as upcycling waste materials found in the home (*Edcraft Gamified Learning* [17]). For example, the *GAIA* project touched on all the above skills, by having students work collaboratively to build and monitor environmental sensors using internet-of-things technologies. Table 8 summarises the key themes on how gameful interventions promoted social and domain-specific skills in our corpus.

5 DISCUSSION

This systematic literature review synthesised literature from 39 gameful interventions—namely game-based learning (GBL, n=30), gamification (GF, n=7) and game-authoring (GA, n=5)—published over the past five years. With GBL being the historically older approach in comparison to GF and GA [19], it is not surprising that GBL interventions dominated the corpus. As such, whilst our paper contributes knowledge to GF and GA for children's ES education, it goes most deeply into the design of GBL.

5.1 What GBL pedagogies can offer to ES

Overall 93% of GBL were designed to build understanding, primarily through their cause-effect mechanisms [62]. However, the game genres analysis showed there were profound differences, both in terms of the types of understanding different game genres were designed to engender and the mechanisms that enabled these. Summarised under Table 6, we reflect on their strengths and weaknesses from an ES prism. Given the limited representation of strategy games in the corpus, the discussion centres on the remaining four genres.

Two of the GBL genres advanced new possibilities for building ES understanding. In adventure games, this was achieved through interactive narratives and environmental stewardship game roles. Underscoring the potential role of adventure games for ES learning, GBL research has shown how this game genre allows players to enact and experiment with authentic identities [28], whilst other research has raised the prospect of these games fostering empathy toward virtual characters and environments in ways that raise awareness of social justice, an issue that is crucial to ES learning [39]. In contrast to the opportunities afforded by adventure games, simulation games made use of (i) the three pillars of sustainability (environmental, societal, economic) and (ii) multiple domains of sustainability (e.g., transport, energy). In doing so, they promoted systems-thinking, which, as detailed in 2.1, is vital to understanding ES [57, 79]. Nonetheless, like previous research [96, 109], we found that most of these games were not designed to address both factors holistically. We hope interaction designers can use these factors as an explicit resource in future game design. This work will need to consider co-designing such game mechanics with children, and developing co-design methods to this effect, to ensure children can grapple with the complexity of ES as an interconnected system. Given that the simulation genre was often extended with the strategy genre in some games in our corpus, one avenue to explore is whether the strategy genre could offer the much-needed cognitive scaffold to help children process and understand the multiple dimensions of systems-thinking. To this end, strategy games have been shown to allow children to think through their actions and how these affect the actions of others [81].

The two remaining game genres – action and puzzle/trivia games – contrasted with ES education principles. Action games visualised cause-and-effect (e.g., plastic in oceans cause fish to die) and were designed to test correct/incorrect ES knowledge of the waste domain (e.g., which types of rubbish get sorted into which bin). These games were thus limited to categorisation-type, rote-learning tasks with binary or few options, which suited the reaction-time and hand-eye coordination mechanics typical of this genre. It is perhaps because of the easy match between action mechanics and rote learning that action games were so dominant in the corpus. Yet, this design approach prioritised facts over a critical, purposeful and interconnected understanding of ES [8, 63, 97]. Moreover, in focusing on waste sorting, action games reaffirmed the use of fossil fuels to make plastic rather than questioned the use of plastic in the first place, embracing what Stevenson argues as the conservative (as opposed to radical) approach [97]. Similar patterns were found for puzzle and trivia games, although one such game [72] made use of the three pillars of sustainability and reflected alternative ways of living (e.g., upcycling clothes rather than purchasing new/used), evidencing the opportunity for using this genre toward fostering systems-thinking. One possible explanation for the conservative use of action games and trivia/puzzle games is that these were generally targeted toward children in primary school, whose critical thinking skills are less well developed. In contrast, simulation games, which tended to look at sustainability more holistically, were targeted more toward children in secondary school. An alternative explanation may arise through situating our findings geographically; the use of action and/or trivia/puzzle games focusing on waste (n=12 total) was proportionally higher in interventions arising from the Global South (six out of the 12 games [2, 53, 55, 78, 87, 95, 112]) in comparison to the Global North (seven out of 12 [6, 14–16, 38, 51, 52, 75, 84, 95, 111]), representing 50% of the interventions from the Global South and 25% from the Global North. This suggests that there may be a shift toward other domains of sustainability in more developed countries, where there are more resources to support more radical forms of climate action/mitigation. Our analysis thus underscores the need to inform GBL design efforts with ES education theories more broadly, whilst highlighting the impetus to reflect postcolonial and indigenous perspectives in these future design imaginaries [59, 114].

In response to Vasalou and Gauthier [108], who critiqued the lack of connection between game design and children's physical environment, only three GBL interventions positioned the gaming activity "in place", thereby connecting the game world to the child's physical world to enhance the transferability of understanding. This was achieved through computer vision, by either categorising real-world items [14–16] or analysing objects in the environment that were mapped to categories in a trivia bank [22, 23]. A different approach was to situate the GBL intervention outdoors [88], combining narrative-driven, location-based tasks with simulated economic and environmental consequences to model systems-thinking. These exemplars open new avenues for future work for exploring the technical possibilities of combining computer vision and location-based gameplay as resources to engender situated and complex systems-thinking. Moreover, such an approach might foster opportunities for children to reconnect with nature [50], particularly if the game fantasy/narrative aims to enhance children's wonder in nature as 'self-arising' [10], which has yet to be explored.

