A Review of Empirical Studies on Gamification in K-12 Environmental Education: Is This Chocolate-Covered Broccoli?

Feiran Zhang
Department of Computer Science
Norwegian University of Science and Technology (NTNU)
Trondheim, Norway
ORCID: 0000-0002-2890-5915

Sofia Papavlasopoulou
Department of Computer Science
Norwegian University of Science and Technology (NTNU)
Trondheim, Norway
ORCID: 0000-0002-1974-0522

Julie Holte Motland
Department of Computer Science
Norwegian University of Science and Technology (NTNU)
Trondheim, Norway
ORCID: 0009-0003-1532-0453

Michail Giannakos
Department of Computer Science
Norwegian University of Science and Technology (NTNU)
Trondheim, Norway
ORCID: 0000-0002-8016-6208

***Abstract*— Environmental education (EE) plays a vital role in engaging young people in exploring environmental issues and developing their sense of responsibility to the environment. Although gamification appears to be a promising way to motivate and engage K-12 students, it is unclear how it should be implemented in EE and whether it holds promising results similar to other contexts, such as science and engineering education. This paper reports a systematic literature review analysing the 28 papers published in the last five years. The results show how gamification has been employed to support EE and in what contexts. More specifically, the findings of this review contribute to our knowledge in the following three aspects: (1) EE strategies for implementing gamified interventions, (2) gamification strategies and elements utilised in EE, and (3) reported outcomes of gamified EE intervention. Finally, the paper discusses the implications for future related research on developing gamified interventions for EE.**

Keywords—Gamification, K-12, Environmental Education, Game Element, Review

I. INTRODUCTION

Environmental issues, such as the climate change crisis, water pollution and air pollution, have gradually become growing concerns in our society. Environmental Education (EE) is an approach to educating citizens of all ages about our environment, becoming aware of foreseeable problems, and being motivated to act towards their solutions [1]. Incorporating multidisciplinary principles from, e.g., learning sciences, behavioural psychology, sociology, health education, and marketing [2], EE comprises approaches, tools, and programs that foster environmental awareness, understanding, knowledge, skills and attitudes that empower individuals to take responsible action [3]–[5]. EE is a timely topic that is relevant to all individuals; for example, making EE available and inclusive can bring us closer to reaching the Sustainable Development Goals (SDG) of the United Nations [6]. This concept was stressed already in the 1970s at the first UNESCO Inter-governmental Conference on EE, advocating the broader application of EE in formal and non-formal education. Recently, UNESCO has further underlined the importance of implementing EE as a core curriculum component in all countries by 2025 [6]. However, one can argue that traditional EE needs to catch up to its intended objectives of fostering environmentally friendly institutions and practices, given its narrow focus on environmental problems and its limited ability of curricular reforms to address the cause of environmental issues [7]. This indicates an urgent need to improve understanding and awareness at both the individual and societal levels, especially among young children whose future behaviours will define the development of our society.

Previous research has suggested that educators should provide chances for active, hands-on learning activities that let students use what they learn to solve real-life environmental issues [7]. Mercer et al. 2017 [8] have argued that gamification is a promising way to engage children with such activities, and gamification has become increasingly valuable as a methodological resource in education [10]. In this paper, we examine gamification in learning contexts associated with digital technology that refers to embedding game elements in platforms/applications/systems or other digital tools, and we use the term "gamified digital tool" to describe them generally. Using game design engages students, helping them dramatically improve their academic, cognitive, and social skills [9]. Implementations of gamified systems have been shown to increase user engagement and motivation towards learning and have a high level of user enjoyment, which can contribute to positive learning outcomes [11]. However, given the recognised benefits of gamification in education and the fact that empowering children's values for the environment is more relevant than ever before, it remains to be seen if this concept applied in EE appears to be a "chocolate-covered broccoli". This especially triggers more unanswered questions regarding how gamification can empower EE and how it should be implemented.

To this end, we aim to fill the gap in the literature by conducting a systematic literature review of empirical studies published over the past five years on the intersection of gamification usage and EE interventions for K-12. This review aims to contribute to research and practice identifying strategies regarding gamification elements conducive to empowering EE, providing a systematic and focused approach to the topic. More specifically, this review seeks to answer the following questions: (1) What are the EE strategies, and how have they been implemented in the gamified interventions? (2) what are the gamification strategies and elements, and how have they been used in EE? (3) what are the reported outcomes of the gamified EE interventions?

XXX-X-XXXX-XXXX-X/XX/$XX.00 ©20XX IEEE

II. BACKGROUND

A. Environmental Education: Promises and Barriers

EE is an approach that engages children, educators, and communities in working cooperatively and democratically towards resolving environmental topics, concerns, and problems [12]. The ultimate goal of EE is to increase citizens' environmental awareness and knowledge, correspondingly encouraging them to adopt pro-environmental behaviours [7].

The implementation of EE yields many benefits for children. For example, EE often encourages children to be in contact with nature to become more physically active [13]. In addition, there have been few attempts to pair EE with technology-enhanced learning activities, leveraging the potential benefits for children. For example, Ruchter et al. 2010 [14] compared the effects of mobile computers and traditional approaches in EE with 185 children. Their results demonstrated that technology-enhanced EE increased children's motivation to engage with environmental activities and interest in environmental literacy.

Regarding EE implementation in schools, Galushin and Doraiswami categorised three main traditional approaches [15]. These are reflected in the following aspects: (1) By incorporating multiple courses into the course schedule, environmental concerns can be spread throughout all or a meaningful portion of the school curriculum; (2) one existing school topic may include one part tailored to teach about environmental conservation; (3) environmental conservation may be taught as a separate topic alongside other disciplines in an integrated course. Comparing EE education with other educational contexts, especially science, technology, engineering, arts, and mathematics that emphasise facilitating the student's intellectual capability, EE addresses how they should live and, in particular, calls for behavioural change [2] While most traditional teaching approaches raise awareness of environmental issues they may fail to promote action and engagement, calling for more research on different ways and opportunities to support EE learning activities for children.

B. Benefits of Gamification in Educational Contexts

There is a growing interest in using games in contexts of education, business, and marketing sectors to support engagement and enhance the quality and productivity of actions [11], [16]. As a result, an emerging method known as "gamification" has been widely but inconsistently defined as the selective addition of game features into an interactive system such as computers, mobile and personal devices [17], [18]. According to Deterding et al. 2011 [17], gamification generally leverages game elements in a non-game context. For example, a mapping review on gamification in educational contexts [19] proposed a set of game elements, including game mechanisms (e.g., points, badges, leaderboards, progress bars, levels, and avatars) and associated design principles behind these (e.g., challenges, feedback, storytelling, competition, cooperation, and time restrictions).

Various studies have shown the advantages of gamification in educational contexts for children. For instance, gamification allows children to approach knowledge and skills with "learning by failure," which is common in game-like contexts, helping them avoid negative emotions without the humiliation aspect that typically comes in more traditional educational settings [20]. In addition, gamification can provide children with an engaging learning experience in school [21]. As an illustration, a gamified learning environment was found to promote the motivation of children with dyslexia [22], boost their reading motivation, and enhance their reading skills, which may last for numerous semesters [23]. Similarly, another study [24] demonstrated the promise of using gamification to increase motivation and enhance practice engagement in children with functional articulation disorder. Other reported promises of using gamification concepts in the literature include improving children's grades [25], their motivation to learn science [26], and their satisfaction with homework [27].

Overall, gamification appears to be a promising approach with many benefits for children, applied in various contexts, including EE [10], [28]–[32]. Thus, further investigation of the implementation of gamification in EE will give evidence-based insights into the current trends in this aspect and give future directions.

