

Insights on game-based learning for educating on environmental protection and sustainable development

Nuno Aluai Carvalho^{1,2*} , Maria José Rodrigues^{2,3} , Tiago Ribeiro^{2,4} , Clara Vasconcelos^{2,3} 

¹ Instituto Politécnico de Bragança, Bragança, PORTUGAL

² Science Teaching Unit, Faculty of Sciences, University of Porto, Porto, PORTUGAL

³ Transdisciplinary Research Center in Education and Development, Instituto Politécnico de Bragança, Porto, PORTUGAL

⁴ Interdisciplinary Center of Marine and Environmental Research, Matosinhos, PORTUGAL

Received 25 February 2025 ▪ Accepted 04 November 2025

Abstract

Earth's life-supporting system is on the verge of falling into non-Holocene-like conditions since humanity continues to have unsustainable behaviors. Humans are poorly involved in protecting the earth's natural systems and must transform their socioeconomic and cultural practices. Education for sustainable development (ESD) can facilitate these transformations by directing change into a sustainable path. Game-based learning has emerged as a promising tool in ESD, showing effectiveness in analog and digital formats. Bibliometric analyses can reveal insights into future research on shifting human practices through education. Sample was assembled ($n = 463$) and analyzed using RStudio, Microsoft Excel, and statistical package for the social sciences. Results indicate that the quantity of literature is increasing exponentially (coefficient of determination [R^2] = 0.940). While quality standards adopt a decreasing trend through time ($\beta = -0.707$, $p = 0.001$, $R^2 = 0.754$) and correlate negatively with literature accumulation ($r = -0.625$, $T = -0.487$, $\rho = -0.615$, $p < 0.05$). Multi-correspondent analysis showed conceptual gaps in the literature on ocean literacy, climate change and circular economy subtopics. Digital learning environments account for most reports ($n = 311$, 67.2%) compared with analog ones ($n = 132$, 28.5%) or hybrid ($n = 20$, 4.3%). Digital environments unit good evidence albeit they should not constitute the total period of training. Meanwhile, bibliometric analysis traces a comprehensive map and, at the same time, contributes to the discussion around procedures and metrics for assessing the literature.

Keywords: digital learning, education for sustainable development, environmental education, game-based learning, serious games, scientometrics

INTRODUCTION

Evidence shows that six of nine planetary boundaries are outside the safe operating space, threatening subsystems that regulate and enable life as we know it (Richardson et al., 2023). Systemic transformations are required, and individual and collective behavioral changes are mandatory to live on a safe and just planet (Gupta et al., 2024; Powell et al., 2024). Aligning humanity in a sustainable development (SD) pathway requires a systematic shift in six building blocks (Sachs et al., 2019). Some of them interact in an interwoven and permutable manner with this research through education. Quality education is the fourth sustainable development goal (SDG), targeting the improvement of

educational strategies, access to education for those unable to attend formal education and reducing inequalities within and beyond education itself (Gupta et al., 2024; Sachs et al., 2019; United Nations, 2015).

The wealthiest 10% of people are the most responsible for inflicting environmental damage (Karthar et al., 2020; Oswald et al., 2020). Between 23-62% of the world's population fail to have access to basic human needs. However, all humans have the right to satisfy their basic needs, such as having access to education (Gupta et al., 2024; United Nations General Assembly, 1948). While technological advancements may yield more systemic efficiency, individual behavioral changes remain necessary to ensure a prosperous future (Chen et

Contribution to the literature

- Investigation delves into the intersection between game-based learning, environmental protection and sustainable development by analysing a comprehensive set of scientific literature.
- Study shows, through quantitative and qualitative criteria, that while scientific production has been increasing, quality standards have been diminishing over time.
- Research lays down building blocks for future research by highlighting critical research gaps and potential avenues inside and outside digital learning environments.

al., 2018; Gupta et al., 2024; Pedinotti-Castelle et al., 2021; Powell et al., 2024; Springmann et al., 2018). Education for sustainable development (ESD) and environmental education (EE) can instigate societal changes by involving multiple actors in a collective shift to develop pro-environmental behaviors (Gupta et al., 2024; Powell et al., 2024; Zsóka et al., 2013). However, individual efforts to tackle environmental problems are too little calling for an improvement in educational strategies to operationalize ESD and EE (Gupta et al., 2024; Powell et al., 2024; Richardson et al., 2023).

As a multidimensional and cross-disciplinary subject, sustainability demands innovative educational approaches to build upon student-centered learning environments (Martín-Hernández et al., 2021). Serious games and game-based learning (GBL) are suitable options for their playfulness (e.g., edutainment), which prompts more engaging environments thus fostering the learning potential of educational activities (Huizinga, 1955; Schrader, 2023). Serious games are designed to focus on pedagogical objectives, specifically crafted to amplify learning (Schrader, 2023). In contrast, GBL encompasses the broader use of games, game elements or any game-like activities within educational practices, integrating playful strategies to enhance engagement and understanding (Schrader, 2023). This research explores operational approaches within serious games and GBL, focusing on various formats: gamification, simulation games, mobile games, augmented reality, virtual reality, role-playing games, board games, and tabletop games. Each of these modalities offers distinct pathways to enrich educational environments through structured, game-centered interactions.

GBL demonstrated positive effects in science education while enhancing attitudes toward SD. Nonetheless, there exist several gaps in research where further inquiry can improve the overall pedagogical effectiveness. This bibliometric analysis shows which approaches within GBL and which topics demand future research outlets. While contributing through novel bibliometric analysis procedures.

GAME-BASED LEARNING CONCEPTUAL NARRATIVE

The United Nations Educational, Scientific, and Cultural Organization (UNESCO) has endorsed digital

learning programs and projects to address SDG4 (UNESCO, 2020). Interactive interfaces of digital learning environments may promote the development of competencies (knowledge, attitudes, and skills). Nonetheless, digital platforms facilitate access to misinformation, making students and young users particularly vulnerable (Howard et al., 2021). Furthermore, some authors argue that digital learning environments could exacerbate the dispersive effect among students, distressing learning (Aaron & Lipton, 2017; Pedro et al., 2018).

ESD demands active learning environments that promote awareness and understanding of the problems whilst stimulating essential competencies to act autonomously (Leal-Filho et al., 2015; Stanitsas et al., 2019). Research on game-based educational resources softens the limitations in education settings hence addressing SDG4 targets (Shenkoya & Kim, 2023; UNESCO, 2020). This potential is recognized in the literature through a worldwide growing interest in games as educational resources, strategies and methodologies for science teachers, educators, and science communicators (Lin et al., 2025; Morais et al., 2022; Scurati et al., 2022; Stanitsas et al., 2019). GBL and serious games gathered good educational performance among various sustainability subtopics (e.g., Gao et al., 2021; Kioupi et al., 2022; Kirchherr & Piscicelli, 2019; Martindale et al., 2024; Shimabukuro et al., 2022).