5.2 Gamification as a reinforcer of sustainable action

In contrast to GBL, by removing the confines of the game-world, GF enabled ES learning to be positioned in the everyday lives and environments of children. It linked gaming elements to everyday actions that children can realistically take, making visible children's agency [1, 64]. As such, GF built children's ES understanding and improved their domain-specific and social skills *through sustainable action*. Our analysis contributes two design strategies through which this was achieved: (i) converting actions into currency in line with their carbon footprint, and (ii) prompting reflection on the visualisation of resource use as a motivator to action, e.g., through quests/challenges (Table 7). These are important contributions as they demonstrate how GF's game elements can be designed to enhance action-orientation and child agency.

Nonetheless, these design strategies also raise new open questions about how GF is currently designed to foster ES learning. Interestingly, papers employing GF to facilitate understanding of resource use did not reflect on children's ability to comprehend the units of resource measurement (e.g., kW/h), which has been identified as problematic for adults [99]. As such, there is potential for future research to explore whether GF's affordance to connect units of measurement to tangible actions allows children to directly relate their resource use to the activities they engage in. Moreover, we found that competition was a core design element across most GF interventions intending to draw attention toward fluctuations/differences in resource units consumed by children/classes/schools. Whilst this kind of competition is thought to motivate behaviours, the everyday contextual factors affecting how resources are used went unrecognised, such as those that might mediate a school's resource consumption (e.g., number of students, construction of building, local climate), reasons behind a child's choice of transportation method (e.g., distance from school, parents' schedules), or other embodied conservation competencies that are not measured (e.g., taking the stairs instead of the elevator). Future efforts in GF's application to ES could explore ways to design game features that support a critical lens, allowing children to consider these everyday factors, social drivers and consequences behind un/sustainable actions, linking to previous critiques of how GF has been designed for adults' ES learning [32]. Finally, aligned with our earlier argument in relation to the conservative ES approach taken to design action/trivia games, the focus of GF on resource consumption reemphasises the critique that most GF in our corpus were designed to reduce existing consumption behaviours rather than radically transform our ways of living [32]. Indeed, in some instances [17, 87, 102] this conservative approach was utilised to engage children in short-term, one-off sustainable actions through rewards. While raising the question of whether GF is an effective intervention when it is time-bound, we also ask whether rewards in this case may inadvertently incentivise children toward further consumerism, e.g., taking showers every day of the week to record the time in the app [87, 102], an issue that has been also previously discussed in the literature [32]. With GF bringing ES learning beyond the classroom into schoolgrounds, outdoors, and homes, we thus argue that there is potential for future research to explore how this gameful intervention could be designed to foster children's transformative ES actions.

5.3 Opportunities and questions for constructionist game authoring and children's voices

The five GA interventions in our paper corpus were all designed to offer children opportunities to openly and critically explore ES topics of interest, whilst at the same time developing 21^{st}-century skills (e.g., creativity, inquiry, problem-solving, and collaboration) through a collaborative game design process [43]. Unlike GF which were led by sustainable action, GA interventions did not activate this strategy directly, per Monroe et al. [62]. However, they offered an affordable and adaptable means for children to express their own authentic voices and life experiences in relation to sustainable presents and futures, which has been acknowledged as critical for their wellbeing [107]. Given the cost of developing GBL and GF interventions [46], GA interventions could be more accessible to schools and also malleable for children to express local environmental considerations. Nonetheless, GA papers consisted only 10% of the corpus, which suggests more guidance on how to implement and scaffold GA interventions in and outside of schools is needed. We now turn our attention to children's self-expression and communicative intension which was a crucial theme underpinning GA.

Children expressed both *positive* views in their games, with intention to motivate child-accessible action (e.g., planting trees, litter picking), as well as *negative* views, intending to shock and provoke their audience (e.g., struggle between polluters and cleaners, environmental destruction, harm to wildlife). Notably, the negative views dominated the child-authored games in our corpus, which contrasts with much of the literature that emphasises the need for hopeful pedagogies when engaging children in ES [21, 70, 71]. Whilst this negative framing of ES could be interpreted to reflect climate anxiety and the suspension of hope, it is also possible that GA moved children away from a less critical (conservative) perspective to an activist (radical) one [i.e., 97] that challenges existing systems and expresses a need for change to their audiences. The action/trivia GBL genres (5.1) and GF (5.2) in the corpus typically failed to challenge current paradigms of living, so children's voices in GA offer fresh perspectives on how this could be achieved in game design. In fact, we posit that children were more successful at applying the action genre to foster critical ES understanding than were the GBL interventions examined in this review. While the GBL action games in our corpus typically focused on categorisation-type knowledge that reinforced the status quo, the action games created by children challenged the status quo by applying action mechanics (i.e., hand-eye coordination) in ways that forced future players to encounter uncomfortable situations. This speaks to Khaled's concept of reflective game design, where "designing for surprise" can push players towards reflecting on their play experiences, thereby "sensitising players towards underlying assumptions and values inherent in familiar systems, and provoking them into deeply exploring, questioning and co-creating responses to problems in light of their own experiences and beliefs" [42].