C. Other Related Reviews

One recent review by Kalogiannakis et al. 2021 [33] on using gamification in science education revealed that most gamified applications in the science education context increased students' motivation while some improved students' engagement. Furthermore, this review reported that the top five often used game elements include competition, leaderboards, points, levels, and progression. Another review by Anil Yasin and Abbas 2021 [34] on the role of gamification in engineering education unveiled that electronic-based gamification tools increased engineering students' participation. Moreover, Dicheva et al. 2015 [19] categorised the design principles and game elements applied in education in general. Their results suggest that the most adopted design principles in gamification for education were visible status, social engagement, freedom of choice, freedom to fail and rapid feedback. Not surprisingly, the most used game elements were points, badges, leaderboards, and avatars. Our review aims to contribute to showing possible patterns in terms of the use of game elements and the impacts of gamification in motivating and engaging students.

From the EE point of view, a review by Ardoin et al., 2018 [35] investigated EE outcomes with K-12 students, and another by Williams and Dixon 2013 [36] focused on academic outcomes within the context of school gardens. Both reviews pointed out the positive outcomes in terms of environmental knowledge, attitudes, and skills. Our review attempts to identify outcomes related to EE and gamification, advancing new insights into the efficacy of gamified EE with K-12 students.

III. METHODS

A. Search Strategy

We carried out a systematic literature review following the approach of Kitchenham [37], covering papers written in English and published between 2019 and 2023. The search was conducted on three major databases, i.e., Scopus, ERIC, and Web of Science. As shown in Table I, three sets of search strings (i.e., gamification, EE, and K-12) were used to search in the fields of "Titles and Abstract".

TABLE I. SEARCH STRINGS

Keywords	The strings and combination of keywords
Gamification	("Gamification" OR "Game" OR "Gaming" OR "Gamified" OR "Gameful") AND

EE	(“Environmental Education” OR “Environmental Science” OR “Ecology Education” OR “Outdoor Education” OR “Adventure Education” OR “Global Education” OR “Conservation Education” OR “Field studies”) AND
K-12	(“Child*” OR “Pupil” OR “Kid*” OR “Youth*” OR “Teen*” OR “Adolescent” OR “Student” OR “K12”)

B. *Inclusion and Exclusion Criteria*

Only papers that fall into the scope of using a gamified digital tool for K-12 students in EE were included. By gamification, we mean the game-inspired features such as points, badges, leaderboards, and levels. As for K-12 students, we refer to children in the age range equivalent to K-12 students. The conceptualisation of EE in this review refers to “all educational programs, information campaigns, or any other organised efforts at confronting peoples’ understanding of, attitudes toward, or behaviour affecting our natural recourses”, as described in [38].

In addition, we exclude the records if: (**a**) it did not involve a digital aspect; (**b**) it exclusively reports tools or activities for making games; (**c**) no game rules, elements, or mechanisms were mentioned; (**d**) no environmental issues, awareness or behaviours were addressed; (**e**) it did not involve players/learners equivalent to K-12 students; and (**f**) it is not a peer-reviewed empirical study with less than five pages.

C. *Selection Process*

The search happened on 26 October 2023, initially giving 256 results, while there were 15 additional papers identified from other sources. A total of 26 duplicate records and 16 publications written in languages other than English were removed from the records.

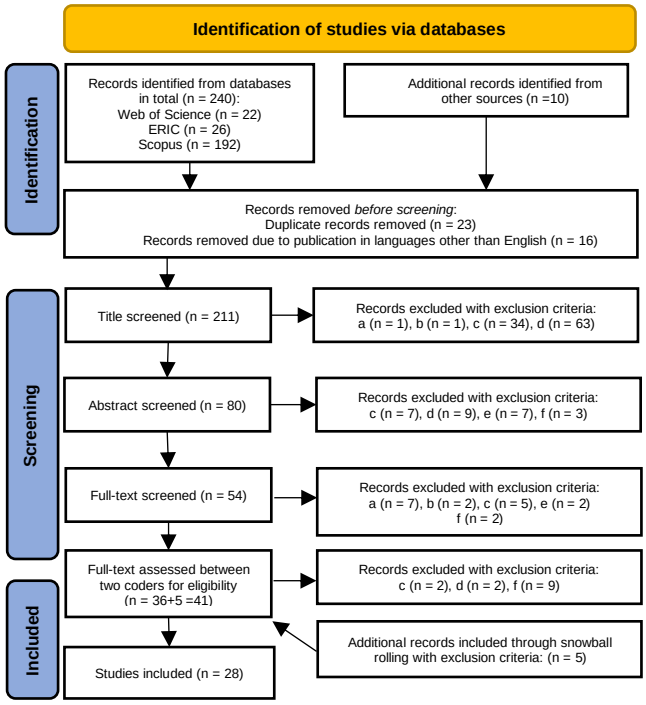

Fig. 1. PRISMA flow chart of the selection process. (The annotations for “a”, “b”, “c”, “d”, “e”, and “f” in this flow chart can be found in section B: Inclusion and Exclusion Criteria.)

This review eventually included 28 papers after the title and abstract screening, full-text analysis, and rolling back to relevant studies in reference to selected papers. Figure 1 illustrates the PRISMA flow chart [39] of the selection process for this review. The Inter-rater reliability for the final selection had a Cohen’s kappa value of 0.94, which indicates an excellent agreement between coders.

D. *Data Extraction*

The selected studies were coded using the framework for EE strategies developed by Monroe et al. 2008 [40] as a classification for EE context. According to this, there are four categories of EE intervention: (1) convey information to increase instructions or to build awareness about a specific topic, (2) build understanding to clarify and enhance the understanding of information and issues, and generate concern, (3) improve skills by providing a chance to practice a specific skill or encourage behavioural change, and (4) enable sustainable actions to build transformative capacity for leadership, creative problem solving, and monitoring.

We coded the gamification strategies based on previous taxonomy [11], [41], [42], [19], which includes (1) goal-setting, objective-based features to engage players in activities, (2) achievement and growth: tokens given when achieving a predefined goal, (3) feedback: receiving constant feedback on performance through the experience, (4) reinforcement: gaining rewards or avoiding punishments, (5) compare progress: monitoring progress with self and others, (6) social connectivity: interacting with other people, and (7) playfulness: paying out an alternative reality.

Based on a taxonomy regarding outcomes of gamification in cooperative activities [42], we extend and categorised the reported outcomes of gamified EE interventions into four broad categories: (1) learning outcomes, (2) psychological outcomes, (3) behavioural outcomes, and (4) perceived usability.

IV. Results

A. *Overview of the State-of-Art*

As seen in Table II, most selected studies involved children around the age of middle school students (e.g., [31], [32], [43]–[51]), while some involved young children around the age of primary school students (e.g., [10], [30], [52]–[57]) and a few focused on the age of high school students (e.g., [58]–[61]). It is worth noting that some studies (e.g., [28], [62]) targeted a broader age range. Especially we observed that a few studies (e.g., [29], [63]) involved both young kids and adolescents, whilst one [64] involved youth and their parents. It would be valuable for future research to focus on how and whether the age appropriateness of a gamified EE digital tool could influence its effects.

Overall, all the reviewed empirical studies focused on either the usability and/or the efficacy of their gamified EE interventions. When it comes to the research design, our review found that only 12 out of 28 reviewed studies used a quasi-experimental comparison between subjects (e.g., [29], [32], [43], [48], [49], [52], [54], [59], [60]) or within-subjects (e.g., [31], [44], [58]). The most often used research approaches for data collection were questionnaires, surveys, and interviews, usually after the intervention. One notable exception was using a pre-and-post survey in several studies (e.g., [31], [43], [45], [46], [49], [56]) to compare the differences before and after the intervention. Furthermore, observations, video/audio/screen recordings, field notes, ecological momentary assessment and game usage data were used in some studies as supplementary data sources for examining how the intervention unfolds.