Practitioners approaching sustainability subjects need to be supported by multiple scientific disciplines (Daneshpour & Kwegyir-Afful, 2022; Leal-Filho et al., 2015; Stanitsas et al., 2019). Sustainability problems should be dealt with locally whilst thinking globally (United Nations Division for Sustainable Development, 1992). That demands an interdisciplinary practice, an opportunity for science education to showcase how different scientific fields interact, weaving the human web of knowledge. To answer complex questions like the ones posed by sustainability, science education must provoke students to understand the interplay and interchangeability between scientific fields while prompting competencies inherent to different disciplines (Daneshpour & Kwegyir-Afful, 2022). Research on science education recommends active educational approaches where students experience didactically meaningful activities (Li et al., 2024; Martín & Ariza, 2024). GBL and serious games have the

potential to integrate interdisciplinarity in active learning settings (Gao et al., 2021; Martindale et al., 2024). Below, approaches of GBL and serious games and the state of play of previous bibliometric studies are discussed.

Conceptualization of Educational Approaches With Games

Gamification consists of applying games and/or principles of games in non-game contexts (Deterding et al., 2011; Teixeira & Vasconcelos, 2024; Torres-Toukoumidis et al., 2022). Additionally, some researchers conceptualize gamification as the accumulated actions participants take to create their own game, i.e., game design (Deterding et al., 2011). Others refer to gamification as ludic learning experiences (Deterding et al., 2011; García-Jurado et al., 2019; Hamari et al., 2014; Högberg et al., 2019). Making the gamification concept dubious. Nevertheless, to conduct this bibliometric analysis, game design and other gamification strategies got categorized as approaches within the scope of gamification. Gamification has collected supportive evidence on enhancing intrinsic participant motivation, engagement and learning (e.g., Miao et al., 2022; Shenkoya & Kim, 2023; Tobon et al., 2020). Besides these indicators, most games created for educational purposes serve short-term didactic activities and become useless shortly after (Guillen & Hamari, 2023). Furthermore, gamification can also bring together negative indicators of effective student learning (Almeida et al., 2023).

Simulation games are played in digital environments, enabling students to make decisions by interacting with the digital interface, prompting consequences of actions perceived multi-sensorially—by image, sound, and vibrations (Cohen et al., 2016; Dalgarno & Lee, 2009; Nguyen et al., 2024). Feedback systems may foster problem-solving and cultivate decision-making (Cohen et al., 2016; Nguyen et al., 2024). Simulation games approach is associated with good participant motivation, engagement and learning (e.g., Kioupi et al., 2022; Occhioni et al., 2023), being predominantly used in physics and chemistry teaching (Li et al., 2024; Spitha et al., 2024).

Video games are high-budget games created without any pedagogical goal since their primary focus is entertainment and leisure. Nonetheless, they serve as pedagogical tools (Ivory, 2013). Video games show good motivational indicators (Santos et al., 2023), but researchers are concerned about the outcomes of scientific inaccuracies featured in them, e.g., in chemistry education (McGowan & Scarlett, 2021; Santos et al., 2023).

Mobile games are games in digital environments supported by mobile devices, smartphones or tablets (Aaron & Lipton, 2017; Pedro et al., 2018; Sung et al.,

2016). The mass dissemination of smartphones transformed mobile gaming. Estimates indicate that mobile games represent 49% of the global market in 2023, representing about 3.38 billion individuals (NewZoo, 2024). Similarly, mobile games demonstrated good indicators to educate for environmental protection and SD (e.g., Dunn et al., 2021; Sung et al., 2016; Thomas-Walters & Veríssimo, 2022). Teachers and educators should still account for the dispersive effect of such settings (Aaron & Lipton, 2017; Pedro et al., 2018).

Augmented and virtual reality are distinct approaches (Milgram et al., 1995; Zekeik et al., 2025). Augmented reality refers to the incorporation of digital or artificial elements in a pre-existing natural environment, and it can feature almost any smartphone (Bacca et al., 2014; Milgram et al., 1995). Virtual reality is rendered through expensive technological devices conceiving digital or artificial environments of their own (Dalgarno & Lee, 2009; de Freitas, 2008; Galeote et al., 2023; Milgram et al., 1995). Both approaches present good motivational and educational indicators in ESD (e.g., Bacca et al., 2014; Galeote et al., 2023; Karakus et al., 2019; Lampropoulos et al., 2023; Ying et al., 2024). In some cases, comparing virtual reality with analog approaches did not verify significant learning discrepancies (Galeote et al., 2023). Additionally, dispersive effects got noticed in a chemistry teaching study (Morais et al., 2022).

Role-playing games enable participants to adopt different stakeholder roles, assuming distinct responsibilities and abilities toward a particular situation. This approach benefits pedagogical efficiency by misaligning personal agenda from situational problems (e.g., Schrier, 2015), ultimately fostering skills like problem-solving, critical thinking, communication, interpersonal interaction, emotional intelligence, and creativity. While simulation games focus on technical and conceptual understanding of problems, role-playing games and board games effectively promote social and soft skills whilst favoring attitudes and behaviors towards the environment (Kirchherr & Piscicelli, 2019; Scurati et al., 2022). In this analysis, the industry notion of role-play games is categorized as simulation games because they occur in digital environments centering players on leveling up a character.

Board games are used in analog educational settings through a board upon which players assume a pawn and move under specific pre-established rules. Board games are effective for ESD (e.g., Gao et al., 2021; Lin et al., 2025; Martindale et al., 2024; Robinson et al., 2021; Shimabukuro et al., 2022; Sierra & Suárez-Collado, 2021). Stanitsas et al. (2019) claim that there is a growing investment in board game production for educational purposes. It should be noted that some non-digital games have reported better learning outcomes than digital games (Edwards, 2014; Ernest et al., 2014; Khuyen

et al., 2024; Talan et al., 2020; Tomlinson & Masuhara, 2009).

Similarly, tabletop games are among the analog approaches, including card games and puzzles (Huizinga, 1955). This approach is commonly applied for toddlers and preschool children, prompting good learning outcomes and developmental evidence (Klofutar et al., 2022; Torralba-Burrial & Dopico, 2023).

Digital learning environments are prevalent among the GBL approaches. COVID-19 pandemic has leveraged the integration of digital technology in education during a period where education worldwide was digitally sustained (Wang et al., 2024). At the same time, the ubiquitous presence of social media bonds people to digital devices all day long. Overuse of such environments is hardly controlled outside school and may result in consequences with social, emotional and behavioral implications (Böttger & Zierer, 2024; Hanno et al., 2022). COVID-19 school closures and curfews jeopardized children's development and adolescents' learning (McCoy et al., 2021). In addition, Sweden, a country on the frontier of digital education, has abandoned a digital school to include analog learning environments (The Guardian Associated Press in Stockholm, 2023). That may sound like a warning. It remains unclear whether it affects skill acquisition, development, critical thinking, emotional intelligence, creativity, citizenship, empathy, solidarity, sociability, collaboration and autonomy.