5.4 Limitations

However, there are some limitations to our findings. The five-year time frame is a possible limitation of this work, given that we have excluded earlier gameful interventions that may have taken different design approaches. However, based on reviews prior to 2018 [1, 39, 64, 96], we can be reasonably confident that our results extend the work of others and have not missed any crucial design themes. Our selection of papers was also limited to those published in English and, although English is the most common language in academic texts, it means that we may be missing important work from regions in the world where English is not the primary language (e.g., from the Global South). Future work might repeat this review, looking exclusively at work published in languages other than English to see if the trends we have observed in this review are transferable. Additionally, our paper corpus included only three gameful interventions that combined GBL, GF, and GA approaches in a single intervention. These showed some plausible benefits of combining approaches, e.g., by applying knowledge learned in GBL to real-world action through GF [22, 23, 87], fostering collaboration between children using GBL and adults using GF [22, 23], and by making GA more feasible by having children modify and extend the design of pre-existing GBL interventions [47]. However, more work that combines gameful approaches is necessary to investigate the different ways in which these intervention types may complement each other to support ES learning.

6 CONCLUSION

The climate crisis has created a time of great uncertainty for children and their futures, raising the need for new approaches that support children to learn about ES and prepare them for living with climate impacts. A central focus in CCI literature [108], gameful interventions could offer the potential to engage children in new forms of ES learning, yet there is little guidance on how to design these technologies. Addressing this gap, our systematic literature review reports a critique of 39 gameful interventions, including game-based learning (GBL), gamification (GF), and game-authoring (GA) approaches. Designed and published over a five-year period, the interventions were critically analysed through the lens of ES theories and our own bottom-up analysis of their design features. Our research broadly elucidates the distinctive ways that gameful interventions can align with a previous framework of ES education strategies, whilst evidencing that GF is particularly well suited to engender children's sustainable action [62]. Drawing from the critical analysis presented within the discussion, we argue that the dominant focus on knowledge-centric approaches to GBL, as well as the over-representation of certain domains (e.g., waste sorting), limits the significance of gameful interventions for children's ES learning. Grounded in our discussion and summary Tables 6-8, we offer four future strands for gameful interventions that have the potential to bring a distinctive contribution to ES learning:

(1) New stewardship identities that invite children to try out new ways of enacting their environmental roles. For example, through designing authentic game roles explored in game narratives.
(2) Situating learning in the physical world to support transferable learning. This can be achieved through place-based game tasks, computer vision to connect game actions to real world actions, or gamifying long-term collective action within communities.
(3) Engendering systems thinking to develop critical thinking of the multi-faceted nature of ES. For example, through simulating or triggering children's thinking about the interconnectedness of different sustainability pillars and domains of living.
(4) Promoting children's voices, self-advocacy, and even dissent over climate change. By offering game environments that allow for unfettered but supported self-expression, with a focus on radical (over conservative) perspectives of climate adaptation and mitigation that challenge social structures.

Our critical discussion also shows that there are challenges in designing games to foster these four types of learning, leading us to raise new questions about the future design of GBL, GF and GA.

7 SELECTION AND PARTICIPATION OF CHILDREN

No children participated in this work.