TABLE II. OVERVIEW OF REVIEWED STUDIES

Study	Year [a]	Setting	Student [b] (N)	Age [c]	Duration [d]	Cont [e]	Research Focus	Data collection
Aarhus [51]	2023	Science Museum	41	12-14	20 mins	NO	Usability, Efficacy	Questionnaire, Game Usage Data, Interview
Barcena-Vazquez [28]	2023	Museum	27	13-18	45 mins	NO	Usability, Efficacy	Questionnaire
Bailbao-Aiastui [52]	2022	School	36	11-12	200 mins	YES	Usability, Efficacy	Questionnaire, Observation
Caiola [53]	2023	Summer Camp	62	6-9	50 mins	NO	Usability	Questionnaire, Interview, Observation, Notes, Video Recordings
Chiang [29]	2021	-	32	6-15	30 mins	YES	Usability, Efficacy	Questionnaire
Fokides [30]	2020	School	49	9-10	90 mins	NO	Usability, Efficacy	Pre (Knowledge) Test, Questionnaire, Evaluation Sheet
Harker-Schuch [47]	2020	School	401	12-13	45-50 mins	NO	Efficacy	Questionnaire
Hobbs [63]	2019	Public Events, One-off School	>8000	4-16	4 years	NO	Usability	Questionnaire, Post-It Notes, Observation Notes, Verbal reporting, “smiley face” Feedback Card, Word Walls
Horn [64]	2020	Home	26	6-26	-	NO	Usability	Interview, Video Recording
Janakiraman [59]	2021	School	89	16-17	50 mins	YES	Efficacy	Survey, Interview, Observation, Scorecard
Janakiraman [60]	2021	School	89	16-17	1 week	YES	Efficacy	Questionnaire, Interview
Kawas [54]	2020	Home	15	9-12	3 weeks	YES	Usability	Log data, Diary, Interviews, Video and Audio Recordings, Ecological momentary assessment (survey)
Leitão [31]	2022	School	98	11-14	5 sessions	YES	Efficacy	Pre-and-Post Survey
Leitão [44]	2022	School	98	12-14	5 sessions	YES	Efficacy	Observation, Questionnaire
Lin [55]	2019	-	34	9-12	15 mins	NO	Efficacy	Questionnaire, Interview, Game Data, Screen recording
Lombana [48]	2022	Online Zoom	41	11-14	-	YES	Usability, Efficacy	Knowledge Test, Questionnaire
Mead [46]	2022	Online Summer Program	30	15	180 mins	NO	Usability, Efficacy	Pre-and-Post (Knowledge) Survey, Evaluation Form, Observation
Mylonas [62]	2023	School	723	10-18	2 years	NO	Efficacy	Questionnaire, Game Usage Data, Observations
Neset [61]	2020	-	195	15-19	60-90 mins	NO	Efficacy	Survey, Reflection, Game Content
Occhioni [49]	2023	School	136	11-14	4 hours	YES	Efficacy	Pre-and-Post (Knowledge) Test, Questionnaire
Ricoy [10]	2022	School Centers	83	8-9	4 weeks	NO	Efficacy	Reflection Note (E-diaries), Questionnaire
Tocto [56]	2023	School	93	6-7	25 mins	NO	Efficacy	Pre-and-Post (Knowledge) Test
Torralba-Burrial [57]	2023	Online	-	6-12	-	NO	Efficacy	Questionnaire
Trefzger [50]	2023	Conservation Centre	20	13-15	-	NO	Usability	Formative Assessment
Tsai [43]	2020	School	35	12-13	6 weeks	YES	Efficacy	Interview, Pre-and-Post (Competence) Survey
Wang [32]	2023	School	32	12	135 mins	YES	Efficacy	Pre-and-Post (Knowledge) Test, Questionnaire
Wommer [45]	2022	School	21	11-15	180 mins	NO	Efficacy	Pre-and-Post Test, Questionnaire
Zainuddin [58]	2020	School	94	15-16	6 weeks	YES	Efficacy	Questionnaire, Interview, Quizzes

[a.] Publication **Year**;

[b.] Numbers of **Students** in the experimental group;

[c.] Equivalent **Age** to corresponding grades in the local system;

[d.] **Duration** of the intervention (i.e. game session) excluding the session for data collection;

[e.] Whether it includes a **Control** group or not.

The gamified intervention duration varied in reviewed studies. Most of the gamified digital tools engage the players for dozens of minutes (e.g., [47], [53], [55], [56], [28], [29], [59], [51]) or a few hours (e.g., [30], [32], [45], [46], [49], [52], [61]), while only a few spanning over weeks (e.g., [10], [43], [54], [58], [60]) or even years (e.g., [62], [63]). Furthermore, our review found that most studies conducted in the school context (e.g., [10], [30]–[32], [43]–[45], [47], [49], [50], [52], [56], [58]–[60], [62]), while some took place in informal settings such as museums [28], [51], conservation centres [50], homes [54], [64], summer camps [53], and one-off schools [63]. Additionally, there are three studies [46], [48], [57] taking place entirely online during the COVID-19 pandemic, which suggests the promising potential for the digital transformation of gamified EE interventions.

B. The Strategies of Environmental Education and Its Link to the Game

Table III shows that the EE topics of reviewed studies varied from a general focus on nature or sustainability to more specific issues such as species and ecosystems, climate, energy and recycling. The **convey information (CI)** strategy appears to be a fundamental basis in all reviewed studies. Players can easily acquire particular information and build awareness about a specific topic by following the learning material in the gamified apps. Our review reveals that most reviewed studies applied a few other strategies on top of it, while two of the reviewed studies (e.g., [50], [58]) exclusively applied CI in their applications. As Monroe [40] pointed out, the **build understanding (BU)** strategy helps uncover misconceptions in novel or complex issues. Many studies used this strategy by showing students certain EE concepts, e.g., endangered species [30], sustainability [57] and the hypothetical consequences of specific issues, e.g., Climate adaptation [61], and Freshwater ecosystems [48]. Rather than just developing knowledge and understanding, the **improve skills (IS)** strategy seeks to "build skills that enhance or change practice, performance and behaviour" [40]. This strategy has been mostly used in scenarios where the players are engaged in drill-based tasks such as waste management (e.g., [10], [31], [44], [55], [56]) and energy assumption management (e.g., [64]). This strategy engages players with targeted assistance of the game in repeated practices, which facilitates the transference of procedural knowledge about desired behaviour. Despite that, many studies triggered or promoted sustainable actions in-game, but only two of the reviewed studies address the **enable sustainable actions (SA)** strategy by providing opportunities to practice pro-environmental behaviours, e.g., energy saving [62] and waste management [10] with follow-up experimentation in real-life situations.

TABLE III. EE STRATEGIES AND ITS LINK TO THE GAME

Topic	EE strategy	How it is linked to the game	
		Scenarios	***Technology***
Nature and Environment	CI + BU	Expedition Reef [51]	Web app with VR
	CI + BU	Sounds in nature [53]	Mobile app with Recorders
	CI	Natural trail [50]	Mobile app with AR
	CI	Natural disasters [58]	Web app
	CI + BU	Protect the environment [29]	Web app with VR
	CI + BU	Volcanoes, animal habitats [63]	Web app with VR
Sustainability	CI + BU	Urban sustainability [49]	Web app
	CI + BU	Fishery sustainability [57]	Web app
	CI + BU	Renewable sources of energy [59], [60]	Web app
	CI + BU	Renewable and non-renewable energies [52]	Web app
Species and Ecosystems	CI + BU	Endangered species [30]	Mobile apps with HMDs
	CI + BU	Entomology [45]	Game manual, Camera with adaptive lens, WhatsApp
	CI + BU	Birds, insects, and trees in nature [54]	Mobile app with Built-in Camera
	CI + BU	Life on the Earth [46]	Web app with VR
	CI + BU	Freshwater Ecosystems [48]	Web app
	CI + BU	Ocean Shellfish [43]	Web app
Climate	CI + BU	Global warming [28]	Web app
	CI + BU	Climate Systems [47]	-
	CI + BU	Climate adaptation [61]	Web app
Energy	CI + BU + IS	Household assumption [64]	Mobile app, Broad game
	CI + BU + IS + SA	Energy saving [62]	Web/mobile platform, Sensors
Recycling	CI + IS	Recycling and ocean literacy [31], [44]	Mobile app
	CI + IS	Resource classification and recycling [55]	Web app
	CI +IS + SA	Waste management [10]	Web/mobile apps
	CI + IS	Recycling [56]	Web app
	CI + IS	Waste sorting [32]	Web app

CI – Convey Information; BU – Build Understanding; IS – Improve Skills; SA - Enable Sustainable Actions.