Previous Analyses

This bibliometric analysis assessed the quantity and quality of scientific production (SP) within the GBL and serious games related to ESD or EE. Bibliometric studies regarding literature metrics contribute to mapping literature (Chang et al., 2010; Mao et al., 2010; Song et al., 2019; Zupic & Čater, 2014). Evidence shows that bibliometric analysis in education-related topics leads to more refined approaches and practices (Chang et al., 2010).

Previous research observed a growing interest in education through games by an increasing scientific corpus (Hallinger & Wang, 2019; Hallinger et al., 2020; Trinidad et al., 2021; Tsai & Fan, 2013). Countries linked to higher scientific outputs by authorship nationality frequency are the USA, Canada, Germany, the UK, and Australia (Hallinger et al., 2020; Hallinger & Wang, 2019; Trinidad et al., 2021). Previous analyses verified that digital environments are more frequent than analog environments (Hallinger et al., 2020; Talan et al., 2020). There are still some identified gaps in previous bibliometric analysis which this research aims to contribute to address.

MATERIALS AND METHODS

This research aims to contribute to the understanding of current paradigms of GBL and serious games research to ESD and EE, ultimately leading to insights for future research and practice. Three research questions (RQs) guide bibliometric analysis.

RQ₁. How has SP focused on GBL and serious games to educate for environmental protection and SD evolved quantitatively and qualitatively?

RQ₂. Which subtopics emerged within the GBL and serious games approaches to educate for environmental protection and SD?

RQ₃. Which approaches are well established in the GBL and serious games scientific research field to educate for environmental protection and SD?

SPAR-4-SLR protocol enabled bibliometric data collection and refinement associated with other bibliometric analysis procedures (Paul et al., 2021) (Figure 1).

RQ₁ aims to quantify and understand the quality of SP within this scope to trace a more comprehensive map of scientific literature, expanding concerns beyond its quantification (Chang et al., 2010; Kuhn, 1970; Mao et al., 2010; Song et al., 2019; Zupic & Čater, 2014). **RQ₂** and **RQ₃** highlight procedural or conceptual gaps by identifying approaches and subtopics requiring more research. Both **RQ₂** and **RQ₃** involve gauging the frequency of approaches.

Previous research lacked an exhaustive categorization of approaches and learning environments regarding GBL to educate for environmental protection and SD (Hallinger et al., 2020; Stanitsas et al., 2019). As Chang et al. (2010) argued, categorizing approaches identifies which approaches require further research while unlocking a more precise map of scientific literature. Thereby, learning environments and approaches were quantified in tandem during the categorization process.

Sampling Process

Bibliometric data were collected from Web of Science and Scopus because of their academic relevance and comprehensiveness (Singh et al., 2021). In both databases, Web of Science and Scopus, semantic priority was established inserting text inside quotation marks (""). Search fields were separated by the addition Boolean operator (AND). Then, the search within the field was used to narrow the total capture of search.

In Web of Science, data were exported in plain text format (.txt). Meanwhile, in Scopus, data were exported in bibtex format (.bib). Afterwards, RStudio package "convert2df()" converted files into bibliometric data frames yielding a prior sample without individual scrutiny (n = 826). Along with this procedure, duplicated

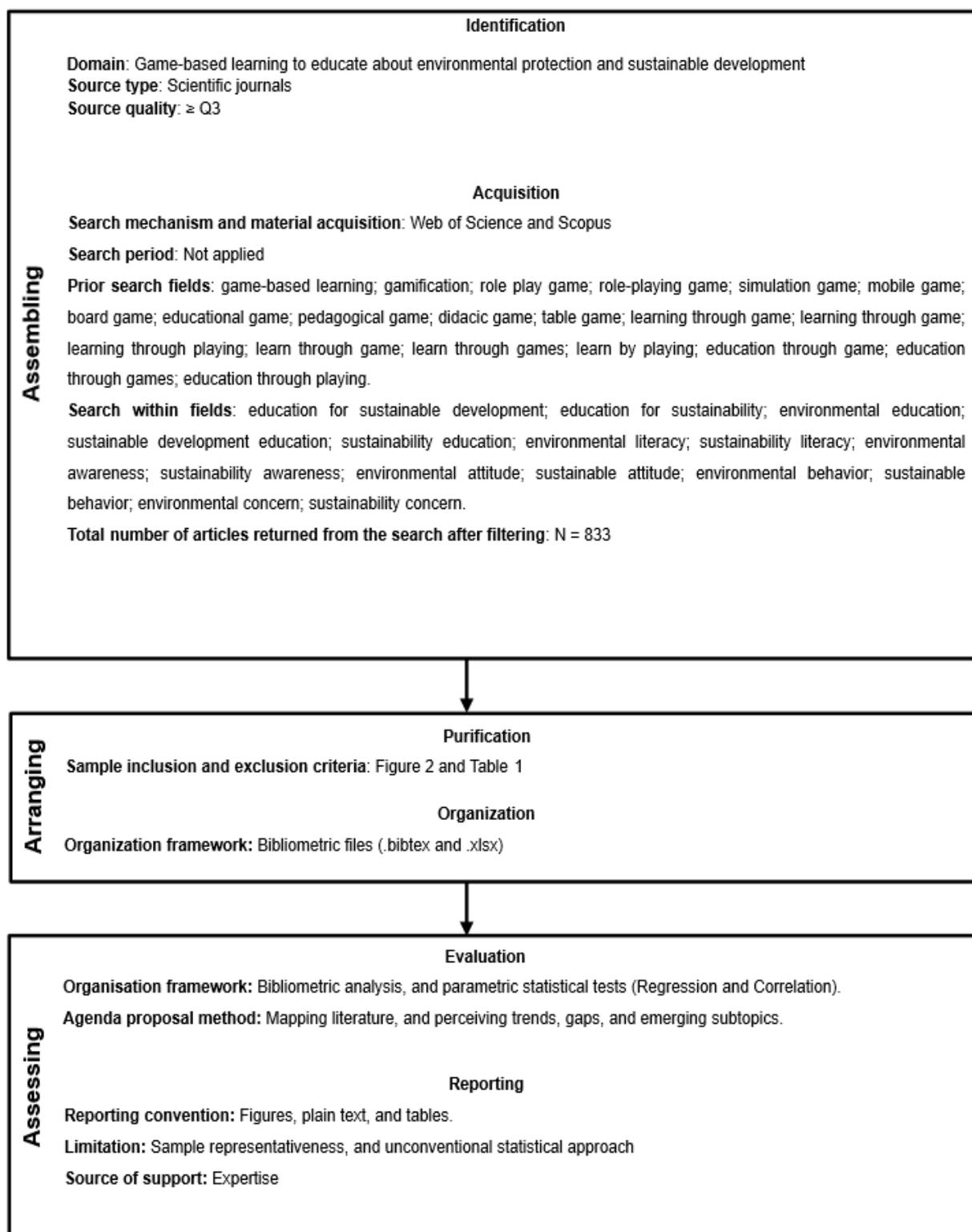


Figure 1. SPAR-4-SLR protocol operationalization (Source: Authors' own elaboration)

