Digital technologies in environmental education: Implications for teacher education and professional development

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Abstract
This study comprehensively analyzes the relationship between information and communication technologies (ICT) and environmental education (EE) to uncover prevalent themes and research gaps. The preferred reporting items for systematic reviews and meta-analyses protocol guided the selection of relevant documents, employing a hermeneutic framework for analysis. The Scopus database was used for the search, covering the publication period from 2001 to 2024. The following search criteria were used (TITLE-ABS-KEY (ict) AND TITLE-ABS-KEY ("ENVIRONMENTAL EDUCATION")) filtering by document type and selecting articles published in journals, conference proceedings, and systematic reviews. 59 documents were identified, of which 33 met the eligibility and inclusion criteria. Findings indicate that ICTs increasingly serve as mediators of environmental learning, enhancing experiential learning through active methodologies like gamification and augmented reality. Key factors include teacher training in technological skills, improved student motivation and critical thinking, and the adaptation of digital tools to diverse educational contexts. However, barriers persist, including inadequate infrastructure, insufficient teacher preparation, and the tension between digital engagement and direct interaction with nature. The conclusion highlights that effective ICT integration in education necessitates ongoing teacher training and the formulation of new research avenues that consider contextual factors.

Keywords: environmental education, ICT, sustainability, systematic review, teacher training

INTRODUCTION

The growing intersection between information and communication technologies (ICT) and environmental education (EE) has become a strategic axis in current debates on sustainability and educational transformation. In a global scenario marked by ecological crises, social inequalities and dizzying technological advances, it is essential to rethink how to educate critical citizens committed to the environment. In this context, this study conducts a systematic review with the aim of understanding how ICTs are integrated into EE, analyzing their potential, limitations, tensions and research projections.

Environmental Education

There is still plenty of debate regarding what constitutes EE. Put simply, EE can equally mean a process, a scientific discipline, dimension, or a field of knowledge. EE-as-process, which studies the interface of man versus nature, finds firm fitment in modern western thought. Since the late Stockholm Conference of 1972, the way EE has been defined in hegemonic discourses and in legal instruments is that it has to be viewed somewhere along the continuum of an environmental formation process. This perspective derives from conservationist and resource-based educational approaches.

This article is part of the state of the art of the doctoral work called "*Pedagogical practices of environmental education mediated by digital technologies,*" currently in progress in the framework of the doctorate in educational sciences of the Universidad del Tolima.

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Contribution to the literature

- The review reveals the transformative impact of digital technologies.
- By examining existing studies, the article identifies methodological limitations such as infrastructural barriers and insufficient teacher training, advocating for context-sensitive and participatory research designs.
- The review highlights ICT's ability to enhance experiential learning while cautioning against excessive reliance on technology absent adequate infrastructure and pedagogy.

EE is defined as that complex educational process, dynamic and strategical in nature, aimed at fostering deep transformation at the present, individual, and social levels (Diaz-Patiño, 2025). First, this process-oriented however remains as a toolset to equip and create positive attitudes, strong values, adequate knowledge, and instill skills to enable collaborative action for environmental sustainability by both individuals and communities (Ardoin et al., 2020).

This education way, the EE way, viewed as a scientific discipline, attempts an approach to the knowledge claims that are scientific in nature and their ways of production by identifying an object of study under EE-assigned study object of an environment. Being established as the integrated discipline that crosses all the traditional boundaries, it merges the natural and social sciences in full relevance with the role of environmental educators as intermediaries-that interpret and translate the results generated in the academy to the stakeholders and the public, thereby emphasizing the need for grounding their work with a solid research base (Fang et al., 2023). In that rubric of discipline, factors to socialize include the professionalization aspects of the discipline and study on its object; even though the characterization about the subject can also imply an extra limitation on the inter-disciplined nature of EE, pulling it more towards positive modes of difficult interpretation among other scientific communities.

Now, EE in an interdisciplinary and transformational knowledge area transcends simple transmission of ecological knowledge into an ethical, social, and political educational practice. From an educational perspective, it promotes learning processes that develop critical and socio-ecological competencies among learners (Shephard et al., 2019). In ethical terms, it aims to foster values and attitudes of care for the environment, incorporating sustainability as a moral principle into individual and collective decision-making (O'Flaherty & Liddy, 2018).

As a social dimension, EE promotes communal cultures of empathy and collaboration toward cultural change for sustainability. Lastly, politically, it is a domain for training environmental citizens and acting together on global issues while stimulating agency and critical thought as foundations for environmental justice (Georgiou et al., 2021).

Digital Technologies and EE

Numerous academic studies and empirical analyses by different researchers in the field of educational technology suggest that ICTs have a significant and transformative potential to enhance different pedagogical methodologies, facilitate deep and meaningful learning experiences for students, and strengthen awareness and understanding of environmental issues in a wide range of educational contexts and levels (Baena-Navarro et al., 2024; Fernández et al., 2019; Millward et al., 2024).

The role of digital technologies goes beyond an instrumental function, ICTs are emerging as mediators of transformative experiences that promote active, collaborative, and interdisciplinary learning (Fauville et al., 2014). Their incorporation has facilitated the connection between environmental theory and practice, allowing complex problems such as climate change or biodiversity loss to be addressed from more dynamic methodological frameworks (Ganguly, 2025).

Several studies reflect a consensus on the need to strengthen teacher training as a key condition for effective integration of ICT in EE (Åhlberg et al., 2001; Alvarez-García et al., 2018; Fisher & Binns, 2016; Paredes & Arruda, 2012). This training must go beyond the technical domain and incorporate critical approaches that articulate digital knowledge with eco-social competencies and contextualized pedagogical practices (Adu & Mireku, 2016; Fernández, 2020). Important methodological trends are also emerging. Among them are the use of virtual reality, gamification, artificial intelligence and interactive media as innovative resources to promote environmental awareness (Bohomazova, 2022; Ganguly, 2025).

However, it has been noted that the uncritical adoption of these technologies can render local practices invisible, reproduce digital divides, and promote decontextualized education if they are not integrated in a reflective and situated way (Fauville et al., 2014; Huang et al., 2017; Kumpulainen, 2022). It is important to recognize that this particular process is accompanied by challenges that may impede its proper development and diminish its impact. The academic literature reports structural barriers such as a lack of technological infrastructure, poor teacher training, and limited equitable access to digital resources (Nunes et al., 2024; Pino-Perdomo, 2023).

These conditions, which are particularly acute in rural or vulnerable contexts, call into question the democratizing potential of ICTs. In addition, there are pedagogical and epistemological concerns: there is a latent tension between the benefits of ICTs and their possible role in disconnecting students from nature (Jukes & Lynch, 2024; Lynch & Thomas, 2024; Millward et al., 2024), as well as their environmental impact (Zapico, 2012). This debate reveals a persistent duality about their role: are ICTs allies of sustainability or agents of eco-social fragmentation?

It also reveals divergent hypotheses that cut across the field. Some authors argue that ICTs can be catalysts for behavioral change and environmental awareness (García-Hernández et al., 2023; Sissa, 2012; Zhang et al., 2022), while others stress that their use without a critical pedagogical intentionality does not guarantee deep learning or ethical commitments (Brečka et al., 2022; Lowan-Trudeau, 2023). These contrasting positions reinforce the need for research that approaches ICTs from a relational ontology, considering their ethical, material and symbolic implications within a broad educational ecosystem (Kumpulainen, 2022; Zabala & Villalobos, 2010).

Teacher Education Within the ICT–EE nexus: Conceptual Articulation

Recent research places teacher education as the pivotal mediator that enables ICT to contribute meaningfully and sustainably to environmental teaching and learning. Large-scale studies show that teachers' self-efficacy for education for sustainability together with ICT competence predict their capacity to translate digital tools and knowledge into effective classroom practices (Ghazali et al., 2024). Therefore, teacher education should target not only technical competences but also pedagogical confidence and contextualization skills that allow educators to adapt sustainability content to diverse settings (Ibourk et al., 2025).

Conceptually, productive articulation emerges from integrating pedagogical, technological and disciplinary dimensions–for example through participatory curriculum design and adapted TPACK approaches for EE. Participatory curriculum interventions have produced institutional curriculum changes that embed sustainability across teacher education programs when ICT is strategically used (Makrakis & Kostoulas-Makrakis, 2023). Mentoring and "mirrored practice" models further enable transfer of effective technological uses into classrooms by allowing trainee teachers to observe and replicate context-sensitive practices modeled by teacher educators (Vandeyar & Adegoke, 2024).

Methodologically, the evidence supports incorporating hands-on experiences (low-cost environmental sensors, geo-mobile projects, digital storytelling, and instructional kits) in teacher preparation because such activities develop both environmental and digital literacies and support situated, evidence-based learning (Pino et al., 2025). In short, to strengthen the theoretical framing of the ICT–EE nexus, teacher education should be conceived as continuous, context-sensitive, and multifaceted–combining

(a) TPACK development and self-efficacy building,

(b) participatory and mentored professional learning, and

(c) practice-based, place-based digital experiences–so that technology mediates EE critically and transformatively (Ghazali et al., 2024; Makrakis & Kostoulas-Makrakis, 2023; Pino et al., 2025; Vandeyar & Adegoke, 2024).