C. Gamification Strategies and Its Elements

As seen in Table IV below, the most frequently used elements for **goal-setting** in EE based games were quests, challenges, levels and missions. Concerning **game rules and guidelines**, most studies used quizzes, rules, narratives, storylines and avatars as the game design elements. In relation to the **achievement** metrics, the majority used points and scores, while several studies used other complementary indicators, including coins, game monetary, stars and tokens. When it comes to the **feedback** on players' achievement, some studies used progress bars and different forms of feedback, e.g., based on multisensory data or given by the virtual agent. Not all the reviewed studies implemented elements such as badges and other forms of rewards for **reinforcement**. Similarly, some common elements are used for **comparing progress** with self (e.g., timer) or others (leaderboards, scoreboard, and competition). Only a few studies applied elements such as collaboration, working in a team, or collaborative play for **social connectivity**. Last but not least, we found a large variety in terms of the elements previous studies used in response to **playfulness**. Most of them either used additional devices (e.g., cameras, sensors, voice recorders) to use with the gamified app or combined complementary technologies such as AR and VR with their apps. Moreover, four studies [10], [45], [54], [62] combined gamified apps with real-life exploration in their gamified EE interventions.

Interestingly, we found patterns emerging between the use of game elements and the underlying research objectives. First, for example, we found that studies utilised aspects like making the progression visible to mastery with the use of points, levels [31], [45]; facilitating social connectedness with the use of leaderboards [31], [52], competition [52], [58] or immediate feedback [45]; or adding more playfulness by combining gameplay with real-life activities [10] or other multimedia [30] in the gamified interventions aiming for enhancing students' **motivation**. Second, in the case of studying **learning outcomes**, early studies tend to embed achievement and reinforcement elements (e.g., points, scores, badges, coins, rewards) [46], [43], [58], [28], [52], [44], [55],

[62], [49], [10], [56], [32], [45], [51] to access and track the progress, adding game rules such as quiz [47], [49], [52] and providing immediate feedback [45], [46], [55] to enhance learning. Furthermore, we noticed that some studies focusing on evaluating **usability** often used elements for goal settings (e.g., missions, levels) [28], [46], [52], [54], [63], for social connectivity (e.g., collaboration, team), for game rule and guidelines (e.g., avatar, narrative, storyline, level-up) [28]–[30], [50]–[52], [64], and some playfulness elements enrich the user experience [30], [53].

TABLE IV. GAMIFICATION STRATEGIES AND ITS ELEMENTS

Gamification Strategy	Game Design Elements in Reviewed Studies
Goal-setting	Missions ([28], [57], [61], [62]), Levels ([43], [45], [52]), Challenges ([45], [46], [49], [54], [56], [63]), Quest ([32], [45], [46], [51], [52], [54], [61], [62], [65]).
Game rules and guideline	Avatar ([28], [29], [46]–[52], [55], [64]), Personalisation ([54]), Narrative ([28], [30], [32], [46], [47], [61]), Storyline ([29], [47], [55], [57]), Roleplay ([61]), Rules ([10], [45], [59], [60]), Quiz ([32], [43], [47], [49]–[53], [58], [62]), Level-up ([51], [59]–[61]), Unlockables ([28], [32], [46], [50], [51], [62]).
Achievement	Points ([31], [43]–[46], [51], [52], [55], [56], [58], [62], [64]), Game Monetary ([51], [64]), Scores ([10], [55], [56], [58]–[60], [62]), Token ([54]), Stars ([61]), Coins ([28], [32], [46], [61]).
Feedback	Virtual/ Pedagogical Agent ([32], [51], [54], [56]), Progress Bar ([45], [46], [51], [54]), Multisensory Feedback ([53]), Dashboard ([53]), Instant Feedback ([10], [45], [46], [55]).
Reinforcement	Rewards ([28], [43]), Badges ([28], [31], [32], [43], [44], [49], [52], [54], [55], [58]), Award ([52]), Certificate ([58]), Prize ([45]).
Compare progress	Leaderboard ([31], [44], [51], [52], [58]), Competition ([44], [45], [50], [52], [58], [62]), Scoreboard ([56]), Timer ([45], [48], [55], [56]).
Social connectivity	Collaboration ([10], [45], [53], [62], [63]), Collaborative Play ([59]), Team ([28], [30], [51], [58], [62], [64], [65]).
Playfulness	Music ([30], [58]), Meme ([58]), Complementary Cards ([32], [43], [64]), Audio-video mashup composition ([53]), Voice Recorders ([53]), Camera ([54]), Camera with Adaptive Lens ([45]), Sensors ([62]), 360° video ([30]), Virtual Reality ([29], [46], [51]), Augmented Reality ([50]), Real-life Exploration ([10], [45], [54], [62]).

D. The Outcomes of Gamified EE Interventions

As seen in Table V below, our review demonstrated various reported positive **learning outcomes** from implementing gamified EE interventions. These positive outcomes include improvements in knowledge, awareness, and understanding of EE concepts, general learning performance and other related skills and competencies. We observed that the potential factors for such positive outcomes may be related to (1) dynamic **representation of the processes and mechanisms** (e.g., impacts and consequences) of certain EE concepts [28], [47], [61] that may not be easily feasible to explore in real-life, (2) **repeated practices** of desired pro-environmental behaviours [55], (3) **instant prompts and feedback** [32], [43], [44], [55] to improve relevant knowledge and provide opportunity for reflections, and (4) **combination of game and real-life exploratory activities** [10], [45] to enable building connections between gameplay and daily practices. In contrast, we also found that the competitive effect of the leaderboards, points, and badges in [44] was found to have a negative impact on the learning outcomes. In addition, a study by Zainuddin et al. 2020 [58] showed no significant differences in student achievement between paper-based quizzes and gamified e-quizzes. Similarly, another study [52] reported that there was no statistically significant improvement in students' academic performance. The possible challenges could be due to the lack of familiarity that teachers need to deal with while implementing gamified EE programs [49], [62], time constraints that more time may be needed to allow for deeper class discussion [46], and cognitive load that especially single players may experience regarding the consequences of their choices in a game [61].

TABLE V. THE OUTCOMES OF GAMIFIED EE INTERVENTION

Type of Outcomes	Reported Outcomes in Reviewed Studies	
	Positive Effect	***Negative/Neutral Effect***
Learning	Improved Environmental Knowledge ([44], [46], [47], [51], [55]–[57], [65]), Environmental Awareness ([10], [28], [29], [49], [62]), Understanding on EE Concepts ([45], [61], [64]), Academic Performance ([32], [48]), Skills e.g., digital literacy, collaboration ([10]), and Scientific Competencies ([57]).	There is no significant improvement in academic performance [52] and learning achievement [58], and negative results in learning outcomes [44].
Psychological	Increased Motivation ([10], [30], [31], [45], [52], [58]), Attitudes ([59], [60]), Engagement ([49], [54], [58], [62]), Flow ([32]), Immersion ([29]), Concentration ([63]), Presence ([30])29/02/2024 13:33:00 Regulation ([31]), and Behavioural Intention ([59]).	Mixed results on amotivation [31], and a notable drop rate of inactive users [62].
Perceived Usability	High Satisfication ([52], [53]), Fun ([55], [63]) and Enjoyment ([30], [50], [63]).	Low perceived usefulness [30], [44], and easiness [30].