documents were removed ($n = 97$) and relevant documents were included ($n = 90$) in the prior sample. RQ_3 guided the final steps of the sampling by narrowing the sample through a documental analysis. More information on the sampling process can be found in Figure 2.

Software

Data treatment was undertaken in RStudio (2023.12.1: Build 402) with Bibliometrix package, similar to previous research recommendations (Ellegaard & Wallin, 2015). Statistical package for social sciences) (v. 29.0.0.0; Build 241) and Microsoft Excel (v. 2403; Build 16.0) computed statistical tests, arithmetic calculations.



Figure 2. Sampling process criteria and parameters (Source: Authors' own elaboration)

Visualization elaborated on Microsoft Excel (v. 2403; Build 16.0).

Procedure

Several previous analyses were reviewed to find proper parameters of analysis of SP regarding quantity and quality standards (Carvalho & da Conceição Martins, 2024; Hallinger & Wang, 2019; Hallinger et al., 2020; Karakus et al., 2019; Tobon et al., 2020; Trinidad et al., 2021; Tsai & Fan, 2013).

RQ₁ analysis procedure

Separation of SP in periods accounting for annual number of publications is widely used (Hallinger & Wang, 2019; Trinidad et al., 2021). Tracing a function enabled identifying a trend regarding the quantity of SP while controlling its respective coefficient of determination (R^2).

Unlike quantity, which can be assessed by decomposing annual SP, various metrics may evaluate quality standards. Recently, academic institutions advocated for more precise metrics to rank institutions. Until now, metrics are quantity-centered thus favoring the number of publications over the quality of scientific

outputs (Universität Zürich, 2024), leading to strain debates. Apart from them, citations are a well-established variable for understanding the quality standards of research (e.g., Hallinger & Wang, 2019). Other bibliometric analyses have used mean citation per year (MC) and the potential of being cited (PC) as proxies for assessing the quality of SP (Carvalho & da Conceição Martins, 2024). PC was calculated using the quotient between MC and citable years. Citable years were obtained by subtracting the concerning year from the last year recorded (2024), except for the last year, which counts as one because, logically, citable years must be positive natural numbers (N).

Categorical regression and correlation tests were applied to understand quality standards, based on previous research (Carvalho & da Conceição Martins, 2024). For the categorical regression, years were defined as an ordinal independent variable, while MC and PC, continuous ones, were defined as dependent variables or predictors. Model produced by the categorical regression self-sustains its efficiency in predicting the evolution of MC and PC through time. Neither the maximum apparent error in the first iteration (0.306) with a satisfactory R^2 ($R^2 = 0.697$) nor the minimum apparent error in the eleventh iteration (0.246) with a higher adjustment ($R^2 = 0.754$) are capable of dismantling the model's coefficient. Meanwhile, SP, MC, and PC were used as variables for the correlation test. Exploratory correlation tests led to a more accurate procedure by disregarding period 1. Pearson's coefficient (r), Kendall's coefficient (T), and the Spearman coefficient (ρ) verified the co-occurrence direction and intensity of the abovementioned variables.

Submitting bibliometric data to categorical regression and correlation tests ensured a thorough assessment regarding the evolution of quality standards through time (categorical regression) and the direction and intensity of its relationship with literature accumulated corpus (correlation test) was made (Carvalho & da Conceição Martins, 2024). Literature accumulates significantly over time. Thus, these two statistical tests help corroborate one another.

RQ₁ methodological procedure included other bibliometric parameters, such as the most productive journals and countries. Countries were profiled regarding development as Global North or Global South countries using the United Nations Conference on Trade and Development guidelines and the human development index (United Nations Conference on Trade and Development, 2024; United Nations Development Programme, 2024). Furthermore, Lotka's Law (Coile, 1977) was applied to trace a trend line while calculating its R^2 , quantifying the most prolific authors.

RQ₂ analysis procedure

RQ₂ aimed to identify subtopics that require further research. Author's keywords (SE = 0.05184) integrated a cluster analysis with the spin-glass clustering algorithm. Additional filters were applied, namely removing conceptually redundant author's keywords ("serious games", "serious game", "game-based learning", "educational game", "educational games", "games", "learning", "environmental education", and "education for sustainable development") and considering words as synonymous ("energy", "energy saving", "energy conservation", "board games" and "board game") attending to semantical proximity and practical coherence.

Cluster analysis prompted an individual assessment of approaches, subtopics and participants using frequency (n), percentage (%), relevance [0, 1] and development rate [0, 1]. Relevance was measured through the PageRank centrality algorithm provided by RStudio (2023.12.1: Build 402). Development rate was computed by scaling clusters' coordinates separately for approaches, subtopics and participants. Approaches and participants were added to enhance the understanding of ongoing research. While centrality demonstrates relevance, comparative frequency within every cluster presents the development rate. A multi-correspondence analysis of individualized approaches and subtopics revealed gaps within this scope. Hence, conceptual variance (CV) is an independent variable that describes the ease of copulating thematic universe, either approaches or subtopics. Moreover, internal variance (IV) is a dependent variable that translates monotony and versatility of either approaches or subtopics within thematic universes. CV and IV concepts interpret respectively dimension one and dimension two of the multi-correspondence analysis (Tobon et al., 2020; Trinidad et al., 2021).

RQ₃ analysis procedure

RQ₃ guided the sampling process by explicitly demanding a categorization of scientific literature. Categorization examined a prior sample (n = 826) using pre-established parameters of content analysis to avoid biasing interpretation (**Table 1**), while quantifying approaches (e.g., simulation games) and learning environments (digital or analog). During this process, documents outside the intended scope were removed (n = 363), culminating in the final sample (n = 463).

Conceptualization of the approaches was highly fruitful, and it should be noted that role-play games in digital environments were categorized as simulation games (Kirchherr & Piscicelli, 2019; Scurati et al., 2022) and game design and mobile applications with game elements but that are not games were categorized as gamification (Deterding et al., 2011; García-Jurado et al., 2019; Torres-Toukoumidis et al., 2022).