In this line, the present study aims to answer the following problem questions, constructed from the relational category of EE and ICT:

1. What is the current relationship between digital technologies and EE, mainly in relation to teachers in different educational contexts?

2. What are the main structural, pedagogical, and epistemological challenges that limit the meaningful and sustainable integration of ICTs in EE, particularly in teacher training?

3. What research trends are emerging around the ICT-EE nexus in current studies?

The main objective of this research is to provide a critical and comparative synthesis of the state of the art on the relationship between ICT and EE, emphasizing the role of teacher education and training as a key condition for effective and sustainable pedagogical integration. Among the main conclusions are the need to strengthen teacher training in digital and eco-social competences and the importance of articulating technological innovation with local contexts, territories and knowledge. This integrative and situated approach aims to contribute to the design of sustainable, ethically committed and technologically relevant educational ecosystems.

Finally, briefly mention the main aim of the work and highlight the principal conclusions. As far as possible, please keep the introduction comprehensible to scientists outside your particular field of research.

METHODOLOGY

Methodologically, the research was developed under the qualitative approach, characterized by the understanding of the phenomenon (Hernandez-Sampieri & Mendoza, 2018) from the specific case study (Creswell & Creswell, 2018). The method used was a systematic review based on the preferred reporting items for systematic reviews and meta-analyses (PRISMA) model (Page et al., 2021).

A thorough and methodical review of the existing literature was conducted, and the resulting report of this systematic review was organized according to established protocols outlined in the PRISMA, which articulates the critical components necessary to achieve transparency and accuracy in literature reviews. This adherence to established guidelines enhances the credibility of findings and facilitates reproducibility. In summary, this comprehensive review represents a significant contribution to the existing literature and provides a solid framework for future research. The meticulous attention to detail and systematic rigor employed in this study underscore its value to the academic community.

Chronology

The search was conducted between 2001 and 2024.

Search Strategy

The Scopus database was used to search, given its relevance and high scholarly impact. There was no discrimination in terms of language or geographical area. The following search criteria (TITLE-ABS-KEY (ict) AND TITLE-ABS-KEY ("ENVIRONMENTAL EDUCATION")) were used to include the title of the article, the abstract and the keywords (TITLE-ABS-KEY). It was also filtered by document type, defined as articles published in journals, conference proceedings and systematic reviews ((LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "re"))).

From the selected documents, an analysis of the articles was made considering the relationship between the use of digital technologies and EE. From the selected documents, each document was hermeneutically categorized based on the defined category "relationship between ICT and EE" in order to obtain the emerging categories. From the documents that fit the category, the gap analysis of the proposed research and future research was analyzed.

Inclusion and Exclusion Criteria

Documents related to the search terms were retrieved, books and book chapters were excluded and academic articles, proceedings and systematic reviews were included. Full texts were screened and reviewed for inclusion/exclusion by the two authors. Before the formal sifting began, an initial calibration phase using an amount equal to 10% of all the absorbed items was conducted in order to refine the inclusion and exclusion criteria and establish mutual understanding in the analytical categories. During the selection process, each reviewer independently evaluated each item and assigned them into categories: inclusion, exclusion, or uncertainty. Discrepancies were discussed until consensus was reached. During the data extraction and interpretive coding phase, both evaluators carefully scrutinized the documents that had been classified under the broad theme "the relationship between ICT and EE." From this coding, additional theoretical subcategories emerged that were later validated through consensus. The measures of reliability between the evaluators have been instituted in order to ensure methodological integrity using Cohen coefficient (α) during the filtering and selection phases. The initial reviewer called for inclusion of 32 papers after reviewing the 55 documents, while the latter reviewer argued for 36, and the evaluators eventually came to a consensus on 33 cases. The kappa (α) correlated Cohen reflected a reliability coefficient value found to be equal to 0.85 for the evaluators whereby it affirms a typically high level of agreement between the reviewers. This substantial agreement clearly underlines the strength and consistency in applying the pre-established inclusion and exclusion criteria contained in the study. The methodology adopted is to enhance replicability as well as methodological rigor. See **Figure 1** for the PRISMA flow chart.

Hermeneutical Analysis

Hermeneutical analysis was performed using a qualitative analysis matrix developed in Microsoft Excel to methodologically structure and elaborate significances and themes emerging from the chosen studies. The analytical process was arranged in three successive phases of coding, which have been open, axial, and selective-conforming to the guidelines of the interpretative hermeneutical method and thematic analysis procedures prescribed by Creswell and Creswell (2018) and Hernandez-Sampieri and Mendoza (2018).

Open coding

Each document was repeatedly examined during this first stage. In Excel chart form, the units of meaning relevant under the primary category of "relationship between ICT and EE-off" were documented accordingly. Every cell contained the relevant extracts of the cell or quotes, supplemented with analytic annotations and keywords. Preliminary codes came out from this scrutiny.

Axial coding

During this stage, initial codes were merged and reordered in order to unveil patterns, interconnections, and conceptual alignments. Sub-syphons that ultimately resulted from this comparison generated a reflection of the linkage. This made for easy aggregation and conceptual coherence.
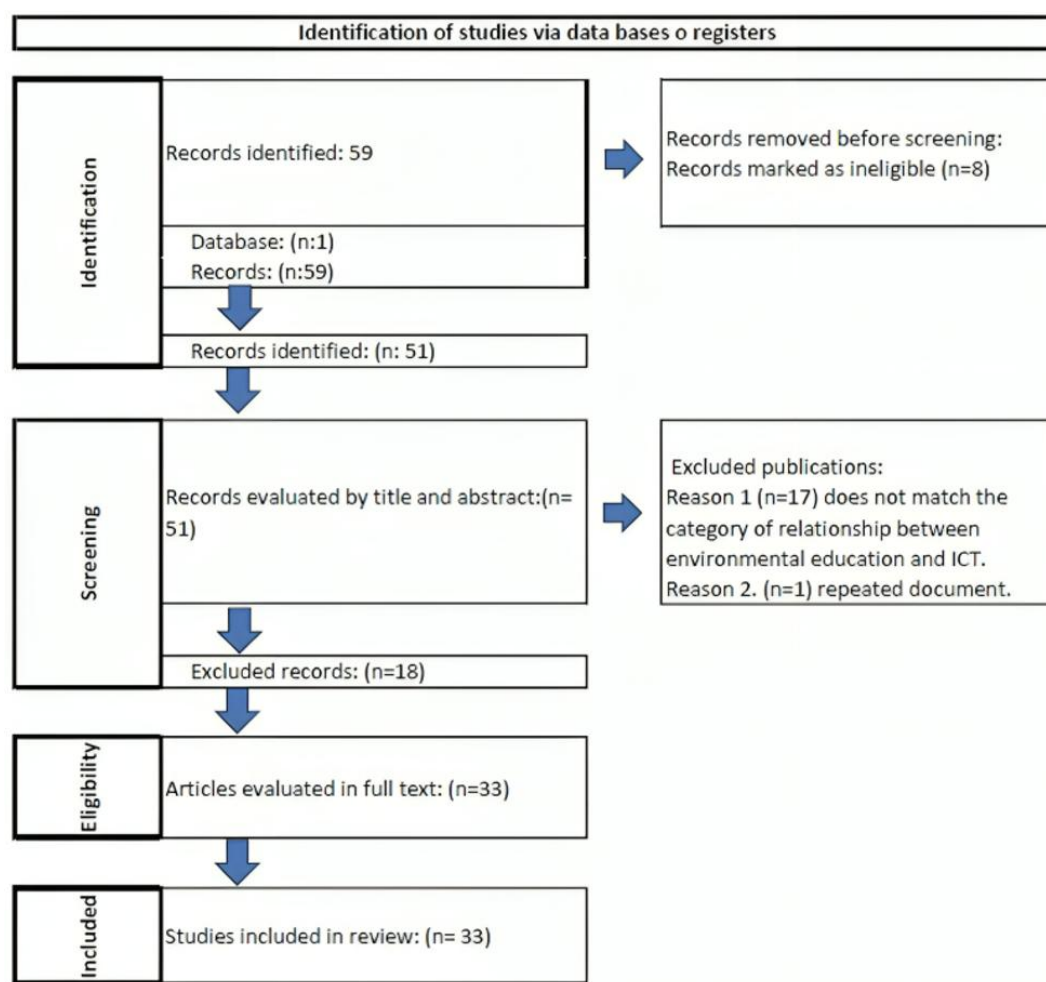
Figure 1. PRISMA framework (adapted from the PRISMA 2020 statement [Page et al., 2021])

Selective coding and interpretation

In the last stage, subcategories were incorporated into major interpretive themes explicating the interface between ICTs and EE. This step included a full-blown hermeneutic interpretation of the texts for understanding implied significations, epistemic frames, and educational orientations inherent in the scrutinized studies. Then came the mappleton results in an Excel file that facilitated the visualization of the hierarchy of codes and subcategories.