Many studies reported positive **psychological outcomes** in terms of analysing how gamification can motivate and engage players in games with intrinsically fulfilling experiences, as shown in Table V. Based on the results reported in the selected studies, the attributing factors for such good outcomes include (1) **feelings of presence and immersion** [29], [30] in simulated game environments that allows understanding EE concepts in more realistic experience, (2) **social connectedness and friendly competition** [51], [52], [58], [62] with other players, (3) **sense of freedom and autonomy** [31], [51], [62] in terms of the rich choices to promote children initiative to follow the activities, and (4) **rapid feedback** [59], [60] on achievement in game. One negative outcome we observed concerns a notable drop rate of inactive users during their two-year-long intervention in the study by Mylonas et al. 2023 [62], which poses a not surprising challenge for future research to sustain children's interests and motivations in long-term gamified EE interventions. Furthermore, Leitão et al. 2022 [31] pointed out that using leaderboards increased children's amotivation, while other elements, such as points and badges, decreased amotivation. Another potential barrier identified in [60] was cognitive load, as individual players tend to show more frustration compared with collaborative players. In comparison, one study [51] reported unexpected disruption by the pedagogical agent, which may have delivered excessive information or interacted with the users too often.

With respect to **perceived usability**, some studies reported participating children had high satisfaction and enjoyment towards the gamified digital tools, as shown in Table V. It appears the **interactivity** (e.g., [53], [64]) that allows the players to interact with the system and engaged in different ways was a contributing factor for positive usability outcomes. In addition, only a few reported low perceived usefulness and easiness; age suitability can influence their acceptance and perceived usability [53].

V. Discussion

This review presents findings from 28 papers on gamification in EE interventions targeting K-12 students. Overall, this review advances new insights into possible EE strategies and gamification elements future research can use for K-12 EE and contributes a novel research agenda proposing to beware of game design decisions and combine gamification with emerging technologies.

In general, most studies yield positive results regarding, e.g., student motivation and enjoyment. These findings align with prior research regarding reported outcomes in using gamification in general [11] and in other contexts, such as science education [33]. On the other hand, many studies yield positive learning outcomes in terms of environmental knowledge, which is consistent with an early review [35] on EE outcomes with K-12 students. All these encouraging results suggest that gamification is a promising approach to enhance EE and has the potential to support SDGs. This review indicates that gamified EE interventions can encourage EE to happen in informal settings such as museums and homes as well. In this way, gamified digital tools in our reviewed studies extended the traditional way of implementing EE in schools (as described in [15]).

Below, we argue and explain why gamification in EE could be beyond the chocolate-covered broccoli effect. Next, we outline emerging patterns of gamification and EE based on the findings from this review. Last, we wrap up our discussion by presenting practical implications for researchers and practitioners.

A. Gamified EE Can Be Beyond Sugar Coating

One classic criticism about games for learning is the chocolate-covered broccoli concept, which refers to games that seek to sugar-coat non-academic gameplay on bad pedagogy to make it fun [66]. Now, questions arise: *Is gamified EE chocolate-covered broccoli? Does gamification make shaping one's attitudes or behaviours straightforward by introducing points and rewarding badges?* Given the findings of this review, we tend to argue that gamification in EE could be beyond simply sugar-coating for the following two main reasons. First, our review showed that various EE topics (e.g., endangered species, energy saving, climate change) were addressed, and more than one EE strategy has been utilised in most of the reviewed studies to enhance players understanding and relevant knowledge about EE concepts. One has argued that pedagogical concepts should be seamlessly interwoven with the gameplay [67] to avoid sugar-coating. The findings of this review demonstrate that EE topics in the analysed studies seem to be connected with gameplay using the gamification elements that fit the context, as shown in Table III. Second, this view reveals various positive outcomes (e.g., learning gains, increased motivation, enjoyment, and so on.) from the reviewed gamified EE. These outcomes indicate good educational and entertainment values of gamified EE.

There are some risks that may come with gamification. For example, using interactive quizzes as a standalone game element may sugar-coat educational purposes with play and not bring entertainment value to what is supposedly labelled a game. In the study by Zainuddin et al. 2020 [58], for example, they compared paper-based quizzes with gamified quizzes that use a variety of elements, like badges, leaderboards, avatars, competition, music, etc., for learning about natural disasters. The results of this study showed that students were motivated and engaged in learning by involving these game elements; however, there was no significant improvement in students' overall learning achievement. This example suggests that emphasising game elements made the quizzes fun but may lack educational value due to the low connectivity between the topic (i.e., natural disasters) and the gameplay (i.e., quizzes with points and leaderboards). Therefore, avoiding the chocolate-covered broccoli effect requires more thoughtful game design decisions and a holistic strategy for the entire gamified EE program via seamlessly connecting the educational concept to the selection of the game elements.

To summarise, based on the reported results in the specific reviewed studies, gamification in EE could be beyond simply sugar-coating. However, there might also be publication bias, where researchers tend to report positive outcomes. More actions need to be followed to validate the effectiveness of gamified EE interventions further and especially identify its longitudinal effect.

B. An Emerging Pattern of Gamification and EE

While only a few use the strategy of improving skills to practice sustainable actions, most papers are geared toward educating about environmental issues using the strategy of conveying information, which is consistent with previous research that shows that this strategy forms the core of many EE interventions [40]. Importantly, the strategy of enabling sustainable activities for promoting how people might lead more sustainable lives is largely lacking in reviewed studies. Students can improve their ability to make ethical decisions in their daily lives by increasing their awareness. While acting and learning to live sustainably are vital, combining the two might be a superior approach in EE by frequently involving students in practising sustainable related skills and enabling sustainable behavioural change. Previous research on building children's sustainability awareness [62] suggested that playful experiences can provide positive outcomes in educational settings by considering school constraints and incorporating them into schools' daily routines. We encourage future studies to explore the strategy of enabling sustainable actions in EE and examine what possible combination of multiple EE strategies could yield the best outcomes in certain environmental topics.

Previous research [68] has identified many psychological barriers that may limit the cultivation of pro-environmental behaviours during EE, such as limited cognition, limited behaviour and so on. It becomes apparent that the major challenge for EE compared with other science education is to empower behavioural change. This is also confirmed by the results in this review, which showed that only two out of 28 reviewed studies applied the strategy enabling sustainable actions that are helpful to promote actual behavioural change in real-life situations.

According to the taxonomy in the behaviour change wheel [69], the main factors attributed to behaviour change in EE include motivation, capability and opportunity. Our review reveals that, to a different extent, all the interventions addressed the students' motivation by adding game elements as external rewards or stimuli. This tends to be the primary purpose of incorporating gamification in EE in our reviewed studies. On top of addressing motivation, many studies also addressed psychological capability by providing tasks (e.g., quizzes or missions) or introducing concepts (e.g., through narrative, storyline) to enable players to acquire related knowledge and skills. However, most reviewed studies stopped here without providing sufficient opportunities for sustainable actions to occur in real life. Only a few digital tools, e.g., energy saving [62] and waste management [10], reinforced the opportunity by building the connections between gameplay and real-life situations to promote and enable sustainable behaviours. To address this identified gap, future work can combine emerging technology (e.g., using sensors to collect data in authentic contexts) and gamification (e.g., visualising data with game rules and mechanisms).