REFERENCES

[1] Albertarelli, S. *et al.* 2018. A survey on the design of gamified systems for energy and water sustainability. *Games.* 9, 3 (2018), 1–34. DOI:https://doi.org/10.3390/g9030038.
[2] Alfahid, A. *et al.* 2021. DoItRight: An Arabic Gamified Mobile Application to Raise Awareness about the Effect of Littering among Children. *International Journal of Advanced Computer Science and Applications.* 12, 12 (2021), 151–157. DOI:https://doi.org/10.14569/IJACSA.2021.0121220.
[3] Alves-Oliveira, P. *et al.* 2019. Empathic Robot for Group Learning: A Field Study. *ACM Transactions on Human-Robot Interaction.* 8, 1 (2019), 1–34. DOI:https://doi.org/10.1145/3300188.
[4] Antle, A.N. *et al.* 2014. Emergent dialogue: Eliciting values during children's collaboration with a tabletop game for change. *ACM International Conference Proceeding Series.* (2014), 37–46. DOI:https://doi.org/10.1145/2593968.2593971.
[5] Antle, A.N. *et al.* 2011. Towards Utopia: Designing tangibles for learning. *Proceedings of IDC 2011 - 10th International Conference on Interaction Design and Children.* (2011), 11–20. DOI:https://doi.org/10.1145/1999030.1999032.
[6] Appel, Y. *et al.* 2019. A serious game to inform young citizens on canal water maintenance. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics).* 11899 LNCS, (2019), 394–403. DOI:https://doi.org/10.1007/978-3-030-34350-7_38.
[7] Bayley, M. *et al.* 2020. Serious Game Design to Promote Energy Literacy among Younger Children. *ACM International Conference Proceeding Series.* (2020), 531–537. DOI:https://doi.org/10.1145/3441000.3441047.
[8] Bedi, G. and Germein, S. 2016. Simply Good Teaching: Supporting Transformation and Change Through Education for Sustainability. *Australian Journal of Environmental Education.* 32, 1 (2016), 124–133. DOI:https://doi.org/10.1017/aee.2015.52.
[9] Benton, L. *et al.* 2018. A critical examination of feedback in early reading games. *CHI Conference on Human Factors in Computing Systems - Proceedings.* 2018-April, (2018). DOI:https://doi.org/10.1145/3173574.3173947.
[10] Bonnett, M. 2007. Environmental education and the issue of nature. *Journal of Curriculum Studies.* 39, 6 (2007), 707–721. DOI:https://doi.org/10.1080/00220270701447149.
[11] Brady, C. *et al.* 2022. Designing with Feeling. (2022), 315–326. DOI:https://doi.org/10.1145/3501712.3529725.
[12] Burke, A. and Crocker, A. 2020. "Making" Waves: How Young Learners Connect to Their Natural World through Third Space. *Education Sciences.* 10, 8 (2020), 1–17. DOI:https://doi.org/10.3390/educsci10080203.
[13] Carmona-Moya, B. *et al.* 2021. Eimeca: A proposal for a model of environmental collective action. *Sustainability (Switzerland).* 13, 11 (2021). DOI:https://doi.org/10.3390/su13115935.
[14] De Carolis, B. *et al.* 2019. Investigating the Social Robots' Role in Improving Children Attitudes toward Recycling. The case of PeppeRecycle. *10th IEEE International Conference on Cognitive Infocommunications, CogInfoCom 2019 - Proceedings.* (2019), 301–306. DOI:https://doi.org/10.1109/CogInfoCom47531.2019.9089994.
[15] Castellano, G. *et al.* 2019. Learning waste recycling by playing with a social robot. *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC).* (2019), 3805–3810.
[16] Castellano, G. *et al.* 2021. PeppeRecycle: Improving Children's Attitude Toward Recycling by Playing with a Social Robot. *International Journal of Social Robotics.* 13, 1 (2021), 97–111. DOI:https://doi.org/10.1007/s12369-021-00754-0.
[17] Cheng, K.M. *et al.* 2022. An evaluation of online Edcraft gamified learning (EGL) to understand motivation and intention of recycling among youth. *Scientific Reports.* 12, 1 (2022). DOI:https://doi.org/10.1038/s41598-022-15709-2.
[18] Coakley, D. and Garvey, R. 2015. The great and the green: Sustainable development in serious games. *Proceedings of the European Conference on Games-based Learning.* 2015-Janua, 2002 (2015), 135–143.
[19] Deterding, S. *et al.* 2011. From Game Design Elements to Gamefulness: Defining " Gamification ." *MindTrek'11* (Tampere, Funland, 2011), 9–15.
[20] Eriksson, E. *et al.* 2022. The Role of Learning Theory in Child-Computer Interaction - A Semi-Systematic Literature Review. *Proceedings of Interaction Design and Children, IDC 2022.* (2022), 50–68. DOI:https://doi.org/10.1145/3501712.3529728.
[21] Finnegan, W. 2022. Educating for hope and action competence: a study of secondary school students and teachers in England. *Environmental Education Research.* 29, 11 (2022), 1617–1636. DOI:https://doi.org/10.1080/13504622.2022.2120963.
[22] Fraternali, P. *et al.* 2018. A Socio-Technical System Based on Gamification Towards Energy Savings. *2018 IEEE International Conference on Pervasive Computing and Communications Workshops, PerCom Workshops 2018.* (2018), 59–64. DOI:https://doi.org/10.1109/PERCOMW.2018.8480405.
[23] Fraternali, P. and Gonzalez, S.L.H. 2019. An Augmented Reality Game for Energy Awareness. *12th International Conference on Computer Vision Systems* (2019), 629–638.
[24] Friman, H. *et al.* 2020. Ubiquitous Learning of Renewable Energy and Environmentalism to Various Israeli Populations. *Proceedings - 2020 International Symposium on Educational Technology, ISET 2020.* (2020), 114–117. DOI:https://doi.org/10.1109/ISET49818.2020.00033.
[25] Gabriel, S. and Schmölzer, B. 2022. Climate4Kids: A Gamified App Teaching about Climate Change. *Proceedings of the European Conference on Games-based Learning.* 2022-Octob, (2022), 236–243. DOI:https://doi.org/10.34190/ecgbl.16.1.356.
[26] Gandini, P. *et al.* 2019. Sustainable and aware mobility explained to children. *Sustainability (Switzerland).* 11, 23 (2019). DOI:https://doi.org/10.3390/su11236668.
[27] Gee, J.P. 2005. Good Video Games and Good Learning. *Phi Kappa Phi Forum.* 85, 2 (2005), 33–37.
[28] Gee, J.P. 2007. *What Video Games Have To Teach Us About Learning And Literacy.* Palgrave MacMillan.
[29] Giannakos, M. *et al.* 2020. Mapping child–computer interaction research through co-word analysis. *International Journal of Child-Computer Interaction.* 23–24, (2020), 100165. DOI:https://doi.org/10.1016/j.ijcci.2020.100165.
[30] Gizzi, V. *et al.* 2019. Junkbox, a waste management educational game for preschool kids. *Interaction Design and Architecture(s).* 40 (2019), 46–56. DOI:https://doi.org/10.55612/s-5002-040-003.
[31] Glavič, P. 2020. Identifying key issues of education for sustainable development. *Sustainability (Switzerland).* 12, 16 (2020). DOI:https://doi.org/10.3390/su12166500.
[32] Guillén, G.M. *et al.* 2022. Gamified apps for sustainable consumption: A systematic review. *CEUR Workshop Proceedings.* 3147, (2022), 135–145.
[33] Heintz, S. and Law, E.L.C. 2015. The game genre map: A revised game classification. *CHI PLAY 2015 - Proceedings of the 2015 Annual Symposium on Computer-Human Interaction in Play.* October (2015), 175–184. DOI:https://doi.org/10.1145/2793107.2793123.
[34] Henriques, M. and Fernandes, J. 2020. Environmental Sustainability: A study on the impact of information systems on game-based learning and gamification. *Proceedings of the 14th International Multi-Conference on Society, Cybernetics and Information* (2020), 203–207.