Support software

The quantitative data processing was programed essentially by using Microsoft Excel. Since data needed to be organized, references for quotes documented, codes allocated, and for defining underlying themes, Microsoft Excel was very helpful. While not a tool that could be noted as specialized for qualitative data analysis, it greatly assisted in enabling the process to maintain visualized traceability and transparency in the coding process as well as cross-review between evaluators via version control.

Saturation criteria

Hermeneutic saturation occurred when all analyses did not emerge any new codes and conceptually-significant sub-categories, while the topics established remained interpretatively stable. Saturation was thus confirmed by the theoretical principle of redundancy (Creswell & Creswell, 2018), involving the point where the last article did not provide appreciable new information. This was realized only after a careful review of the documents, securing instances of the consistency and theoretical density of emergent categories.

Interpretative synthesis

As a result of the hermeneutic process, articulative theoretical categories emerged that elucidated the interplay between educational digitalization and EE from pedagogical, technological, and ecological perspectives. These segments provided the point of reference for considering existing gaps and searching for new directions for research in order to obtain an in-depth view of the phenomenon under investigation.

Table 1. Related articles of the relationship between ICT and EE in the literature reviewed

Question	ICT-EE sub-category	Related authors codified
What is the current relationship between digital technologies and EE, mainly in relation to teachers in different educational contexts?	Teacher training	A3, A4, A7, A11, A15, A16, A17, A19, A20, A22, A23, A24, A26, & A32
	Strengthening environmental and digital literacy	A2, A8, A10, A13, A15, A23, A26, A27, A29, & A31
	Design of innovative ICT-based didactic proposals	A3, A5, A7, A11, A15, A21, A23, A25, & A26
	ICT as a promoter of critical thinking and environmental awareness	A1, A4, A6, A15, A18, A19, A23, & A33
	ICT as a tool for participation, collaboration and empowerment	A4, A9, A12, A14, A23, A24, A28, & A33
	Conditions, limitations and challenges for its implementation	A17, A20, A21, A22, A30, A31, & A32
	EE impact assessment and analysis tools	A10, A15, A20, & A29

RESULTS

Documents related to the search terms were retrieved, books and book chapters were excluded, and academic articles, proceedings and systematic reviews were included. Full texts were screened and reviewed for inclusion/exclusion by the two authors. See **Figure 1** for the PRISMA flow chart.

Based on the results, a hermeneutic analysis of 33 categorized documents was performed (See **Table A1** and **Table A2** in **Appendix**).

Qualitative Analysis of the Relationship Between ICT and EE in the in the Reviewed Literature (Research Question 1)

This section addresses research question 1: What is the current relationship between digital technologies and EE, mainly concerning teachers across educational contexts?

Table 1 shows the related articles of the relationship between ICT and EE in the literature reviewed.

Teacher training

A specific category that runs through most of the analyses relates to teacher training in digital and environmental literacy, a sine qua non for effective pedagogical integration of ICT. Millward et al. (2024) mention the importance of improving teacher training in outdoor digital tools. Zuhriyah (2023) suggests training teachers to strengthen critical thinking from an environmental perspective. Ayerbe-López and Perales-Palacios (2023) mention the need for teacher training in sustainable strategies through ICT. Álvarez-Herrero and Hernández (2021) emphasize the implementation of training programs in educational technology. Díaz et al. (2020) highlight the weakness of teachers in interdisciplinary pedagogical practices.

Fernández (2020) argues that the emergence of ICT requires changes in teaching practices, making them an essential mediating agent in teaching and learning processes. Miyaji and Fukui (2020) showed that technology-mediated EE lessons significantly increased the confidence and desire of trainee teachers to participate in and teach EE classes. Paredes-Labra et al. (2018) argue that there is an urgent need to prepare teachers to promote ecological critical thinking from ICT. Midoro (2017) argues that teacher training should accompany any digital policy. Ugolini et al. (2016) analyze the level of digital literacy as a determinant of success. Gutiérrez-Perez and Perales (2014) propose an approach based on the professional development of teachers. Fauville et al. (2014) show that the implementation of ICT in EE is hampered by insufficient professional training of teachers in technology and computer skills. Zoakou et al. (2007) point out that teacher training is key in contexts with limited infrastructure. Leppisaari and Lee (2012) insist on collaborative models of teacher training. These studies highlight the need for comprehensive training that not only addresses digital literacy but also fosters a critical and collaborative approach to the educational process.

Strengthening environmental and digital literacy

ICTs make it possible to address digital literacy and EE simultaneously. Martini et al. (2024) point out that they promote digital and socio-emotional skills. Ricoy and Sánchez-Martínez (2022) point out that they develop eco-social and digital competences. Santos and Ortenzi (2021) emphasize the need to develop multimodal communicative competence that involves visual, gestural, auditory, and spatial dimensions. Díaz et al. (2020) mention that they promote critical ecological and technological education. El Batri et al. (2022) point out that virtual platforms support environmental research processes. Davies et al. (2012) link educational video games to the development of scientific skills. Ojeda et al. (2012) emphasize that digital literacy enables a better reading of the environment, and the proliferation of virtual tools such as the Web and interactive programs serves to promote ecological awareness and environmental literacy among citizens. Obara et al. (2009) point out that the use of the Internet promotes a critical interpretation of the natural environment. Fauville et al. (2014) highlight the transversality of learning when ICTs are used in EE. These studies highlight the importance of integrating ICTs in EE, as

they not only enrich learning, but also promote greater ecological awareness among students.

Design of innovative ICT-based didactic proposals

Several studies highlight the use of ICT as a tool for designing active, creative and contextualized didactic proposals. Millward et al. (2024) explore the integration of mobile applications in outdoor activities. Pol et al. (2023) promote contextualized pedagogical proposals that link global issues and local experiences. Ayerbe-López and Perales-Palacios (2023) show that ICTs enable contextualized strategies in sustainability. Álvarez-Herrero and Hernández, (2021) analyze their integration from STEM approaches. Díaz et al. (2020) state that ICTs expand interdisciplinary teaching strategies. Sangiorgio et al. (2017) highlight the link between formal and informal learning spaces. Leppisaari and Lee (2012) advocate collaborative and inclusive ICT-based models. Pontes-Pedrajas and Varo-Martínez (2014) value their application in meaningful educational practices and environmental modeling. Fauville et al. (2014) show that ICTs offer sustainable alternatives to field trips or practical experiments, which are often limited by budget, time, or safety concerns.

ICT as a promoter of critical thinking and environmental awareness

The ability of ICTs to stimulate critical thinking and strengthen environmental awareness is one of the most consistent axes in the research analyzed. Tsakakis et al. (2024) highlight how digital resources make it possible to work on the SDGs through active methodologies. Zuhriyah (2023) emphasizes the importance of ICTs in strengthening critical thinking. Álvarez-Herrero (2023) points out that these technologies help students analyze their reality and propose sustainable alternatives. Díaz et al. (2020) show that they promote a reflective interpretation of the environment. Paredes-Labra et al. (2018) mention how they promote a critical attitude towards environmental issues. Thysiadou et al. (2019) highlight their use to develop ecological awareness from digital literacy. Fauville et al. (2014) found that ICT has the potential to support problem-based, action-oriented, and critical thinking instructional practices. Vrasidas et al. (2007) consider that they allow for the contextualization and critical meaning of environmental knowledge.

ICT as a tool for participation, collaboration, and empowerment

Several research studies address how ICTs foster participation, collaborative, and empowering environments in EE. Bilbao-Aiastu and Miranda-Urquij (2022) explain that they facilitate collective work at local and global levels. Zuhriyah (2023) highlights their role in group learning dynamics. Picanço et al. (2021) emphasize

their ability to consolidate collective ecological thinking. Khurvalieva (2020) showed that the use of ICT makes the educational process more attractive and modern, sparking involuntary interest and activating attention. Roy et al. (2012) mention that they motivate environmental action.

Gutiérrez-Perez and Perales, (2014) point out that digital environments strengthen dialog and participation. Vrasidas et al. (2007) point out that they enable the creation of critical learning communities.

Conditions, limitations and challenges for its implementation

Several authors identify challenges in the integration of ICT in EE. Miyaji and Fukui (2020) warn that without a pedagogical approach, video games lose their educational effectiveness. Ugolini et al. (2016) emphasize the role of institutional infrastructure. Midoro (2017) raises the need for articulated policies. Zoakou et al. (2007) highlight the technological gap as a constraint. Obara et al. (2009) point out that the lack of digital teacher training can hinder its use. Sangiorgio et al. (2017) emphasize the uneven availability of resources. Papastergiou et al. (2011) warn of instrumental biases in use. These challenges require a multidimensional approach that includes continuous teacher training, the development of inclusive policies, and adequate investment in technological infrastructure to ensure that ICTs are effectively integrated into educational processes.