C. Practical Implications of EE and Gamification

Various game elements are used across the interventions identified in this review; some of the most popular are points, leaderboards, and badges. Previous research has stated that these three most used gamified digital tools are due to their straightforward implementation [17]. However, there are some contradictory results regarding the effectiveness of gamification in terms of learning outcomes and motivation. For example, elements such as points, leaderboards and badges positively affected the student experience in some studies [58], [70]. On the contrary, the game element leaderboards might lead to competitiveness, as shown in [23], to negatively affect students' learning outcomes. These contradictory results support the idea that gamification is not a practical one-size-fits-all approach. Competition is essential for engagement but must be handled carefully to avoid negative consequences. We suggest future research to examine the use of gamification across different age groups, genders, ethnicities, and in various educational settings to gain practical insights into how to better design gamified environments depending on the context that is applied. In addition, some other aspects should also be considered when designing these applications, for example, guaranteeing and keeping the users' attention on the activities [71] and leveraging new possibilities for evaluating and designing educational technologies [72].

Furthermore, multiple studies utilised the game element levels. One study emphasised how the use of various difficulty levels contributed to positive results in terms of scientific competencies for both high and low achievers in the experimental group [43]. This aligns with previous heuristics claimed by Malone 1980 [73] that variable difficulty levels should be playable to enhance user enjoyment and create fun in learning through educational games. Similarly, as suggested by van Roy and Zaman 2017 [74], some theory-based gamification heuristics can be considered in order to improve gamification design, for example, "set challenging but manageable goals", "make the system flexible", "create a need-supporting context" p.104.

One of the most often mentioned purposes for employing gamification is to foster attitudes that provide cognitive knowledge and emotionally engage students by illustrating the negative consequences of bad behaviour [59]. Nevertheless, there might be considerable individual differences in what motivates users intrinsically. Previous research [75] has argued that a gamified intervention may be improved if the user's intrinsic motivators are identified to guide the development of the gamified system. For example, one can define target behaviour, measure players' performances, and then present feedback and rewards accordingly [76]. However, we observe a gap in reviewed studies where these in-depth analyses of players' motivators and corresponding customisation are under-represented. We recommend future efforts to reinforce the possibility of personalisation on avatars, storylines, and missions to meet the individual's goals and ambitions in games.

VI. Conclusion

To the best of our knowledge, this review is the first attempt to articulate the intersection of EE and gamification and provide an in-depth investigation of how gamification has been implemented in EE and its impacts in the context of K-12 education. Overall, this review contributes to our understanding of (1) the EE strategies, (2) the gamification strategies and game elements, and (3) the reported outcomes of reviewed gamified EE interventions. Our findings suggest that gamification is a promising approach to support students' motivation and understanding of EE. We suggest future research focus on specific game elements and EE concepts and identify the longitudinal effect on EE.

Acknowledgement

We want to thank the ERCIM fellowship and the Surrounded by Science project. The first author received an ERCIM fellowship. The Surrounded by Science project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 101006349. This publication only reflects the author's view, and the European Commission is not responsible for any use that may be made of the information it contains.

References

[1] W. B. Stapp, "The Concept of Environmental Education," *Environmental Education*, vol. 1, no. 1, pp. 30–31, Sep. 1969, doi: 10.1080/00139254.1969.10801479.

[2] J. E. Heimlich and N. M. Ardoin, "Understanding behavior to understand behavior change: a literature review," *Environmental Education Research*, vol. 14, no. 3, pp. 215–237, Jun. 2008, doi: 10.1080/13504620802148881.

[3] N. M. Ardoin, A. W. Bowers, and E. Gaillard, "Environmental education outcomes for conservation: A systematic review," *Biological Conservation*, vol. 241, p. 108224, Jan. 2020, doi: 10.1016/j.biocon.2019.108224.

[4] M. C. Monroe and M. E. Krasny, *Across the Spectrum: Resources for Environmental Educators*, Third Edition. Washington, DC.: North American Association for Environmental Education, 2016.

[5] UNESCO, "The Tbilisi Declaration: Final Report," USSR, Tbilisi, Oct. 1977.

[6] UNESCO urges making environmental education a core curriculum component in all countries by 2025, UNESCO

[7] K. Bywater, "Investigating the Benefits of Participatory Action Research for Environmental Education," *Policy Futures in Education*, vol. 12, no. 7, pp. 920–932, Oct. 2014, doi: 10.2304/pfie.2014.12.7.920.

[8] T. G. Mercer, A. P. Kythreotis, Z. P. Robinson, T. Stolte, S. M. George, and S. K. Haywood, "The use of educational game design and play in higher education to influence sustainable behaviour," *International Journal of Sustainability in Higher Education*, vol. 18, no. 3, pp. 359–384, Jan. 2017, doi: 10.1108/IJSHE-03-2015-0064.

[9] A. Manzano-León *et al.*, "Between Level Up and Game Over: A Systematic Literature Review of Gamification in Education," *Sustainability*, vol. 13, no. 4, p. 2247, Feb. 2021, doi: 10.3390/su13042247.

[10] M.-C. Ricoy and C. Sánchez-Martínez, "Raising Ecological Awareness and Digital Literacy in Primary School Children through Gamification," *International Journal of Environmental Research and Public Health*, vol. 19, no. 3, 2022, doi: 10.3390/ijerph19031149.

[11] J. Hamari, J. Koivisto, and H. Sarsa, "Does Gamification Work? – A Literature Review of Empirical Studies on Gamification," in *2014 47th Hawaii International Conference on System Sciences*, Jan. 2014, pp. 3025–3034. doi: 10.1109/HICSS.2014.377.

[12] J. Davis, "Young Children, Environmental Education, and the Future," *Early Childhood Education Journal*, vol. 26, no. 2, pp. 117–123, Dec. 1998, doi: 10.1023/A:1022911631454.

[13] C. Maller, "The hidden benefits of environmental education: contact with nature and children's health and wellbeing," *Echo: The Journal of the Home Economics Teachers Group*, vol. 43, no. 1, pp. 16–22, Dec. 2020, doi: 10.3316/ielapa.200404612.

[14] M. Ruchter, B. Klar, and W. Geiger, "Comparing the effects of mobile computers and traditional approaches in environmental education," *Computers & Education*, vol. 54, no. 4, pp. 1054–1067, May 2010, doi: 10.1016/j.compedu.2009.10.010.

[15] V. M. Galushin and S. Doraiswami, "Three Approaches to Environmental Education in the Schools," *The Journal of Environmental Education*, May 2014.

[16] J. Hamari, "Transforming homo economicus into homo ludens: A field experiment on gamification in a utilitarian peer-to-peer trading service," *Electronic Commerce Research and Applications*, vol. 12, no. 4, pp. 236–245, Jul. 2013, doi: 10.1016/j.elerap.2013.01.004.

[17] S. Deterding, D. Dixon, R. Khaled, and L. Nacke, "From Game Design Elements to Gamefulness: Defining 'Gamification,'" 2011.

[18] S. Deterding, "Gamification: designing for motivation," *interactions*, vol. 19, no. 4, pp. 14–17, Jul. 2012, doi: 10.1145/2212877.2212883.

[19] D. Dicheva, C. Dichev, G. Agre, and G. Angelova, "Gamification in Education: A Systematic Mapping Study," *Journal of Educational Technology & Society*, vol. 18, no. 3, pp. 75–88, 2015.

[20] W. H.-Y. Huang and D. Soman, "A practitioner's guide to gamification of education," 29, 2013.

[21] Mapua University, Philippines, E. B. Blancaflor, K. D. G. Camaongay, J. A. S. Chua, and G. A. Echanes, "A Gamified Educational Learning Module for Core Subjects in an Elementary Level," *IJIET*, vol. 12, no. 11, pp. 1280–1285, 2022, doi: 10.18178/ijiet.2022.12.11.1751.

[22] D. Gooch, A. Vasalou, L. Benton, and R. Khaled, "Using Gamification to Motivate Students with Dyslexia," in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, in CHI '16. New York, NY, USA: Association for Computing Machinery, May 2016, pp. 969–980. doi: 10.1145/2858036.2858231.