Table 1. Documental analysis criteria for categorization

Parameter 1	Parameter 2	Parameter 3	Category
Focused on education for environmental protection or SD	Inside serious games and GBL	Gamification approach is used either in a digital or analog environment ¹ .	GM
		Used simulation games as an educational approach ² .	Sim
		Mobile games or gamified apps with educational purposes are used.	MB
		Used augmented reality as an educational approach.	AR
		Used virtual reality as an educational approach.	VR
		Used video games as an educational approach.	VG
		Used role-play games as an educational approach.	RP
		Used a table game as an educational approach.	TB
		Used multiple approaches within the serious game or GBL framework or other educational methods.	O
		It is a literature review.	Excluded
It is a bibliometric analysis.	Excluded		
It is a meta-analysis.	Excluded		
	Focused on psychometric scale validation.	Excluded	
	Outside serious game and GBL	Excluded	
Did not focus on education for environmental protection or SD			Excluded

Note. ¹ Gamification category includes the game design approach and mobile applications which are not games & ²Simulation games category includes role-play games in digital educational environments

Table 2. Periods of annual scientific production

Period	Years	Designation	n	%	Average production per year
1	[1986, 2012]	Embryonic period	28	6.05	1.56
2	[2013, 2024[Growing period	435	93.95	36.25

This research may not comprehend the entire research paradigm of educating people about environmental protection and SD through games. During the categorization process, it became obvious that many manuscripts fall short in providing a concrete conceptualization of approach and subtopics of focus. Indeed, many lack conceptual framing and use dissonant terminologies.

RESULTS

Following section exhibits the main findings of the three RQs (RQ₁, RQ₂, and RQ₃), presented in three subsections.

Quantitative and Quality Standards Analysis (RQ₁)

Literature assessments benefit from dividing literature into periods regarding the number of publications (Hallinger & Wang, 2019; Trinidad et al., 2021). Then, two periods were defined (Table 2) - the embryonic period [1986, 2012] and the growing period [2013, 2024[. The former constitutes the initial steps of this particular research area possessing a diminished number of publications, a lower percentage (n = 28, 6.05%) compared to the latter (n = 435, 93.95%) which describes a period where literature accumulated rapidly.

Disregarding the year of 2024 traces an exponentially growing trend with a high R² (R² = 0.9397) that

determines quantity standards of scientific literature in this specific research area (Figure 3).

Citation-related metrics are commonly used to understand the quality of research (e.g., Hallinger & Wang, 2019). Statistical tests were conducted to examine quality standards. Categorical regression considered Years as the independent variable and MC and PC as dependent variables or predictors. Below, one can see model main outputs and benchmarks (Table 3).

Thereafter, ANOVA test showed statistically significant differences between variables (F = 11.759, p < 0.001). Additionally, model coefficients predict a decreasing trend for MC (β = -0.707, p = 0.001) and an increasing trend for PC (β = 1.156, p < 0.001). Correlation tests deemed SP, MC, and PC as proxies of analysis (Table 4). Coefficients from three different statistical procedures verified a negative co-occurrence between MC and SP (r = -0.625, T = -0.487, ρ = -0.615) with a significant p-value (p < 0.05) for all calculations while showcasing positive relationships between PC and MC (r = -0.816, T = -0.667, ρ = -0.824), highly significant (p < 0.01).

Journals were rated regarding the number of publications (n), the ratio of the total sample size (%), and the h-index (zone) where they belong. Most prominent journals were: Sustainability (n = 66, 14.25%, zone 1), Simulation and Gaming (n = 29, 6.26%, zone 1);

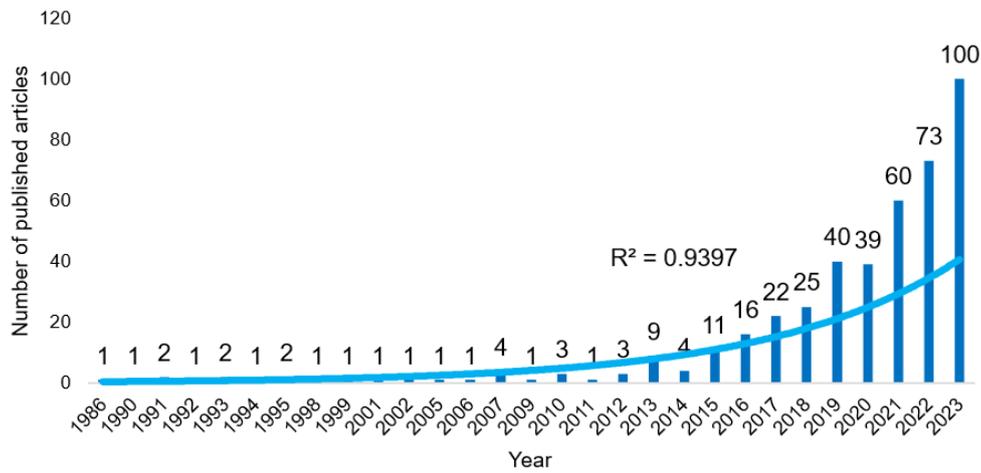


Figure 3. Scientific production evolution (Source: Authors' own elaboration)

Table 3. Categorical regression results

Modeling performance				
R	R ²	R ² _{adj}	Apparent prediction error	
0.868	0.754	0.690	0.246	
ANOVA				
	SS	Gl	MS	F
Regression model	22.625	6	3.771	11.759
Residuals	7.375	23	0.321	
Coefficients				
	β	Bootstrap error	gl	F
MC	-0.707**	0.256	3	7.647
PC	1.156*	0.195	3	35.103

Note. *p < 0.001 & **p = 0.001

Table 4. Correlation tests

	SP	MC	PC
Pearson's coefficient (r)	SP	1	
	MC	-0.625**	1
	PC	-0.221	0.816*
Kendall's coefficient (T)	SP	1	
	MC	-0.487**	1
	PC	-0.205	0.667*
Spearman's coefficient (ρ)	SP	1	
	MC	-0.615**	1
	PC	-0.203	0.824*

Note.*p < 0.01 & **p < 0.05

Interactive Learning Environments (n = 27, 5.83%, zone 1); Environmental Education Research (n = 10, 2.16%, zone 1); Educational Sciences (n = 8, 1.73%, zone 1); International Journal of Sustainability in Higher Education (n = 8, 1.73%, zone 1); Journal of Cleaner Production (n = 8, 1.73%, zone 1); Energies (n = 7, 1.51%, zone 1); Applied Environmental Education and Communication (n = 5, 1.08%, zone 2).