Environmental education impact assessment and analysis tools

ICTs are also being used as a means of evaluation of formative processes in EE. Davies et al. (2012) suggest their use in measuring learning through video games. El Batri et al. (2022) highlight their usefulness in analyzing school research data on the environment. Midoro (2017) suggests that their impact should be assessed from a holistic perspective. Díaz et al. (2020)suggest that digital tools can measure students' level of environmental awareness.

Qualitative Analysis of Research Gaps in the Articles Linking ICT and EE in the Literature Review (Research Question 2)

This section responds to research question 2: What are the main structural, pedagogical, and epistemological challenges limiting the meaningful and sustainable integration of ICT in EE, particularly in teacher training?

26 of the 33 articles have research gaps, grouped in trends from largest to smallest (**Table 2**).

Table 2. Related articles of the research gaps

Question	Sub-category	Related authors
What are the main structural, pedagogical, and epistemological challenges that limit the meaningful and sustainable integration of ICTs in EE, particularly in teacher training?	Lack of studies that focus on teacher training and its connection to the use of technology.	A4, A7, A15, A16, A19, A23, A28, & A29
	Lack of research with large samples, diverse and generalizable contexts.	A3, A8, A9, A10, A11, & A30
	Technical and methodological limitations in research designs.	A3, A10, A17, A25, & A30
	Weak theoretical or pedagogical foundations for digital proposals.	A5, A23, A27, & A33
	Few evaluations of impact and long-term outcomes.	A1, A14, A23, & A24
	Little attention to interactivity and active student participation.	A20 & A26
	Difficulties in effectively integrating technology into the curriculum.	A12 & A13

Lack of studies that focus on teacher training and its connection to the use of technology

Several studies agree that there is still a lack of research on the role of teachers in training in the pedagogical use of technologies, especially in the context of science and EE. This gap is manifested both in the lack of digital skills and insufficient preparation to integrate didactic strategies with a critical and contextualized sense (Fauville et al., 2014; Paredes-Labra et al., 2018; Roy et al., 2012; Zuhriyah, 2023). Some studies mention the scarce practical experience of future teachers in the use of digital tools in their formative processes (Díaz et al., 2020), as well as the need to deepen the relationship between teaching practices and technologies (Ayerbe-López & Perales-Palacios, 2023). Likewise, the lack of integration between digital content and pedagogical competencies to develop meaningful didactic proposals is highlighted (Davies et al., 2012; Fernández, 2020).

Lack of research with large samples, diverse, and generalizable contexts

A recurring trend in the studies reviewed is the limited size and diversity of the samples examined. Many studies focused on specific experiences, case studies, or very limited contexts, which makes it difficult to generalize the results to other educational settings. This limitation is evident, for example, in studies that mention the use of a single institution as a data source, which reduces the ability to extrapolate findings (Álvarez-Herrero & Hernández, 2021; Bilbao-Aiastu & Miranda-Urquij, 2022; Obara et al., 2009; Ricoy & Sánchez-Martínez, 2022). In addition, other investigations have pointed out the lack of comparison between groups or the lack of controlled conditions as an obstacle to validate their results (El Batri et al., 2022; Papastergiou et al., 2011). It is even reported that the studies were developed in short periods of time without sufficient temporal continuity (Millward et al., 2024). These gaps highlight the urgency of designing longitudinal and comparative research that allows for a more robust and transferable understanding of technology-mediated educational processes.

Technical and methodological limitations in research designs

Several authors point out methodological weaknesses in research design. These include lack of data triangulation, reliance on quantitative methods without complementary qualitative analysis, or lack of control groups (El Batri et al., 2022; Miyaji & Fukui, 2020; Papastergiou et al., 2011). These limitations affect the validity and reliability of the results. Similarly, it is noted that some experiences do not have a systematic structure that allows them to be replicated in other contexts (Millward et al., 2024; Pontes-Pedrajas & Varo-Martínez, 2014).

Weak theoretical or pedagogical foundations for digital proposals

Another emerging pattern pertains to the theoretical fragility of numerous educational proposals that incorporate technologies. Despite the integration of digital resources and interactive platforms, these are not consistently supported by robust pedagogical frameworks that provide guidance for their implementation (Pol et al., 2023; Pontes-Pedrajas & Varo-Martínez, 2014). Research indicates that the educational principles underpinning the design of digital tools (Ojeda et al., 2012) and the specific guidelines for their use in the classroom are not thoroughly delineated (Vrasidas et al., 2007). This absence hinders the establishment of reflective and well-founded practices, underscoring the necessity for proposals that delineate technology, didactics, and context.

Few evaluations of impact and long-term outcomes

Another important gap is the lack of studies that evaluate the medium- and long-term impact of educational technology interventions. Some studies point out that although innovative experiences have been designed, no systematic follow-up has been carried out to evaluate their effectiveness in developing competencies (Gutiérrez-Perez & Perales, 2014; Khurvalieva, 2020). This lack of evidence also makes it difficult to justify investments in educational

Table 3. Related articles of future research

Question	Sub-category	Related authors
What research trends are emerging around the ICT-EE nexus in current studies?	Expand the diversity of contexts, samples, and replication of studies	A6, A9, A10, A15, A27, & A29
	Deepen the design, evaluation, and optimization of virtual learning environments.	A3, A11, A20, A26, & A30
	Explore the impact and effectiveness of technology-enhanced active methodologies	A4, A5, A8, A19, & A23
	Integrate environmental and science education into digital environments	A1, A21, A24, &A25
	Promote studies that focus on teacher training in the use of technology	A2, A7, A12, & A14
	Investigate the emotional, motivational and social dimensions of e-learning.	A4, A13, & A16
	Develop new metrics and evaluation tools adapted to the digital environment	A5, A28, & A29

technologies or their sustainability in teaching processes (Fauville et al., 2014). In the same way, it is pointed out that many investigations lack solid conclusions that allow understanding of the real impact of the implemented tools (Tsakakis et al., 2024).

Little attention to interactivity and active student participation

Some studies highlight the need to strengthen the participatory and interactive dimension of digital educational proposals. It is observed that many interventions still reproduce transmissive models in digital environments, without exploiting the potential of the medium to promote active learning, exploration or autonomy (Leppisaari & Lee, 2012). In other cases, it is evident that the digital tools used do not favor student protagonism in the learning process (Midoro, 2017), which limits their meaningful appropriation.

Difficulties in effectively integrating technology into the curriculum

The gap between the potential of technology and its effective integration into the school curriculum is highlighted by some authors. They point to the need for more articulated planning between educational objectives, content and available technological resources (Picanço et al.., 2021; Santos & Ortenzi, 2021). Without this link, technologies run the risk of becoming ancillary or superficial elements, without really contributing to the transformation of pedagogical practices.

Qualitative Analysis of Future Research Identified in the Articles Related to ICT and EE in the Reviewed Literature (Research Question 3)

This section addresses research question 3: What research trends and future directions are currently emerging in studies connecting ICT and EE?

27 of the 33 articles show future research, grouped in trends from largest to smallest (**Table 3**).

Expand the diversity of contexts, samples, and replication of studies

Another notable trend in future research is the broadening of geographical, demographic and methodological contexts. The importance of replicating experiences at different educational levels, in rural areas and with more heterogeneous groups is recognized in order to strengthen the external validity of the results (Bilbao-Aiastu & Miranda-Urquij, 2022; Díaz et al., 2020). Some authors suggest extending the research to other formative stages and to different disciplinary areas, making it possible to validate more inclusive pedagogical approaches adapted to local realities (Álvarez-Herrero, 2023; El Batri et al., 2022). Likewise, comparative and longitudinal studies are proposed, as well as field experiments in different conditions (Davies et al., 2012; Ojeda et al., 2012).

Deepen the design, evaluation, and optimization of virtual learning environments

A dominant trend in research projections is the need to improve the design, implementation, and evaluation of virtual learning environments. Several studies call for the redesign of platforms or methodologies that allow for greater interaction, motivation, and accessibility for students (Álvarez-Herrero & Hernández, 2021). This need also points to the creation of innovative pedagogical solutions that consider both content and user experience (Leppisaari & Lee, 2012). The optimization of these environments is considered essential to ensure meaningful learning, especially in areas such as environmental or science education (Millward et al., 2024; Papastergiou et al., 2011). Proposals include improving the pedagogical, communicative and technological dimensions of instructional design, integrating new elements such as artificial intelligence, gamification or augmented reality (Midoro, 2017).

Explore the impact and effectiveness of technology-enhanced active methodologies

Several studies agree in proposing future research to analyze in depth the impact of active methodologies, such as project-based learning, collaborative learning or flipped classroom, mediated by digital resources. These methodologies need to be validated in terms of pedagogical effectiveness, level of appropriation and development of competencies (Paredes-Labra et al., 2018; Ricoy & Sánchez-Martínez, 2022). In addition, it is suggested to investigate how these strategies contribute to students' motivation, autonomy and creativity (Pol et al., 2023; Zuhriyah, 2023). The challenge is to empirically demonstrate the benefits that can be attributed to these proposals compared to traditional methods (Fauville et al., 2014).