[35] Høiseth, M. and Van Mechelen, M. 2017. Identifying patterns in IDC research: Technologies for improving children's well-being connected to overweight issues. *IDC 2017 - Proceedings of the 2017 ACM Conference on Interaction Design and Children*. (2017), 107–116. DOI:https://doi.org/10.1145/3078072.3079739.
[36] Howard, P.H. and Sterner, T. 2017. Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates. *Environmental and Resource Economics*. 68, 1 (2017), 197–225. DOI:https://doi.org/10.1007/s10640-017-0166-z.
[37] Huda, S.N. and Ramadhan, M.F. 2021. Designing Educational Game to Increase Environmental Awareness. *International Journal of Emerging Technologies in Learning*. 16, 15 (2021), 181–193. DOI:https://doi.org/10.3991/ijet.v16i15.22661.
[38] Ishoj-Paris, Y. *et al.* 2021. AXO: A video game that encourages recycling to preteens. *CHI PLAY 2021 - Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play*. (2021), 350–355. DOI:https://doi.org/10.1145/3450337.3483506.
[39] Janakiraman, S. *et al.* 2018. Using Game-based Learning to Facilitate Attitude Change for Environmental Sustainability. *Journal of Education for Sustainable Development*. 12, 2 (2018), 176–185. DOI:https://doi.org/10.1177/0973408218783286.
[40] Kawaguchi, S. *et al.* 2018. Let's Build Forests for 300 Years: Game-Based Learning in Environmental Education. *Proceedings of the 12th European Conference on Games-based Learning* (Sophia Antipolis, France, 2018), 881–886.
[41] Kersánszki, T. *et al.* 2023. Minecraft Game as a New Opportunity for Teaching Renewable Energy Topics. *International Journal of Engineering Pedagogy*. 13, 5 (2023), 16–29. DOI:https://doi.org/10.3991/ijep.v13i5.36287.
[42] Khaled, R. 2018. Questions Over Answers: Reflective Game Design. *Playful Disruption of Digital Media. Gaming Media and Social Effects*. D. Cermak-Sassenrath, ed. Springer. 3–27.
[43] Kiili, K. *et al.* 2012. Towards creative pedagogy: Empowering students to develop games. *Proceedings of the 6th European Conference on Games-based Learning*. (2012), 250–257.
[44] Kopnina, H. 2016. The victims of unsustainability: A challenge to sustainable development goals. *International Journal of Sustainable Development and World Ecology*. 23, 2 (2016), 113–121. DOI:https://doi.org/10.1080/13504509.2015.1111269.
[45] Küchler, M.G. 2020. Participatory digital educational game production with fifth graders on biodiversity (SDG15). *Proceedings of the 14th International Conference on Game Based Learning, ECGBL 2020*. Dewey 1938 (2020), 769–778. DOI:https://doi.org/10.34190/GBL.20.018.
[46] Kurt 2002. *Game-Based Learning: Present and Future State of the Field*.
[47] Kynigos, C. and Yiannoutsou, N. 2018. Children challenging the design of half-baked games: Expressing values through the process of game modding. *International Journal of Child-Computer Interaction*. 17, (2018), 16–27. DOI:https://doi.org/10.1016/j.ijcci.2018.04.001.
[48] Lamarra, J. *et al.* 2019. Designing for Impact: Shifting children's perspectives of civic and social issues through making mobile games. *Proceedings of the 18th ACM International Conference on Interaction Design and Children, IDC 2019*. (2019), 274–279. DOI:https://doi.org/10.1145/3311927.3323338.
[49] Landers, R.N. 2014. Developing a theory of gamified learning: Linking serious games and gamification of learning. *Simulation & Gaming*. 45, 6 (2014), 752 –768. DOI:https://doi.org/10.1177/1046878114563660.
[50] Lehtonen, A. *et al.* 2018. A pedagogy of interconnectedness for encountering climate change as a wicked sustainability problem. *Journal of Cleaner Production*. 199, (2018), 860–867. DOI:https://doi.org/10.1016/j.jclepro.2018.07.186.
[51] Leitão, R. *et al.* 2022. A systematic evaluation of game elements effects on students' motivation. *Education and Information Technologies*. 27, 1 (2022), 1081–1103. DOI:https://doi.org/10.1007/s10639-021-10651-8.
[52] Leitão, R. *et al.* 2022. Ocean literacy gamified: A systematic evaluation of the effect of game elements on students' learning experience. *Environmental Education Research*. 28, 2 (2022), 276–294. DOI:https://doi.org/10.1080/13504622.2021.1986469.
[53] León, M. *et al.* 2019. An interactive multimedia game "Let's save the water" for the communities of Ecuador and Bolivia. *CEUR Workshop Proceedings*. 2486, (2019), 334–343.
[54] Li, X. *et al.* 2019. Hero: A fighting mobile game with environmental protection theme. *Proceedings - 2019 International Conference on Virtual Reality and Visualization, ICVRV 2019*. (2019), 279–280. DOI:https://doi.org/10.1109/ICVRV47840.2019.00069.
[55] Lin, Y.C. *et al.* 2019. Exploring students' learning and gaming performance as well as attention through a drill-based gaming experience for environmental education. *Journal of Computers in Education*. 6, 3 (2019), 315–334. DOI:https://doi.org/10.1007/s40692-019-00130-y.
[56] Macleroy, V. and Chung, Y. chiao 2023. How Can Digital Storytelling Open Up Spaces for Activist Citizenship Where Young Children Create Stories of Hope and Resilience Across the World? *International Journal of Early Childhood*. 0123456789 (2023). DOI:https://doi.org/10.1007/s13158-023-00371-0.
[57] Mappin, M. and Johnson, E.A. 2005. Changing perspectives of ecology and education in environmental education. *Environmental education and advocacy*. E.A. Johnson and M.J. Mappin, eds. Cambridge University Press. 1–28.