Countries with the highest number of publications were the USA (n = 100, 21.60%), China (n = 62, 13.39%), Spain (n = 38, 8.21%), Germany (n = 35, 7.56%), Italy (n = 27, 5.83%), Portugal (n = 15, 3.24%), the UK (n = 14, 3.02%), Australia (n = 13, 2.81%) and Netherlands (n = 12, 2.59%). Countries were divided based on

development indicators in Global North and Global South countries (United Nations Conference on Trade and Development, 2024; United Nations Development Programme, 2024). Global North countries feature approximately three-quarters of the total authorship sources compared to a quarter from (Global North: n = 347, 74.95%; Global South: n = 116, 25.05%).

Lotka's law sees trends in authorship per number of published articles thus this procedure assesses authorship continuity. From the final sample (n = 463), 1,420 authors were identified. Most authors have published only one article (n = 1,248, 87.89%). A smaller group has published two articles (n = 136, 9.58%), while even fewer have published three (n = 27, 1.90%). Only a few authors have published four or more articles (n = 9; 0.72%). The decreasing power function trend with a high R² (R² = 0.9991) describes a low consistency of authorship and ceases Lotka's law (Figure 4).

Emergent Approaches and Subtopics (RQ₂)

This subsection contains the findings on emerging approaches and subtopics, results of RQ₂ inquiry. Nine clusters were identified through the spin-glass clustering algorithm from the Bibliometrix package. Clusters can be classified based on density and keyword frequency. Furthermore, clusters are classified by relevance,

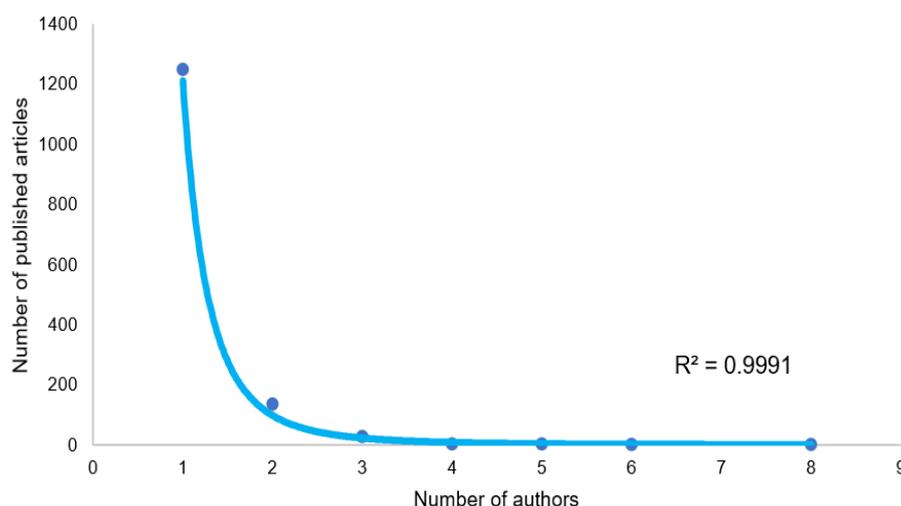


Figure 4. Lotka's law (Source: Authors' own elaboration)

Table 5. Thematic map analysis criteria

	Keywords	Frequency (n)	Percentage (%)*	Relevance**	Development***
Approaches	Gamification	154	58.33	0.145800	1.00000
	Mobile games	29	10.98	0.031250	0.16110
	Augmented reality	26	9.85	0.024530	0.14090
	Simulation games	22	8.33	0.019310	0.11410
	Board games	11	4.17	0.006776	0.04027
	Virtual reality	9	3.41	0.011890	0.02685
	Role-playing games	8	3.03	0.007318	0.02013
	Video games	5	1.89	0.006121	0.00000
Subtopics	Energy	28	38.89	0.041160	1.00000
	Climate change	19	26.39	0.024030	0.62500
	Sustainable consumption	6	8.33	0.010940	0.08333
	Circular economy	5	6.94	0.002856	0.04167
	Ocean literacy	5	6.94	0.005907	0.04167
	Sustainable mobility	5	6.94	0.005645	0.04167
	Recycling	4	5.56	0.005427	0.00000
Public	Higher education	17	68.00	0.020770	1.00000
	Primary school	4	16.00	0.006777	0.00000
	Adult learning	4	16.00	0.005411	0.00000

Note. *To calculate the percentage (%), the subtotal frequency was used from approaches only and sub-topics within sustainability, respectively; **Relevance degree was assessed using the PageRank centrality algorithm; & ***Development degree has considered the total frequency of the cluster's keywords to scale the dataset

network strength, development rate, and interaction strength between networks (Tobon et al., 2020; Trinidad et al., 2021). These procedures result in a semantic map of clusters (Table 5). The most frequent approach is gamification (n = 154, 58.33%), while the most frequent subtopics are energy (n = 28, 38.89%) and climate change (n = 10, 26.39%) and the most frequent participants were enrolled in higher education (n = 17, 68.00%).

After tracing a semantic map of the most frequent approaches, subtopics and participants, a multi-correspondence analysis investigated CV and IV for both approaches and subtopics. CV translates the ease of a cluster to copulate with other clusters, showing interactions in-between approaches and subtopics. IV refers to versatility when y-coordinates are positive (IV > 0) or monotony when y-coordinates are negative (IV <

0). The less frequent approaches in the semantic map are in a versatile quadrant whilst the most incident approaches are in a monotony quadrant (Figure 5).

CV gauging the strength of interaction between networks is quantified by x-coordinates proximity to 0. Therefore, it must be the coordinate absolute value (|CV|). Filters were applied and the multi-correspondence analysis final outputs scrutinize augmented reality (|CV| = 0.68, IV = -0.22), gamification (|CV| = 0.44, IV = -0.46), simulation games (|CV| = 0.53, |IV| = 0.47), role-playing games (|CV| = 0.74, IV = 0.51), mobile games (|CV| = 0.63, IV = -0.62), board games (|CV| = 1.06, IV = 0.73), virtual reality (|CV| = 0.25, IV = 0.81) and video games (|CV| = 0.49, IV = 1.95) as approaches. Meanwhile, examining energy (|CV| = 0.52, IV = -0.93), climate change (|CV| = 1.35,