Integrate environmental and science education into digital environments

A group of studies raises the urgency of developing research that articulates the processes of environmental and science education with the use of technologies. This approach aims not only to innovate resources and strategies, but also to build critical and transformative pedagogies from the digital (Gutiérrez-Perez & Perales, 2014). Future research could address how scientific and environmental literacies are developed through virtual environments and how they contribute to critical thinking, civic action and sustainability (Pontes-Pedrajas & Varo-Martínez, 2014; Tsakakis et al., 2024) It is also recommended to connect science education to local and community realities, taking advantage of the flexibility offered by digital tools (Sangiorgio et al., 2017).

Promote studies that focus on teacher training in the use of technology

Another priority for future research is teacher education and professional development in the pedagogical use of technology. Several authors highlight the need to investigate training programs that strengthen teachers' critical digital literacy and their ability to integrate technologies in a meaningful way (Khurvalieva, 2020; Picanço et al., 2021). It is proposed to study more contextualized training processes, with practical scenarios and focused on the design of ICT-mediated educational experiences (Ayerbe-López & Perales-Palacios, 2023). It is also suggested to move towards collaborative and interdisciplinary teacher training models that allow overcoming technocratic visions (Martini et al., 2024).

Investigate the emotional, motivational and social dimensions of e-learning

Some studies suggest that future research should consider the emotional and motivational dimension of learning in digital environments. It is suggested to study how technological resources affect students' self-esteem, interest in learning, construction of a sense of community, or active participation (Fernández, 2020; Santos & Ortenzi, 2021). This requires incorporating perspectives from educational psychology and the socio-affective approach, integrating qualitative and quantitative measurement tools (Zuhriyah, 2023).

Develop new metrics and evaluation tools adapted to the digital environment

Finally, some studies warn of the need to design and validate new assessment tools that respond to the specificities of the digital environment and the competencies developed there (Roy et al., 2012). Proposals include metrics to measure critical thinking, digital creativity, scientific literacy or online collaborative interaction (Pol et al., 2023). It is also proposed to simplify current tools to make them understandable, adaptable and useful for teachers in real contexts (Davies et al., 2012).

DISCUSSION

The aggregate exchanges made between the digital technologies and EE, especially on the pedagogical development of educators in different educational contexts, turn out to have a clear and summarizing correlation along with the complexities that enrich but darken the mainstream discourse with some findings of the literature. The information in both types of evidence makes teacher training emerge as the most crucial element in the blending of IT: computing with other technologies for education for sustainable development because it essentially facilitates the nurturing of digital and ecological literacy to significantly shift conventional paradigms of education (García-Hernández et al., 2023; Millward et al., 2024). Aligned with the propositions brought forth by Husamah et al. (2025) the findings underscore the need for continuous professional development of the educators to bridge any remaining gaps between technology and sustainability. All training transgresses competence onto critical, ethical, and socioenvironmental dimensions, thus making it possible considering the application of technology in social and environmental contexts (Husamah et al., 2025; Zuhriyah, 2023). However, findings give a broader and nuanced perspective than the available literature on the subject highlighting the notion that reflective inclination and the ethical conscience of educators act as critical mediators in pedagogy methodologies for environmental digital approaches (Ayerbe-López & Perales-Palacios, 2023; Hernández Fernández, 2020). The dominant academic discourse requires evaluating and enhancing the digital and ethical competencies of teachers (Husamah et al., 2025; Millward et al., 2024), yet findings of this study indicate that such enhancement mainly occurs in collaborative practice environments where ICT creates

space for engagement, critical analysis, and transformative initiatives (Bilbao-Aiastu & Miranda-Urquij, 2022; Vrasidas et al., 2007). In addition, results uniquely illustrate that even above viewing inventions as mere instrumental tools, inventions act as cultural intermediaries forming eco-learning communities and, thus, energizing the educators' commitment to sustainability (Gutiérrez-Pérez & Perales, 2014; Picanço et al., 2021). Contrary to the current mainstream academic discourse that underscores the hegemony of ethics, the dangers of technosolutionism, and fragmentation of competencies (Husamah et al., 2025), the findings of this review assert that such hurdles can be recontextualized into the opportunity to cultivate a reflexive, contextual-responsive pedagogy, especially when the latter involves the use of ICT in critical and collaborative educational frameworks (Fauville et al., 2014; Ojeda et al., 2012). However, some contradictions do arise, as do some unexpected results: inadequate technological infrastructure has, until now, precluded widespread use of ICT (Ugolini et al., 2016; Zoakou et al., 2007); however, it has recently been suggested that innovative teaching strategies and novel design ideas are able in a minor way to alleviate these access restrictions through inexpensive or collaborative resources (Millward et al., 2024; Pol et al., 2023).

The findings of the investigation reveal that the critical interplay between ICT and EE is somehow blocked by interconnected structural, pedagogical, and epistemological issues. More specifically, the problems range from teacher training inadequacies and limited pedagogical approaches to technology; methodological and sampling restrictions that weaken existing evidence; theoretical and pedagogical shortcomings of many digital initiatives; lack of student agency, and structural inequalities that are active roadblocks towards sustainability and equity of programs (Fauville et al., 2014; García-Hernández et al., 2023, 2025; Husamah et al., 2025; Millward et al., 2024). In the comparative analysis, the results show a striking absence of research targeted to teacher education combining pedagogical skills with the technological ones (Díaz et al., 2020; Fauville et al., 2014; Paredes-Labra et al., 2018) alongside methodological weaknesses such as small sample sizes and insufficient triangulation (Álvarez-Herrero & Hernández, 2021; El Batri et al., 2022). A further recognition was the conception insufficiency concerning the pedagogical grounds for interventions digital (Pol et al., 2023; Vrasidas et al., 2007), together with very little use of the interactive possibilities to promote student participation (Leppisaari & Lee, 2012), and the impediments to a coherent integration of technology into the curriculum (Picanço et al., 2021). Existing literature speaks of so many surprising parallels: for both findings and the systematic reviews surveyed, teacher education and structural deficiencies were singled out as fundamental barriers to a sustainable integration of ICT

into EE, calling for collaboratively nurturing digital and sustainability competencies (García-Hernández et al., 2023; Husamah et al., 2025). Similarly, they warn against a lack of strong longitudinal studies and a leaning towards techno-solutionism, which promotes an instrumental adoption of technology divorced from any critical pedagogical framework and a transformation in the true sense of the word teaching methodologies (Husamah et al., 2025; Merritt et al., 2022). As for the divergences and unique contributions, our results (El Batri et al., 2022; Fauville et al., 2014; Pol et al., 2023) diverge from the existing literature by providing comprehensive empirical evidence about the identified methodological and pedagogical shortcomings in specific projects, whereas the cited literature (Hajj-Hassan et al., 2024; Husamah et al., 2025) has more of a normative and prospective voice targeting the creation of new immersive and ethical technologies for sustainability. The findings also set forth a particular emphasis on implementation-practical issues, while the literature mainly focuses on epistemological issues, such as surface cognitive outcomes stemming from uncritical ICT implementation (Hajj-Hassan et al., 2024; Merritt et al., 2022). Furthermore, there is a clear desynchronization of the reported findings and those analyzed in the literature given the former's focus on pedagogical-technical interaction, while latter tends to target environmentally sustainable practices pertaining to the digital devices themselves (García-Hernández et al., 2023; Hajj-Hassan et al., 2024). Among some contradictions or unwelcome outcomes, it appears that while some sources state that ICT may replace face-to-face practices as a means of broadening access to environmental learning opportunities (Fauville et al., 2014), environmental educators point out that immersive learning intents to recover the affective and experiential component of environmental learning into the picture, hence producing tension between the virtuality and the ecological connection (Hajj-Hassan et al., 2024; Merritt et al., 2022). While embracing the notion that VR/AR are strengthening ecological empathy (Hajj-Hassan et al., 2024), empirical results show insufficient robust evidence for the development of enduring impact on environmental comprehension or behavior (Gutiérrez-Pérez & Perales, 2014; Tsakakis et al., 2024). Finally, it became evident that although the ICTs have been conceived as little more than a means to empower the learner, many of their initiatives are still replicating old transmission models (Leppisaari & Lee, 2012; Midoro, 2017), contrary to the very expectation that they would promote self-sustained and critical forms of learning as posited in the current literature.