[23] X. Li and S. K. W. Chu, "Exploring the effects of gamification pedagogy on children's reading: A mixed-method study on academic performance, reading-related mentality and behaviors, and sustainability," *British Journal of Educational Technology*, vol. 52, no. 1, pp. 160–178, 2021, doi: 10.1111/bjet.13057.

[24] N. Liu, E. I. Barakova, F. Zhang, T. Han, and J. Feng, "Motivating Online Game Intervention to Enhance Practice Engagement in Children with Functional Articulation Disorder," in *International Conference on Human-Agent Interaction*, Gothenburg Sweden: ACM, Dec. 2023, pp. 221–228. doi: 10.1145/3623809.3623838.

[25] K. Otto, C. Kröhn, and B. Sabitzer, "Immersion into the World of Gaming: An Approach of Introducing Gamification in an Educational Context:," in *Proceedings of the 12th International Conference on Computer Supported Education*, Prague, Czech Republic: SCITEPRESS - Science and Technology Publications, 2020, pp. 245–252. doi: 10.5220/0009343402450252.

[26] C. Hursen and C. Bas, "Use of Gamification Applications in Science Education," *International Journal of Emerging Technologies in Learning (iJET)*, vol. 14, no. 01, Art. no. 01, Jan. 2019, doi: 10.3991/ijet.v14i01.8894.

[27] A. Metwally, A. Yousef, and W. Yining, "Learning Analytics and Perceived Experience of Gamifying Homework Assignments:," in *Proceedings of the 12th International Conference on Computer Supported Education*, Prague, Czech Republic: SCITEPRESS - Science and Technology Publications, 2020, pp. 673–683. doi: 10.5220/0009818606730683.

[28] J. Barcena-Vazquez, K. Caro, K. Bermudez, and H. Zatarain-Aceves, "Designing and evaluating Reto Global, a serious video game for supporting global warming awareness," *International Journal of Human-Computer Studies*, vol. 177, p. 103080, Sep. 2023, doi: 10.1016/j.ijhcs.2023.103080.

[29] T. H.-C. Chiang, "Investigating Effects of Interactive Virtual Reality Games and Gender on Immersion, Empathy and Behavior Into Environmental Education," *Frontiers in Psychology*, vol. 12, 2021.

[30] E. Fokides and M. Kefallinou, "Examining the Impact of Spherical Videos in Teaching Endangered Species/Environmental Education to Primary School Students," *Journal of Information Technology Education: Research*, vol. 19, pp. 427–450, 2020.

[31] R. Leitão, M. Maguire, S. Turner, and L. Guimarães, "A systematic evaluation of game elements effects on students' motivation," *Education and Information Technologies*, vol. 27, no. 1, pp. 1081–1103, 2022, doi: 10.1007/s10639-021-10651-8.

[32] X.-M. Wang, S.-M. Wang, J.-N. Wang, G.-J. Hwang, and S. Xu, "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*, vol. 60, no. 8, pp. 1942–1968, Jan. 2023, doi: 10.1177/07356331221095162.

[33] M. Kalogiannakis, S. Papadakis, and A.-I. Zourmpakis, "Gamification in Science Education. A Systematic Review of the Literature," *Education Sciences*, vol. 11, no. 1, p. 22, Jan. 2021, doi: 10.3390/educsci11010022.

[34] A. Anil Yasin and A. Abbas, "Role of gamification in Engineering Education: A systematic literature review," in *2021 IEEE Global Engineering Education Conference (EDUCON)*, Apr. 2021, pp. 210–213. doi: 10.1109/EDUCON46332.2021.9454038.

[35] N. M. Ardoin, A. W. Bowers, N. W. Roth, and N. Holthuis, "Environmental education and K-12 student outcomes: A review and analysis of research," *The Journal of Environmental Education*, vol. 49, no. 1, pp. 1–17, Jan. 2018, doi: 10.1080/00958964.2017.1366155.

[36] D. R. Williams and P. S. Dixon, "Impact of Garden-Based Learning on Academic Outcomes in Schools: Synthesis of Research Between 1990 and 2010," *Review of Educational Research*, vol. 83, no. 2, pp. 211–235, Jun. 2013, doi: 10.3102/0034654313475824.

[37] B. Kitchenham, "Procedures for Performing Systematic Reviews".

[38] N. M. McGuire, "Environmental Education and Behavioral Change: An Identity-Based Environmental Education Model," 2015.

[39] M. J. Page *et al.*, "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews," *BMJ*, vol. 372, p. n71, Mar. 2021, doi: 10.1136/bmj.n71.

[40] M. C. Monroe, E. Andrews, and K. Biedenweg, "A Framework for Environmental Education Strategies," *Applied Environmental Education & Communication*, vol. 6, no. 3–4, pp. 205–216, Mar. 2008, doi: 10.1080/15330150801944416.

[41] B. Cugelman, "Gamification: What It Is and Why It Matters to Digital Health Behavior Change Developers," *JMIR Serious Games*, vol. 1, no. 1, p. e3139, Dec. 2013, doi: 10.2196/games.3139.

[42] M. Riar, B. Morschheuser, R. Zarnekow, and J. Hamari, "Gamification of cooperation: A framework, literature review and future research agenda," *International Journal of Information Management*, vol. 67, p. 102549, Dec. 2022, doi: 10.1016/j.ijinfomgt.2022.102549.

[43] C.-Y. Tsai, H.-S. Lin, and S.-C. Liu, "The effect of pedagogical GAME model on students' PISA scientific competencies," *Journal of Computer Assisted Learning*, vol. 36, no. 3, pp. 359–369, 2020, doi: 10.1111/jcal.12406.

[44] R. Leitão, M. Maguire, S. Turner, F. Arenas, and L. Guimarães, "Ocean literacy gamified: A systematic evaluation of the effect of game elements on students' learning experience," *Environmental Education Research*, vol. 28, no. 2, pp. 276–294, 2022, doi: 10.1080/13504622.2021.1986469.

[45] F. G. B. Wommer, L. M. N. Sepel, and E. L. S. Loreto, "Insects GO: a gaming activity for entomology teaching in middle school," *Research in Science and Technological Education*, 2021, doi: 10.1080/02635143.2021.1921724.

[46] C. Mead, G. Bruce, W. Taylor, S. Buxner, and A. D. Anbar, "Gamifying Virtual Exploration of the Past 350 Million Years of

Vertebrate Evolution," *Frontiers in Education*, vol. 7, 2022, doi: 10.3389/feduc.2022.836783.

[47] I. E. Harker-Schuch, F. P. Mills, S. J. Lade, and R. M. Colvin, "CO2peration – Structuring a 3D interactive digital game to improve climate literacy in the 12-13-year-old age group," *Computers & Education*, vol. 144, p. 103705, Jan. 2020, doi: 10.1016/j.compedu.2019.103705.

[48] D. A. B. Lombana, R. B. Ventura, Y. T. Chen, and M. Porfiri, "educating Youth About Human Impact on Freshwater Ecosystems Using an Online Serious Game," *IEEE Transactions on Games*, pp. 1–13, 2022, doi: 10.1109/TG.2022.3185959.

[49] M. Occhioni, A. Beccaceci, and E. Paris, "Environmental education in distance learning: using Virtual Worlds to link geosciences and sustainability," *Journal of Geoscience Education*, vol. 0, no. 0, pp. 1–15, 2023, doi: 10.1080/10899995.2023.2266863.

[50] M. Trefzger and T. Schlegel, "Mobile AR in the Wild: Exploring an Augmented Reality Concept for a Nature Discovery Path and evaluating its Serious Game Elements," presented at the ACM International Conference Proceeding Series, 2023, pp. 513–517. doi: 10.1145/3603555.3608555.