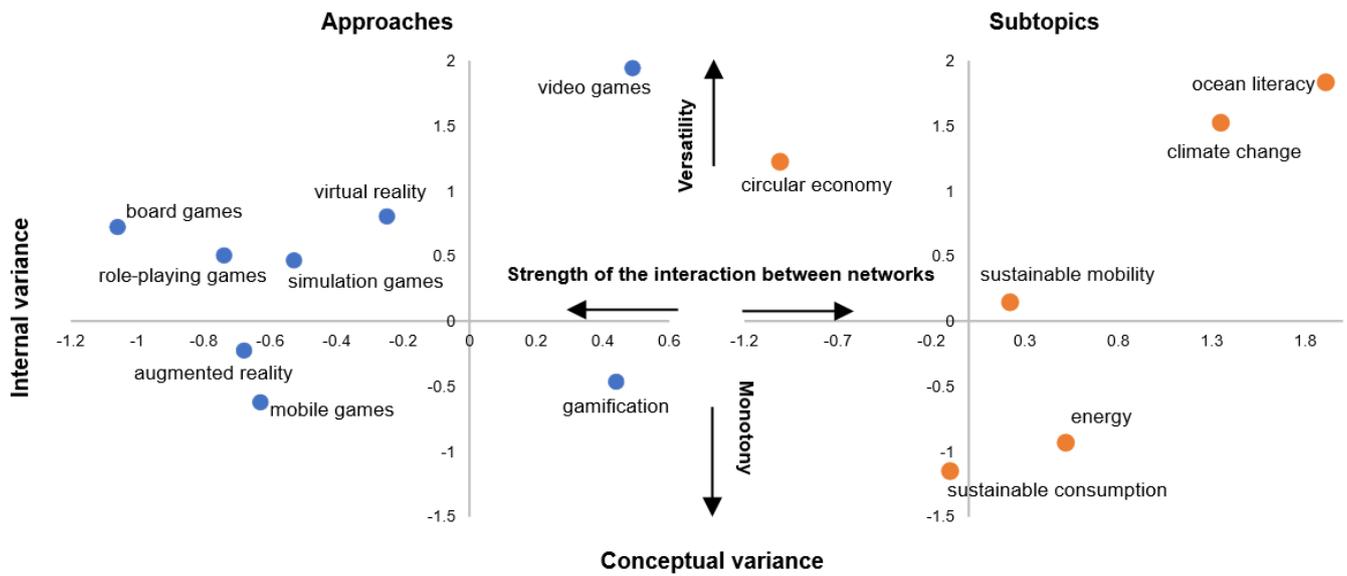


Figure 5. Multi-correspondence analysis (Source: Authors' own elaboration)

Categorization based on approach and learning environment

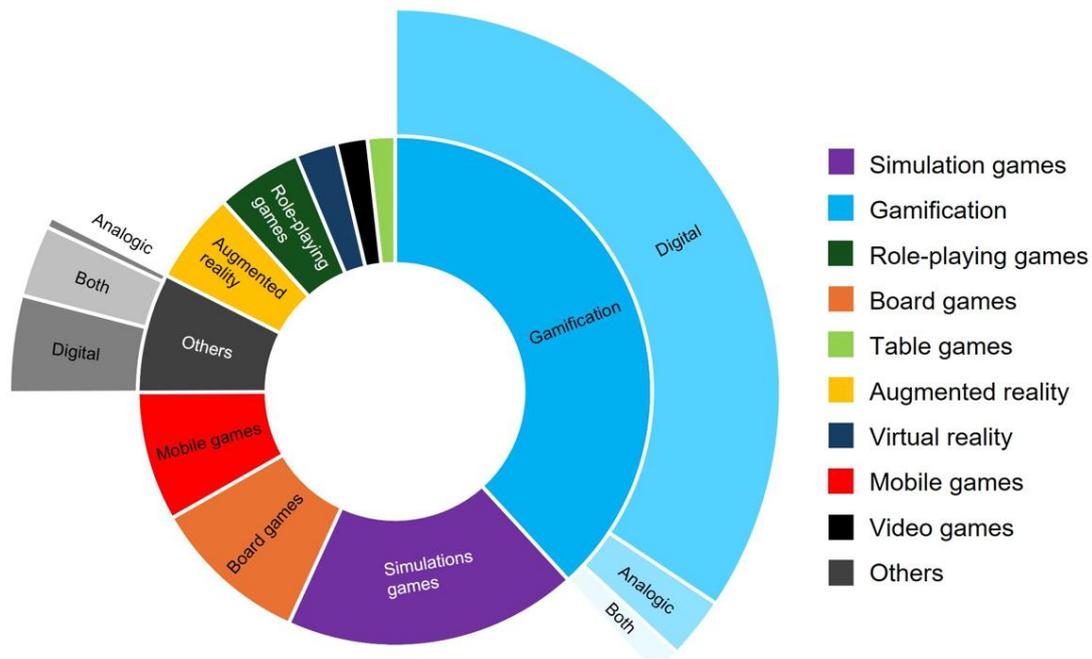


Figure 6. Multilevel doughnut categorization chart (Source: Authors' own elaboration)

IV = 1.53), sustainable consumption ($|CV| = -0.1$, IV = -1.15), ocean literacy ($|CV| = 1.91$, IV = 1.84), sustainable mobility ($|CV| = 0.22$, IV = 0.15) and circular economy ($|CV| = -1.01$, IV = 1.23), as subtopics (Figure 5).

Categorization Regarding Approaches and Learning Environments (RQ₃)

An array of factors dictates education's success. Approach and the learning environment (digital or analog) are two of the most influential ones (Edwards, 2014; Ernest et al., 2014; Hallinger et al., 2020; Talan et al., 2020; Tomlinson & Masuhara, 2009). Categorization analyzed documents through common descriptors

(Table 1) verifying that digital environments are by far the most frequent environments (n = 311, 67.17%) compared with analog ones (n = 132, 28.51%) and activities developed in both learning environments (n = 20, 4.32%) (Figure 6).

Moreover, categorization process quantified the frequency of approaches. To educate for environmental protection and SD, the most frequent approaches are gamification (n = 177, 38.23%), simulation games (n = 86, 18.57%), board games (n = 46, 9.94%), mobile games (n = 38, 8.21%), augmented reality (n = 27, 5.83%), role-playing games (n = 25, 5.40%), virtual reality (n = 12, 2.59%), video games (n = 9, 1.94%), table games (n = 8, 1.73%), among others (n = 35, 7.56%) (see Figure 6).

DISCUSSION

SP on GBL to educate for environmental protection and SD has been increasing (Hallinger & Wang, 2019; Hallinger et al., 2020; Trinidad et al., 2021) close to an exponential trend (see [Figure 3](#)). Excluding 2024, that has not yet finished by the time of this research, was essential to obtain a higher adjustment. Besides quantity indicators, **RQ₁** findings contribute to the discussion on quality standards of literature assessments. Statistical tests gave clues to understand the quality of SP through established citation-related metrics (Carvalho & da Conceição Martins, 2024). ANOVA showed statistically significant differences while Categorical Regression predicted a decreasing trend in MC over time. Both yielded significant probability values. Enabling the rejection of null hypothesis on variables interplay.

Correlation tests utilize SP, MC, and PC as proxies. Three different procedures gathered corroborative evidence pointing in the same direction regarding the co-occurrence of MC and SP. They indicate that MC is negatively correlated to SP, meaning that citation-related metrics decrease whilst publications accumulate. Remember that production increases over time.