[58] Marconi, A. *et al.* 2018. Exploring the world through small green steps: Improving sustainable school transportation with a game-based learning interface. *Proceedings of the Workshop on Advanced Visual Interfaces AVI*. (2018). DOI:https://doi.org/10.1145/3206505.3206521.
[59] Mazzocchi, F. 2020. A deeper meaning of sustainability: Insights from indigenous knowledge. *Anthropocene Review*. 7, 1 (2020), 77–93. DOI:https://doi.org/10.1177/2053019619898888.
[60] Misiaszek, G.W. 2017. Educating the Global Environmental Citizen: Understanding Ecopedagogy in Local and Global Contexts.
[61] Mochizuki, Y. and Bryan, A. 2015. Climate Change Education in the Context of Education for Sustainable Development: Rationale and Principles. *Journal of Education for Sustainable Development*. 9, 1 (2015), 4–26. DOI:https://doi.org/10.1177/0973408215569109.
[62] Monroe, M.C. *et al.* 2008. A framework for environmental education strategies. *Applied Environmental Education and Communication*. 6, 3–4 (2008), 205–216. DOI:https://doi.org/10.1080/15330150801944416.
[63] Monroe, M.C. *et al.* 2019. Identifying effective climate change education strategies: a systematic review of the research. *Environmental Education Research*.
[64] Morganti, L. *et al.* 2017. Gaming for Earth: Serious games and gamification to engage consumers in pro-environmental behaviours for energy efficiency. *Energy Research and Social Science*. 29, May (2017), 95–102. DOI:https://doi.org/10.1016/j.erss.2017.05.001.
[65] Mylonas, G. *et al.* 2021. Designing Effective Playful Experiences for Sustainability Awareness in Schools and Makerspaces. *ACM International Conference Proceeding Series*. (2021). DOI:https://doi.org/10.1145/3466725.3466755.
[66] Mylonas, G. *et al.* 2023. Playful interventions for sustainability awareness in educational environments: A longitudinal, large-scale study in three countries. *International Journal of Child-Computer Interaction*. 35, (2023), 100562. DOI:https://doi.org/10.1016/j.ijcci.2022.100562.
[67] Mylonas, G. *et al.* 2018. Using an educational IoT lab kit and tools for energy awareness in European schools. *Proceedings of the Conference on Creativity and Making in Education*. 20, June (2018), 30–36. DOI:https://doi.org/10.1016/j.ijcci.2019.03.003.
[68] Neset, T.S. *et al.* 2020. Serious gaming for climate adaptation—assessing the potential and challenges of a digital serious game for urban climate adaptation. *Sustainability (Switzerland)*. 12, 5 (2020), 1–18. DOI:https://doi.org/10.3390/su12051789.
[69] Newsome, I. 2020. An educational game bringing awareness to declining insect populations. *CHI PLAY 2020 - Extended Abstracts of the 2020 Annual Symposium on Computer-Human Interaction in Play*. (2020), 326–329. DOI:https://doi.org/10.1145/3383668.3419912.
[70] Ojala, M. 2012. Hope and climate change: The importance of hope for environmental engagement among young people. *Environmental Education Research*. 18, 5 (2012), 625–642. DOI:https://doi.org/10.1080/13504622.2011.637157.
[71] Ojala, M. 2015. Hope in the Face of Climate Change: Associations with Environmental Engagement and Student Perceptions of Teachers Emotion Communication Style and Future Orientation. *Journal of Environmental Education*. 46, 3 (2015), 133–148. DOI:https://doi.org/10.1080/00958964.2015.1021662.
[72] Ouariachi, T. *et al.* 2018. Can serious games help to mitigate climate change? Exploring their influence on Spanish and American teenagers' attitudes / ¿Pueden los serious games ayudar a mitigar el cambio climático? Una exploración de su influencia sobre las actitudes de los adolesc. *Psyecology*. 9, 3 (2018), 365–395. DOI:https://doi.org/10.1080/21711976.2018.1493774.
[73] Paganelli, F. *et al.* 2019. Experiences from Using Gamification and IoT-Based Educational Tools in High Schools Towards Energy Savings. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* (2019).
[74] Page, M.J. *et al.* 2021. PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *The BMJ*. 372, (2021). DOI:https://doi.org/10.1136/bmj.n160.
[75] Panagiotopoulou, L. *et al.* 2021. Design of a Serious Game for Children to Raise Awareness on Plastic Pollution and Promoting Pro-Environmental Behaviors. *Journal of Computing and Information Science in Engineering*. 21, 6 (2021). DOI:https://doi.org/10.1115/1.4050291.
[76] Pierson, A. and Clark, D. 2018. Programming for an audience of younger students: Engaging students in creating computational models to support science learning. *CEUR Workshop Proceedings*. 2128, (2018).
[77] Prensky, M. 2001. Fun, Play and Games: What Makes Games Engaging. *Digital Game-Based Learning*. McGraw-Hill. 1–31.
[78] Priyadarshini, R. *et al.* 2021. Carbon warrior: A game-based environment to understand carbon footprint and its effect on sustainable living. *Proceedings - IEEE 21st International Conference on Advanced Learning Technologies, ICALT 2021*. July (2021), 291–293. DOI:https://doi.org/10.1109/ICALT52272.2021.00094.
[79] Purvis, B. *et al.* 2019. Three pillars of sustainability: in search of conceptual origins. *Sustainability Science*. 14, 3 (2019), 681–695. DOI:https://doi.org/10.1007/s11625-018-0627-5.
[80] Puttick, G. and Tucker-Raymond, E. 2018. Building Systems from Scratch: an Exploratory Study of Students Learning About Climate Change. *Journal of Science Education and Technology*. 27, 4 (2018), 306–321. DOI:https://doi.org/10.