Emerging trends in research reveal extraordinary expansion of the realm of academia toward contextual diversification, enhancement of virtual settings, validation of active methodologies, curricular integration, and teacher development, which implies a

methodological and pedagogical advancement in the area of ICT-assisted EE. These trends evidence a shift from descriptive frameworks toward increasingly empirical ones that are collaborative and adapted to local contexts (Álvarez-Herrero, 2023; Ayerbe-López & Perales-Palacios, 2023; Bilbao-Aiastu & Miranda-Urquij, 2022). The findings stress, in contrast to the reference literature, a need for increased methodological rigor, longitudinal evaluation, and cognitive depth, which are further underscored by Husamah et al. (2025) and Merritt et al. (2022). Both refer to the sustainability of digital EE as being contingent on transcending techno-solutionism, deepening the ethical stance, and promoting transformational learning that exceeds shallow knowledge acquisition. With regard to the concordances, both the findings of this research and contemporary literature highlight an urgent need to bridge the affective and motivational dimensions into digital environments to produce meaningful learning experiences that foster ecological empathy and pro-environment behavior (Fernández, 2020; Hajj-Hassan et al., 2024). They also concur regarding the need for more emotionally engaging and interactive virtual spaces, incorporating tools such as gamification and simulation to facilitate participation and understanding of complex phenomena (García-Hernández et al., 2023; Leppisaari & Lee, 2012). In the same manner, studies on the one hand and the academic discourse on the other have emphasized the need for long-term evaluation of the technological interventions and the cultural contextualization of the digital content as vital elements for sustaining the relevance of digital EE (Husamah et al., 2025; Tsakakis et al., 2024). However, the distinctive contributions of the new findings lie in an emphasis on methodological and contextual diversification. While the key references focus on immersive technologies (VR/AR) and their emotional and behavioral impacts (Hajj-Hassan et al., 2024; Husamah et al., 2025), the current findings widen the horizon toward educational inclusion strategies, professional development of educators, and adaptive evaluation, proposing much wider research contexts incorporating different educational levels, disciplines, and geographical settings (Ayy Erbe-López & Perales-Palacios, 2023; Díaz et al., 2020; Paredes-Labra et al., 2018). Contrary to the technocentric approach promoted in the earlier reviews, these research findings centralize a pedagogical and formative slant, wherein technology is seen as an instrument toward an end that is the promotion of active methodologies and collaborative learning rather than an end itself (Pol et al., 2023; Ricoy & Sánchez-Martínez, 2022). Among the disagreements and unexpected results, one stands out: although the latest literature praises immersive technologies as catalysts for ecological empathy, the findings from this investigation suggest that appropriate evidence is lacking for their sustained effectiveness in fostering environmental

competencies and behavioral change (Papastergiou et al., 2011; Tsakakis et al., 2024). At the same time, while the academic literature attributes deeper learning with the use of VR and AR, the current empirical trend is more pragmatic in character-refocusing effort towards improving accessibility, motivation, and pedagogical design of the conventional virtual environment before scaling up to more complex technologies (Álvarez-Herrero & Hernández, 2021; Midoro, 2017). This dissonance indicates that the field is still undergoing a phase of methodological consolidation prior to the widespread deployment of immersive tools.

CONCLUSIONS

Thus, the findings generated from this research complement and corroborate the prevailing academic discourse, showing that the technology coupling with EE will change from the former instrumental view toward a more transformative view. The newer empirical research depicts educators as not just using these technologies, but also critically, collaboratively, and ethically responsible agents remaking environmental learning from the points of view of sustainability and social activism. Within this context, ICTs are saluted not only as instruments for advancing education but also as essential pieces of groundwork for nurturing a digital ecological pedagogy to tie together knowledge, awareness, and engagement within teacher training frameworks.

In all, a critical examination into these findings shows that the identified limitations are empirical confirmations of the theoretical challenges articulated in literature. These reasons explain why much touted benefits of innovation in technology in EE remain untransformed into sustainable change; framed generic pedagogy, inadequate teacher training, and poorly designed impact assessment matters. In other words, the territory needs empirical longitudinal studies that are more rigorous, teacher training initiatives that address ethics, sustainability, and critical pedagogy, and policies to boost equity and environmental accountability in ICT deployment.

The findings of this study pad confirm and enrich those emerging strands in global literature: there is a convergence around the search for more significant learning experiences under stricter assessments and more ethical-contextual methodologies. The new thinking, however, carries a more pedagogical, inclusive, developmental approach toward improving the quality of applied research, teacher training, and contextual integration of technology into EE. Thus, the domain goes from simple fascination with technology to a more critically and contextually aware understanding of its role in education transformation and societal and environmental issues.

Recommendations

Pedagogic recommendations

Findings indicate that educational practices in EE through ICT should be directed towards a critical, contextualized, and transformational integration of technological tools. It would be appropriate to promote digital pedagogical and eco-social competences enabling educators to use technology tools and active pedagogies such as problem-based learning, urban explorations, or immersive experiences that tie knowledge with environmental initiatives. Teacher training programs would have to set conditions for self-reflection regarding ecological and ethical implications of ICT uses, arguing for critical and contextually situated pedagogy reinforcing environmental awareness and student participation in local and global sustainability efforts.

Structural or policy recommendations

At the institutional and public policies level, the research emphasizes establishing continuing teacher education that fuses digital literacy with critical environmental perspectives. Urgently, the need was indicated to upgrade the existing technology infrastructure and ensure equitable access to devices, connectivity, and digital resources and develop materials in harmony with the sociocultural and environmental contexts of educational communities. Education policies must, however, facilitate ongoing technical and pedagogical assistance, encourage collaborative spaces of teachers, and foster an institutional culture of valuing innovation and ethical application of technologies for sustainability.

Research-oriented recommendations

Findings underline the necessity of conducting research to broaden understanding on the relationship between ICT and EE, overcoming existing methodological gaps. Longitudinal studies with much broader and more diverse samples should also be carried out to assess the real impact of active digital pedagogies. Future research should explore the teaching preparation regarding the pedagogical use of technology; assimilation of environmental and scientific education in digital contexts; and emotional and motivational factors of learning in technological surroundings. Moreover, collaborative and interdisciplinary frameworks for teacher training should be investigated and validation through empirical evidence sought for strategies such as gamification, augmented reality, or collaborative digital learning.

Limitations

The study admits to having its principal limitation by relying entirely on the Scopus database, possibly excluding potentially important literature published in alternative academic sources or in less represented languages. Additionally, the search methodology, which focused on the terms "ICT" and "EE" exclusively within the titles, abstracts, and keywords, may have overlooked relevant research that employed different terminologies or interdisciplinary methodologies. Such limitations justify the prudence in generalizing findings and strengthen the need for further systematic reviews that broaden the parameters of search and databases used.

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APPENDIX A

Table A1. Articles analyzed

Reference	Publication name	Country	Educational level	Study design	Code
Tsakakis et al. (2024)	Opportunities and challenges in advanced communication technologies in the environment: A case of forest management communications	Ontario, Canada	K-12 (elementary and secondary education)	Mixed-methods approach. Descriptive correlational analysis (Chi-square test, Pearson correlation, Mantel-Haenszel correlation).	A1
Martini et al. (2024)	Scenarios and narratives of ICT and environmental education: A pilot study on nursery school teacher's perspectives	Salónica, Greece	Early childhood education (nursery school teachers)	Pilot study/descriptive survey (quantitative analysis of teacher perspectives or opinions on ICT use in EE)	A2
Millward et al. (2024)	Technology and K-12 environmental education in Ontario, Canada: Teacher perceptions and recommendations	Ontario, Canada	K-12 (primary and secondary education)	Mixed-methods design. Descriptive correlational analysis (Chi-square, Pearson correlation, Mantel-Haenszel correlation).	A3
Zuhriyah (2023)	The role of smart education (SE) in supporting digital eco-literacy (DEL)	Indonesia (implied / conceptual context)	Not specified (conceptual/framework)	Conceptual framework/review	A4
Pol et al. (2023)	Communication, socialization, and ITC. The psychosocial construction of sustainability	Spain (Barcelona)	Elementary, secondary, and university students (9-35 years old)	Review/meta-analysis. Longitudinal study (three waves: 2007, 2014, 2023). Content analysis (news) and analysis of variance.	A5
Álvarez-Herrero (2023)	Urban itineraries with smartphones to promote an improvement in environmental awareness among secondary school students	Spain (Alcoy)	High school students	Study based on the collection of data from an evaluation by means of a questionnaire.	A6
Ayerbe-López and Perales-Palacios (2023)	Evaluating a secondary education urban ecology project within the framework of a problem-based learning methodology	Spain (Province of Granada)	Compulsory secondary education (grade 9 and grade 10)	Interpretative qualitative approach. Case study. Analysis by means of a researcher's diary, self-assessment questionnaires and rubrics, and SWOT analysis.	A7
Ricoy and Sánchez-Martínez (2022)	Raising ecological awareness and digital literacy in primary school children through gamification	Northwest Spain	Primary school (Third year, aged 8-9)	Qualitative research, broad case study design. Content analysis (deductive and intuitive).	A8
Bilbao-Aiastu and Miranda-Urquij (2022)	Development of natural science through the gamification and ICT in primary education	Spain (Bizkaia, Basque Country)	Primary education (6th grade)	Mixed methodology research design. Quasi-experimental (control group vs. experimental group with gamification/ICT). Mann Whitney U analysis, questionnaire and systematic observation.	A9
El Batri et al. (2022)	Teaching environmental themes within the scientific awakening course in Moroccan primary school: Approaches, methods and difficulties	Morocco (Fez-Meknes Region)	Primary school (Second cycle: 4th, 5th, and 6th year)	Correlational descriptive design. Stratified sampling. Use of a four-component questionnaire (Likert scale). Descriptive statistical analysis and correlations (Spearman's rho).	A10
Álvarez-Herrero and Hernández (2021)	Itinerarios didácticos con smartphones para promover la educación ambiental y la competencia digital entre el alumnado de secundaria [Educational itineraries with smartphones to promote environmental education and digital competence among secondary school students]	Spain (Alcoy, Alicante)	Secondary education (14 to 18 years old)	Quantitative (non-experimental, descriptive). Use of an ad hoc questionnaire (Likert scale). Complemented with scheduled interviews with teachers and students.	A11
Picanço et al. (2021)	Teachers' perspectives and practices on biodiversity web portals as an opportunity to reconnect education with nature	Portugal (Azores)	Public school teachers	Multimethod approach. Online survey with free word association tests. Prototypical and similarity analysis for social representations.	A12