[51] K. D. Aarhus, J. H. Motland, F. Zhang, and S. Papavlasopoulou, Development and Evaluation of a Gamified Application for Environmental Education: coralQuest. In: Auer, M.E., Tsiatsos, T. (eds) Smart Mobile Communication & Artificial Intelligence. IMCL 2023. Lecture Notes in Networks and Systems, vol 936. Springer, Cham. https://doi.org/10.1007/978-3-031-54327-2_38

[52] E. Bilbao-Aiastui and I. Miranda-Urquijo, "Development of natural science through the Gamification and ICT in Primary Education," *Edutec. Revista Electrónica de Tecnología Educativa*, no. 81, Art. no. 81, Sep. 2022, doi: 10.21556/edutec.2022.81.2577.

[53] V. Caiola *et al.*, "Designing integrated physical–digital systems for children–nature interaction," *International Journal of Child-Computer Interaction*, vol. 36, 2023, doi: 10.1016/j.ijcci.2023.100582.

[54] S. Kawas, N. S. Kuhn, M. Tari, A. Hiniker, and K. Davis, "'Otter this world': can a mobile application promote children's connectedness to nature?," in *Proceedings of the Interaction Design and Children Conference*, in IDC '20. New York, NY, USA: Association for Computing Machinery, Jun. 2020, pp. 444–457. doi: 10.1145/3392063.3394434.

[55] Y.-C. Lin, Y.-H. Hsieh, H.-T. Hou, and S.-M. Wang, "Exploring students' learning and gaming performance as well as attention through a drill-based gaming experience for environmental education," *J. Comput. Educ.*, vol. 6, no. 3, pp. 315–334, Sep. 2019, doi: 10.1007/s40692-019-00130-y.

[56] P. Tocto, G. Dávila, and V. Ayma, "A Serious Game for Recycling Education in Peruvian Children," *Lecture Notes in Networks and Systems*, vol. 692 LNNS, pp. 49–59, 2023, doi: 10.1007/978-3-031-33261-6_5.

[57] A. Torralba-Burrial and E. Dopico, "Promoting the Sustainability of Artisanal Fishing through Environmental Education with Game-Based Learning," *Sustainability (Switzerland)*, vol. 15, no. 17, 2023, doi: 10.3390/su151712905.

[58] Z. Zainuddin, M. Shujahat, H. Haruna, and S. K. W. Chu, "The role of gamified e-quizzes on student learning and engagement: An interactive gamification solution for a formative assessment system," *Computers and Education*, vol. 145, 2020, doi: 10.1016/j.compedu.2019.103729.

[59] S. Janakiraman, S. L. Watson, and W. R. Watson, "Exploring the Effectiveness of Digital Games in Producing pro-Environmental Behaviors when Played Collaboratively and Individually: A Mixed Methods Study in India," *TechTrends*, vol. 65, no. 3, pp. 331–347, May 2021, doi: 10.1007/s11528-020-00571-8.

[60] S. Janakiraman, S. L. Watson, W. R. Watson, and D. P. Shepardson, "Exploring the Influence of Digital Games on Environmental Attitudes and Behaviours Based on the New Ecological Paradigm Scale: A Mixed-Methods Study in India," *Journal of Education for Sustainable Development*, vol. 15, no. 1, pp. 72–99, Mar. 2021, doi: 10.1177/0973408221997844.

[61] T.-S. Neset, L. Andersson, O. Uhrqvist, and C. Navarra, "Serious Gaming for Climate Adaptation—Assessing the Potential and Challenges of a Digital Serious Game for Urban Climate Adaptation," *Sustainability*, vol. 12, no. 5, Art. no. 5, Jan. 2020, doi: 10.3390/su12051789.

[62] G. Mylonas, J. Hofstaetter, M. Giannakos, A. Friedl, and P. Koulouris, "Playful interventions for sustainability awareness in educational environments: A longitudinal, large-scale study in three countries," *International Journal of Child-Computer Interaction*, vol. 35, p. 100562, Mar. 2023, doi: 10.1016/j.ijcci.2022.100562.

[63] L. Hobbs, C. Stevens, J. Hartley, and C. Hartley, "Science Hunters: An inclusive approach to engaging with science through Minecraft," *Journal of Science Communication*, vol. 18, no. 2, 2019, doi: 10.22323/2.18020801.

[64] M. Horn, P. Davis, A. Banerjee, and R. Stevens, "Fight the Power! Games, Thermostats, and the Energy Patriarchy," *International Journal of Designs for Learning*, vol. 11, no. 2, pp. 118–129, 2020.

[65] M. Occhioni, A. Beccaceci, and E. Paris, "Environmental education in distance learning: using Virtual Worlds to link geosciences and sustainability," *Journal of Geoscience Education*, vol. 0, no. 0, pp. 1–15, 2023, doi: 10.1080/10899995.2023.2266863.

[66] Amy Bruckman, "Can Educational Be Fun?," presented at the Game Developer's Conference, San Jose, California, Mar. 1999. Accessed: Dec. 12, 2023. [Online]. Available: https://sites.cc.gatech.edu/fac/Amy.Bruckman/papers/bruckman_gdc99.html

[67] S. R. Foster, S. Esper, and W. G. Griswold, "From competition to metacognition: designing diverse, sustainable educational games," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, in CHI '13. New York, NY, USA: Association for Computing Machinery, Apr. 2013, pp. 99–108. doi: 10.1145/2470654.2470669.

[68] R. Gifford, "The dragons of inaction: Psychological barriers that limit climate change mitigation and adaptation," *American Psychologist*, vol. 66, no. 4, pp. 290–302, 2011, doi: 10.1037/a0023566.

[69] S. Michie, M. M. van Stralen, and R. West, "The behaviour change wheel: A new method for characterising and designing behaviour change interventions," *Implementation Science*, vol. 6, no. 1, p. 42, Apr. 2011, doi: 10.1186/1748-5908-6-42.

[70] S. M. Jones *et al.*, "A 'KAHOOT!' Approach: The Effectiveness of Game-Based Learning for an Advanced Placement Biology Class," *Simulation & Gaming*, vol. 50, no. 6, pp. 832–847, Dec. 2019, doi: 10.1177/1046878119882048.

[71] K. Knaving and S. Björk, "Designing for fun and play: exploring possibilities in design for gamification," in *Proceedings of the First International Conference on Gameful Design, Research, and Applications*, in Gamification '13. New York, NY, USA: Association for Computing Machinery, Oct. 2013, pp. 131–134. doi: 10.1145/2583008.2583032.

[72] S. Lee-Cultura, K. Sharma, G. Cosentino, S. Papavlasopoulou, and M. Giannakos, "Children's Play and Problem Solving in Motion-Based Educational Games: Synergies between Human Annotations and Multi-Modal Data," in *Interaction Design and Children*, in IDC '21. New York, NY, USA: Association for Computing Machinery, Jun. 2021, pp. 408–420. doi: 10.1145/3459990.3460702.

[73] T. W. Malone, "What makes things fun to learn? A study of intrinsically motivating computer games," ProQuest Information & Learning, US, 1980.

[74] R. van Roy and B. Zaman, "Why Gamification Fails in Education and How to Make It Successful: Introducing Nine Gamification Heuristics Based on Self-Determination Theory," in *Serious Games and Edutainment Applications : Volume II*, M. Ma and A. Oikonomou, Eds., Cham: Springer International Publishing, 2017, pp. 485–509. doi: 10.1007/978-3-319-51645-5_22.

[75] K. Seaborn and D. I. Fels, "Gamification in theory and action: A survey," *International Journal of Human-Computer Studies*, vol. 74, pp. 14–31, Feb. 2015, doi: 10.1016/j.ijhcs.2014.09.006.

[76] C. Linehan, B. Kirman, S. Lawson, and G. Chan, "Practical, appropriate, empirically-validated guidelines for designing educational games," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, in CHI '11. New York, NY, USA: Association for Computing Machinery, May 2011, pp. 1979–1988. doi: 10.1145/1978942.1979229.