1007/s10956-017-9725-x.

[81] Raijmakers, M.E.J. *et al.* 2014. Children's strategy use when playing strategic games. *Synthese.* 191, 3 (2014), 355–370. DOI:https://doi.org/10.1007/s11229-012-0212-x.

[82] Rodrigo, M.T. *et al.* 2021. A RECIPE for Teaching the Sustainable Development Goals. *29th International Conference on Computers in Education Conference, ICCE 2021 - Proceedings.* 1, (2021), 451–456.

[83] Roider, O. *et al.* 2019. Merging Virtual World with Real-Life Behavior: A Concept for a Smartphone App to Influence Young People's Travel Behavior. *Transportation Research Record.* 2673, 4 (2019), 241–250. DOI:https://doi.org/10.1177/0361198119835812.

[84] Rossano, V. *et al.* 2023. Mini-games to Motivate and Engage Users in Learning Recycling Rules. *Lecture Notes in Networks and Systems.* 580 LNNS, (2023), 75–80. DOI:https://doi.org/10.1007/978-3-031-20617-7_10.

[85] Salen, K. and Zimmerman, E. 2003. *Rules of Play: Game Design Fundamentals.* MIT Press.

[86] Sanson, A. V. *et al.* Young people and climate change: The role of developmental science. *Developmental science and sustainable development goals for children and youth.* S. Verma and A. Petersen, eds. Springer. 115–137.

[87] Santana, A.F. *et al.* 2022. Save Tuba: A Gamified App for Children to Explore Environmental Issues and Develop Sustainable Behaviors. *2022 IEEE Global Humanitarian Technology Conference, GHTC 2022.* September (2022), 299–306. DOI:https://doi.org/10.1109/GHTC55712.2022.9911044.

[88] Schneider, J. *et al.* 2020. Integrating simulation tasks into an outdoor location-based game flow. *Multimedia Tools and Applications.* 79, 5–6 (2020), 3359–3385. DOI:https://doi.org/10.1007/s11042-019-07931-4.

[89] Shaffer, D.W. *et al.* 2005. Video Games and the Future of Learning. *The Phi Delta Kappan.* 87, 2 (2005), 104–111.

[90] Sharma, R. and Ali, S. 2018. Embedding concepts of sustainability in secondary school mathematics through games based learning. *Proceedings of the European Conference on Games-based Learning.* 2018-Octob, Blurton 1999 (2018), 583–589.

[91] Sherry, J.L. 2010. Matching computer game genres to educational outcomes. *Teaching and Learning with Technology: Beyond Constructivism.* (2010), 214–226. DOI:https://doi.org/10.4324/9780203852057.

[92] Sipone, S. *et al.* 2021. Using classcraft to improve primary school students' knowledge and interest in sustainable mobility. *Sustainability (Switzerland).* 13, 17 (2021). DOI:https://doi.org/10.3390/su13179939.