Table A1 (Continued). Articles analyzed

Reference	Publication name	Country	Educational level	Study design	Code
Santos and Ortenzi (2021)	Social activity and learning de-encapsulation under a multimodal approach in English language teaching	Brazil (Londrina, PR)	Secondary education (9th year)	Qualitative research. Pedagogical intervention focused on multimodality. Use of "intention file" (questionnaire) and visual analysis of student productions.	A13
Khurvalieva (2020)	Technology for the formation of environmental concepts in senior preschoolers by computer	Not Specified (Inferred Eastern Europe/Asia)	Senior Preschoolers	Theoretical analysis and determination of methodological conditions.	A14
Díaz et al. (2020)	Alfabetización digital del profesorado de ciencias ambientales: Un análisis de su competencia tecnógica [Digital literacy of environmental science teachers: An analysis of their technological competence]	Spain (Province of Granada)	Secondary education (environmental science teachers)	Quantitative methodology. Descriptive study. Confirmatory factor analysis.	A15
Fernández (2020)	Relation of the ICT with neuroeducation, inclusion, pluriculturality and environmental education through a confirmatory factorial analysis study	Spain (University of Jaén, Andalusia)	University level (MSc. degree in teacher training)	Non-experimental, descriptive, explanatory and correlational. confirmatory factor analysis of an *ad hoc Likert scale*.	A16
Miyaji and Fukui (2020)	Change in knowledge and awareness in teacher education on Satoyama environmental learning: Through a blend of learning spaces, methods and media	Japan (Satoyama context, inferred)	Teacher education (training)	Quasi-experimental evaluation of blended learning. Uses pre-surveys and post-surveys (Wilcoxon signed-rank test).	A17
Thysiadou et al. (2019)	Integrated teaching for the chemistry subject water chemistry with the use of an educational site	European context (inferred by directives)	Higher or secondary education (water chemistry)	Comparative statistical evaluation/analysis of the use of an educational site. Use of paired sample t-test.	A18
Paredes-Labra et al. (2018)	Preparing public pedagogies with ICT: The case of pesticides and popular education in Brazil	Brazil	Popular education (non-formal)	Qualitative research. Content analysis (interview texts and transcripts) and triangulation of data and researchers.	A19
Midoro (2017)	How teachers and teacher training are changing	Europe (Italy, Finland, Netherlands, Portugal, UK)	Teacher training (in-service teachers and teacher training students)	Evaluation of an online course (EuMedea/MEDEA). Development of an *ad hoc methodology* for the validation of online courses.	A20
Sangiorgio et al. (2017)	An international online competition to stimulate student's interest on ecological issues	University of Salento, Lecce, Italy	Intermediate and high schools	Conceptual/descriptive. Describes the development of a *serious game* ("research game") and an international online competition (ENVRIplus project)	A21
Ugolini et al. (2016)	Environmental education by gaming	Toscana, Italia	Secondary school	A mixed, participatory approach that involves students, teachers, and experts in the learning process.	A22
Fauville et al. (2014)	ICT tools in environmental education: Reviewing two newcomers to schools	Global (review of studies)	Primary, secondary, and higher education (review)	Review and categorization of 16 studies.	A23
Gutiérrez-Perez and Perales (2014)	Sustainability culture and communication technologies: Possibilities for environmental educators	International (12 countries in the Americas and Europe)	Sustainability professionals or educators	Descriptive study by means of an *online* questionnaire (Likert and open questions). Non-statistically representative sampling, focused on trends.	A24
Pontes-Pedrajas and Varo-Martínez (2014)	Educative experience of the use of concept mapping in science and environmental teacher training programmes	Spain (University of Cordoba)	University level (MSc. degree in EE and teacher training)	Educational experience/evaluation. Analysis of quantitative (t-student test) and qualitative (open questionnaire) data.	A25
Leppisaari and Lee (2012)	Modelling digital natives' international collaboration: Finnish-Korean experiences of environmental education	Korea and Finland	School students (elementary or secondary inferred)	Descriptive study of international online collaboration platform (Edu2.0).	A26

Table A1 (Continued). Articles analyzed

Reference	Publication name	Country	Educational level	Study design	Code
Ojeda et al. (2012)	Evaluación de la calidad de webs y blogs sobre educación ecológica [Evaluation of the quality of websites and blogs about ecological education]	Spanish-speaking or international (12 Ibero-American countries)	Environmental professionals or educators (formal and non-formal)	Qualitative and quantitative evaluative study. Delphi procedure for consulting experts. Factor and cluster analysis.	A27
Roy et al. (2012)	Promoting education for sustainable development by using ICT enhanced problem based learning in a developing country	Tanzania (Kauzeni Secondary School)	Secondary education (ages 10-21)	Design research. Quasi-experimental (PBL + video vs. traditional).	A28
Davies et al. (2012)	A matter of interpretation: Developing primary pupils' enquiry skills using position-linked datalogging	UK (inferred, England national curriculum)	Primary school	Longitudinal evaluation. Mixed methods (questionnaires, student evaluations, interviews, observation) with triangulation.	A29
Papastergiou et al. (2011)	Effects of student participation in an online learning community on environmental education: A Greek case study	Greece	Secondary education	Evaluation of an Online Learning Community (OLC). Quasi-experimental design (pre-/post-test). Use of a written questionnaire (CHEAKS knowledge subscale), with t-analysis of paired samples.	A30
Obara et al. (2009)	Environmental education in the upper Paraná River floodplain, municipality of Porto Rico (Paraná State), Brazil	Brazil (Porto Rico, Paraná State)	Elementary and middle/high school	Research-action methodology. Evaluation of a continuous education program.	A31
Zoakou et al. (2007)	A methodology for e-learning scenario development: The UNITE approach	European context (UNITE Project)	Teaching staff/various levels (UNITE school network)	Development of conceptual framework/methodology (UNITE approach). Creation of scenario templates (hybrid between narrative and structured tabular format).	A32
Vrasidas et al. (2007)	ICT as a tool for environmental education, peace, and reconciliation	Cyprus	Not specified (focus on primary or community interaction)	Descriptive project framework and conceptual analysis.	A33

Table A2. Synthesis of findings

Reference	Code	Synthesis of findings
Tsakakis et al. (2024)	A1	- The research emphasizes that the advanced ICT have the possibility to significantly enhance the applied communications and education on natural resources, especially in the environmental education settings, thus indicating a favorable connection between the ICT and the environmental education teaching. - It points out that the immersive technologies, such as augmented reality (AR) and virtual reality (VR), are capable of giving rise to greater student involvement and better understanding of the subject matter as compared to the traditional methods, thus suggesting that the technology can enhance the learning outcomes of students in environmental education. - The paper strongly urges the necessity of the training of teachers in the design and implementation of AR and VR experiences and states that the proper use of these technologies requires expertise, iterative feedback, and collaboration with the stakeholders. - Besides, it proposes that the ICT platforms could be a more powerful contributor to the behavioral change in favor of the environment than the traditional educational strategies and it underlines the necessity of technology integration into the teacher training processes.
Martini et al. (2024)	A2	- The research highlights the significant role of ICT in the enhancement of environmental education, thus indicating that ICT are an important tool for the improvement of teaching methods and student involvement in the environmental issues. - A high percentage of teachers (89.8%) was found to believe that ICT were helpful for the weaker students, while the percentage of the teachers who pointed out the positive impact of the technology on the cognitive aspect of the development was 87.2%, which means that in fact, the technology may improve the learning outcomes in the subject of environmental education. - The study insists on the necessity of ICT training for teachers as the educators have reported a very low level of technological engagement coming from their side implying that there is a gap in the technological knowledge which is necessary to be filled. - In addition, the incorporation of ICT into environmental education is envisaged as a way of obtaining an interactive learning environment, which might turn out to be a factor for the emergence of a pro-environmental behavior among students. - To sum up, the findings indicate that the proper integration of the ICT into environmental education would require the continuous training of the teachers and their support in order to maximize the benefits for the students' learning.
Millward et al. (2024)	A3	- The research investigates the incorporation of the ICT in EE, emphasizing both the potential advantages and the challenges that the relationship entails. It stresses the need for a strategic and reflective integration of ICT that would complement the experiential nature of EE rather than taking away its value. - The teachers voice their concerns regarding the balance between the use of ICT and the traditional pedagogical methods, and they point out the need for a teacher training that will deal with these complexities and will upgrade their technical knowledge. - The research points out the systemic barriers that make the fusion of environmental education and ICT difficult, implying that effective teacher training processes are vital for overcoming these challenges and getting better students' learning outcomes. - Also, the results show that the teachers have different opinions about the best way to use technology in physical education, thus it is important to have continuous professional development in this area. - All in all, the research suggests that although ICTs hold the potential to uplift the primary education sector, the proper teacher training and support remain the key factors in drawing the full benefits of ICTs for the students' learning.
Zuhriyah (2023)	A4	- The research emphasizes the significance of smart education (SE) as a prerequisite for the enhancement of DEL and even points out that the use of technology in education has such a powerful effect that it can almost double the learning outcomes of environmental education for students. - It stresses that teacher training is a key factor for the successful adoption of digital curricula, since the absence of competent skills in ICT may negatively influence the development of learning. - The author also points out that the improvement of teachers' ICT skills is a must for the creation of dynamic and productive atmosphere in the classroom, which is very important for the promotion of environmental education. - Furthermore, the study argues that the provision of e-skills is a good sign of a region's capability to specialize in the new technological areas, especially the eco-friendly ones, which is in line with the environmental education goals. - The overall picture the results give us is that there is a need for teacher training in the technology domain that is both effective and continuous in order to utilize the ICT and enhance environmental education and students' learning.