In the current academic landscape, research quality is often less prioritized than quantitative metrics by focusing on number of publications instead of citability. That still provokes harsh debates on academic ranking metrics (Universität Zürich, 2024). Statistical procedures used here to assess quality standards have been documented in the literature (Carvalho & da Conceição Martins, 2024), and once again, led to cross-statistical and proxy corroborative results. Observations on citation-related metrics registered a decrease over time and as literature accumulates, which may indicate that the current research paradigm has reached a period without significant advancements. This novel is understanding of the current research paradigm unveiled insights to tackle the stationary tendency of research. Education remit is to prepare individuals to overcome challenges. This result supports previous literature on science education that calls for longitudinal, meaningful and context-oriented education research to overcome contemporary challenges (Daneshpour & Kwegyir-Afful, 2022; Li et al., 2024).

Global North countries are the highest contributors to authorship (Hallinger & Wang, 2019; Hallinger et al., 2020; Trinidad et al., 2021). While evidence demonstrates that inequalities critically impact human systems (Gupta et al., 2024), Global South countries, the most affected ones, continue to be marginalized in scientific narratives. Hegemony of Global North countries in scientific discourse may profoundly affect science and society, and Global South countries must develop in scientific research as much as in other socioeconomic indicators. Lotka's law described a decreasing power trend line with a high R^2 , indicating a low continuity of authorship.

Expertise requires time and resources, and every research domain can benefit from that investment.

The semantic analysis delves into emergent domains within this research topic. Data are self-corroborative, as the most monotonous approaches are among the most frequent. Gamification, mobile games, and augmented reality have negative IV indicating a monotonous keyword linkage, unlike board games, role-playing games, simulation games, and virtual reality. Besides education being highly context-dependent, all approaches have been gathering good pedagogical and didactic indicators (Gao et al., 2021; Kioupi et al., 2022; Lin et al., 2025; Martindale et al., 2024; Robinson et al., 2021; Schrier, 2015; Scurati et al., 2022).

Simulation games and virtual reality architecture software requires high budgets, logistical burdens and human resources (Dalgarno & Lee, 2009; de Freitas, 2008; Milgram et al., 1995). Investments in board games and role-playing games may be of interest (Kirchherr & Piscicelli, 2019; Scurati et al., 2022), strengthening their interaction between networks. Often, non-digital games report good learning outcomes compared to digital games (Edwards, 2014; Ernest et al., 2014; Talan et al., 2020; Tomlinson & Masuhara, 2009). Ocean literacy, climate change and circular economy are highly versatile subtopics (Gao et al., 2021; Occhioni et al., 2023; Torralba-Burrial & Dopico, 2023). They are positioned far from the x-axis origin (0, y) and may benefit from more research to strengthen interactions between networks. It must be noted that climate change was the most frequent subtopic on the semantic map. However, climate change is one of, if not the most, broad problems with multifold causes, consequences, and mitigation strategies (Gupta et al., 2024; Powell et al., 2024; Richardson et al., 2023), justifying its versatility. Furthermore, sustainable mobility is also a relevant subtopic to be explored in future activities.

Categorization saw a hegemonic frequency of gamification approach and digital learning environments (Hallinger et al., 2020; Talan et al., 2020). Digitalization is one of the building blocks for SD (Sachs et al., 2019; UNESCO, 2020). Some research entails positive indicators regarding learning in digital settings (Bacca et al., 2014; Dunn et al., 2021; Galeote et al., 2023; Kioupi et al., 2022; Thomas-Walters & Veríssimo, 2022; Ying et al., 2024; Zekeik et al., 2025). Nevertheless, evidence focuses on motivation (Aaron & Lipton, 2017; Howard et al., 2021; Pedro et al., 2018), which can relate to the dispersive potential of digital environments that often lead to poorer educational efficiency compared with analog learning environments (Edwards, 2014; Ernest et al., 2014; Galeote et al., 2023; Khuyen et al., 2024; Morais et al., 2022; Talan et al., 2020; Tomlinson & Masuhara, 2009). Meanwhile, overuse of mobile devices harms well-being, hindering social skills development (Böttger & Zierer, 2024). Some countries that have made great efforts in digitalizing education have retreated

from exclusive digital learning settings (The Guardian Associated Press in Stockholm, 2023). This discussion does not raise dogmatic assumptions. Educational practices do not need to exclude any (analog and digital) and can benefit from both.

INSIGHTS FOR FUTURE RESEARCH AND PRACTICE

Assessment expanded the understanding of the research paradigm focused on game-based education to teach environmental protection and SD. Diverse procedures enable tracing the evolution of quantity and quality standards of scientific research while conceiving a semantic map and analyzing clusters to highlight emerging approaches and subtopics. In addition, categorization supported other findings systematizing information on GBL and serious game approaches that can prompt theoretical discussions.

Bibliometric analysis stresses guidelines for future research on GBL, ESD, and EE. Amidst its output, some should be systematized. It is noteworthy that education is context-dependent, and its success for ESD and EE activities depends on multiple factors. Educators and teachers must prioritize participant needs and motivations integrating multidimensional narratives with social, environmental, and economic features. Science education benefits from focusing on problems related to participants daily lives. That alone bridges scientific gaps between common sense and Science itself.

Aside from conceptual contributions, additional conclusions can guide future research and practitioners. Firstly, research should prioritize quality standards and impact on social, environmental and economic systems. To meet this recommendation, researchers can partner with practitioners to create practice-oriented research initiatives with long-term goals favoring research outputs and education positive impact. Secondly, board games and role-playing games are potential research avenues less reported in the literature. Ocean literacy, climate change and circular economy are versatile subtopics because they link multiple scientific disciplines. Still, those and other subtopics possess plenty of space for investigation with several research gaps. Lastly, besides digital environments bolster motivation among participants, they should not constitute the total period of training as enhancing social and soft skills is mandatory and occasionally constrained by digital settings.

Author contributions: NAC: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing-original draft, and visualization; MJR: conceptualization, resources, writing-review & editing, supervision, project administration, and funding acquisition; & TR & CV: conceptualization, resources, writing-review & editing, supervision, project administration, and funding acquisition. All authors agreed with the results and conclusions.

Funding: This research was supported by the Strategic Funding (refs. UID/04423/2025, UID/PRR/04423/2025 and

LA/P/0101/2020) through national funds provided by the Portuguese National Funding Agency for Science, Research, and Technology (Fundação para a Ciência e a Tecnologia [FCT]).

Ethical statement: The authors stated that the study does not require any ethical approval. No live subjects were involved during the study.

AI statement: The authors stated that no content was generated through AI.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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