[93] Smith, G.G. *et al.* 2019. Teaching climate change science to high school students using computer games in an intermedia narrative. *Eurasia Journal of Mathematics, Science and Technology Education.* 15, 6 (2019). DOI:https://doi.org/10.29333/ejmste/103570.

[94] Sousa, A.M. and Romão, T. 2021. *Encouraging Chemistry Learning Through an Augmented Reality Magic Game.*

[95] Speth, M. *et al.* 2018. Eco champion: A transcultural educational eco game for children. *Proceedings of the European Conference on e-Learning, ECEL.* 2018-Novem, (2018), 523–532.

[96] Stanitsas, M. *et al.* 2019. Facilitating sustainability transition through serious games: A systematic literature review. *Journal of Cleaner Production.* 208, (2019), 924–936. DOI:https://doi.org/10.1016/j.jclepro.2018.10.157.

[97] Stevenson, R.B. 2007. Schooling and environmental education: contradictions in purpose and practice. *Environmental Education Research.* 13, 2 (2007), 139–153. DOI:https://doi.org/10.1080/13504620701295726.

[98] Stevenson, R.B. *et al.* 2017. What Is Climate Change Education? *Curriculum Perspectives.* 37, 1 (2017), 67–71. DOI:https://doi.org/10.1007/s41297-017-0015-9.

[99] Strengers, Y. 2011. Negotiating everyday life: The role of energy and water consumption feedback. *Journal of Consumer Culture.* 11, 3 (2011), 319–338. DOI:https://doi.org/10.1177/1469540511417994.

[100] Sudarmilah, E. and Sabrina, F.N. 2019. Educational simulating game "Plant the tree" in virtual reality for elementary student. *International Journal of Scientific and Technology Research.* 8, 10 (2019), 973–978.

[101] Tang, Y. *et al.* 2018. Algae city - An interactive serious game. *ASEE Annual Conference and Exposition, Conference Proceedings.* 2018-June, (2018).

[102] Thor, D. and Karlsudd, P. 2020. Teaching and fostering an active environmental awareness design, validation and planning for action-oriented environmental education. *Sustainability (Switzerland).* 12, 8 (2020). DOI:https://doi.org/10.3390/SU12083209.

[103] Torres-Harding, S. *et al.* 2018. Children as agents of social and community change: Enhancing youth empowerment through participation in a school-based social activism project. *Education, Citizenship and Social Justice.* 13, 1 (2018), 3–18. DOI:https://doi.org/10.1177/1746197916684643.

[104] Trott, C.D. 2019. Reshaping our world: Collaborating with children for community-based climate change action. *Action Research.* 17, 1 (2019), 42–62. DOI:https://doi.org/10.1177/1476750319829209.

[105] Tziortzioti, C. *et al.* 2018. Raising awareness for water polution based on game activities using internet of things. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* (2018), 171–187.

[106] Tziortzioti, C. *et al.* 2018. Scenarios for Educational and Game Activities using Internet of Things Data. *IEEE Conference on Computatonal Intelligence and Games, CIG.* 2018-Augus, (2018). DOI:https://doi.org/10.1109/CIG.2018.8490370.

[107] UNICEF 2021. The climate crisis is a childs rights crisis: Introducing the children's climate risk index.

[108] Vasalou, A. and Gauthier, A. 2023. The role of CCI in supporting children's engagement with environmental sustainability at a time of climate crisis. *International Journal of Child-Computer Interaction.* 38, July (2023), 100605. DOI:https://doi.org/10.1016/j.ijcci.2023.100605.

[109] Vasalou, A. and Gauthier, A. 2023. The Role of CCI in Supporting Children's Engagement with Environmental Sustainability at a time of Climate Crisis. *International Journal of Child-Computer Interaction.* 38, 100605 (2023). DOI:https://doi.org/https://doi.org/10.1016/j.ijcci.2023.100605.

[110] Venkataraman, B. 2009. Education for sustainable development. *Environment.* 51, 2 (2009), 8–10. DOI:https://doi.org/10.3200/ENVT.51.2.08-10.

[111] Veronica, R. and Calvano, G. 2020. Promoting sustainable behavior using serious games: Seadventure for ocean literacy. *IEEE Access.* 8, (2020), 196931–196939. DOI:https://doi.org/10.1109/ACCESS.2020.3034438.

[112] Wang, X.M. *et al.* 2023. Effects of a Two-Tier Test Strategy on Students' Digital Game-Based Learning Performances and Flow Experience in Environmental Education. *Journal of Educational Computing Research.* 60, 8 (2023), 1942–1968. DOI:https://doi.org/10.1177/07356331221095162.

[113] Yarosh, S. *et al.* 2011. Examining values: An analysis of nine years of IDC research. *Proceedings of IDC 2011 - 10th International Conference on Interaction Design and Children.* (2011), 136–144. DOI:https://doi.org/10.1145/1999030.1999046.

[114] Zidny, R. *et al.* 2020. A Multi-Perspective Reflection on How Indigenous Knowledge and Related Ideas Can Improve Science Education for Sustainability. *Science and Education.* 29, 1 (2020), 145–185. DOI:https://doi.org/10.1007/s11191-019-00100-x.