Table A2 (Continued). Synthesis of findings

Reference	Code	Synthesis of findings
Pol et al. (2023)	A5	- The study points out the very important role played by the ICT in the process of socialization, especially when it comes to EE. It emphasizes the fact that from the year 2010 onwards, social media have become the most important source for the dissemination of pro-environmental knowledge, having outperformed the traditional educational institutions and the media in terms of influence. - Communication and information processing management has been identified as a critical psychological and social aspect to the present-day sustainability that is closely related to the efficient delivery of environmental education. - Not only that, but the research also posits that the instilling of environmental values through education and the media may affect the perception of such values, thus implying the need to train teachers in technological skills for environmental education to be more effective. - Overall, the findings indicate that the enhancement of teacher training in the field of ICT and related technologies is a major factor in the improvement of the students' learning outcomes in the subject of environmental education.
Álvarez-Herrero (2023)	A6	- The research highlights the significance of the integration of technology into environmental education, especially through urban tours that use mobile devices, which aim to raise students' awareness of environmental issues. - Before the activity, a training course for teachers was organized, focused on technical and management issues relevant to the implementation of the scavenger hunt, thus indicating the need for teachers to be trained in the use of technology for educational purposes. - Most of the participating teachers came from scientific and technological backgrounds, which implies that they had a foundation in technological knowledge, but the students had a limited experience with the educational use of smartphones, which means that there is a gap in technology integration of their learning. - The study posits that enhancement of teacher training and technology adoption can lead to better student participation and learning outcomes in environmental education. - Overall, the paper underscores the link between ICTs and environmental education, stressing the necessity of upgrading teacher training in technology to the benefit of student learning outcomes.
Ayerbe-López and Perales-Palacios (2023)	A7	- The study emphasizes the role of the ICT in the process of applying the problem-based learning (PBL) methodology in EE. It points out that high-level ICT skills are often a prerequisite for effective PBL applications, which proves the direct connection between technology and teaching of environmental education. - The challenges related to the use of ICTs, including the disparate results in the first and second year of intervention were, first of all, identified as poor quality and quantity of computing resources. - The study stresses the necessity of teacher training in ICT for physical education, as there have been difficulties in time management and in group work, suggesting that improvement in technology skills can be beneficial for the teaching processes. - Overall, the results imply that though the PBL was successfully implemented, it has far-reaching implications for teacher training and technology integration in artificial education to enhance student learning outcomes. This delineates an obvious necessity for the teachers' continuous training in technology to support the effective teaching of environmental education.
Ricoy and Sánchez-Martínez (2022)	A8	- The study underlines the positive impact that the integration of ICTs has on environmental education, showing that the digital tools usage has a significant effect on not only student's learning experiences of ecology awareness. The digital intervention consisted of several resources such as interactive whiteboards and tablets, which were very important to make students interested in the process and improve their digital literacy. - Teachers reported that the combination of technology and gamification not only aroused the students' imagination but also collaboration and problem-solving skills among the students, thus strengthening independent learning. - The study points out the necessity of empowering the teachers so that they can lead the deployment of the ICT in the environmental education sector, for the successful execution of the programs relies on teachers' technological know-how and on their ability to interlace these instruments into their teaching practice. - To summarize, the findings imply that upgrading teachers' technological skills is the most important thing in order to get the maximum benefit of ICTs in environmental education and eventually, the students getting better grades will be the result.
Bilbao-Aiastu and Miranda-Urquij (2022)	A9	- The investigation emphasizes the incorporation of gamification through ICT into environmental education teaching, which means that the use of innovative methodologies and emerging technologies has a significant potential to greatly enhance educational practices in this field really. - It stresses the necessity of teachers getting technological and pedagogical training so that they can effectively use the technology in their classrooms, which is vital for the improvement of students' learning outcomes. - The research also points out that, even though the application of gamification and ICT does not significantly improve academic performance, it definitely leads to statistically significant gains in student satisfaction and motivation, thus indicating a positive connection between technology use and student participation in environmental education. - On top of that, the paper talks about the role of ICT in creating flexible learning environments and promoting independent and collaborative learning, the latter being very important components of effective environmental education. Overall, the findings emphasize the significance of the technology training of teachers to create better learning experiences in environmental education.

Table A2 (Continued). Synthesis of findings

Reference	Code	Synthesis of findings
El Batri et al. (2022)	A10	- The study reveals that the integration of ICTs and tech tools is at a low level among the faculty, even though these technologies have been recognized for their role in making environmental education more effective and facilitating learning. - There is a notable correlation between the frequent use of active methods and the recognition of difficulties in teaching, which indicates that the teachers using active methods are more aware of the necessity of having effective teaching aids, including technology. - The study has shown that schoolteachers' ongoing training should be based on a systemic and interdisciplinary approach, where the effective use of both methods and active technologies in teaching the 'Scientific Awakening' program becomes part of the teachers' learning process. - Furthermore, the findings imply that the lack of educational tools, including technological resources, significantly influences teachers' pedagogical actions, thereby highlighting the need for technology-related teacher training to be improved. "In summary, the paper emphasizes that the integration of technology into environmental education is a necessity for students' learning improvement and teachers' need for training in this area."
Álvarez-Herrero and Hernández (2021)	A11	- The research highlights the integration of smartphones and various applications in the teaching of environmental education, which points to a positive relationship between technology and environmental awareness among secondary education students. This approach made use of geolocation, augmented reality, and social networking to enhance the learning experiences during educational itineraries in the city of Alcoy. - The study stresses the need to train teachers to use these technologies effectively, as the successful implementation of ICT in environmental education depends on teachers' technical knowledge and their ability to integrate these tools into their teaching practices. - The questionnaire results indicate that the students appreciate the activity and its technological components, which implies that the use of ICT can lead to better learning outcomes for students in environmental education. - Nevertheless, the research also points out a decline in interest among older students, which highlights the need for tailor-made teacher training that addresses the different student technology-related needs in environmental education. Overall, the paper emphasizes the need for integration of ICT in environmental education and at the same time, teacher training needs should be addressed so that they can use these technologies effectively.
Picanço et al. (2021)	A12	- The study emphasizes the increasing integration of digital technologies in biodiversity education and the use of methods such as experiential learning and inquiry-based learning, which can improve environmental education through ICT. - It suggests that when ICT is tuned to the interests of teachers and students, it can enhance communication skills and knowledge, thus supporting the goals of biodiversity conservation. - The research indicates that there is a need to change the views of the teachers regarding the biodiversity and it checks whether the ICT can be a powerful tool in this aspect. - What is more, the paper points out that a significant number of Azorean teachers frequently use the Internet and various ICT tools, which is an everyday commitment that may have been strengthened by the COVID-19 pandemic. - On the other hand, it also mentions that, generally, teachers do not make good use of the biodiversity web portals, which is an indication that there is a need for more technology, fluency and training in the use of these resources for environmental education. Overall, the findings suggest that ICTs have the potential to enhance environmental education, but they also highlight the need to train teachers in technology to be able to realize this potential.
Santos and Ortenzi (2021)	A13	- The research highlights the need to integrate ICT into environmental education, stressing that technological advancements have an impact on almost every field, thus making it planetary awareness that becomes indispensable in education. - The study suggests that the pedagogical intervention was carried out through a multimodal approach, in tandem with the principles of the pedagogy of multi-literacy, thus indicating that technology is a key factor in the enhancement of learning experiences. - Moreover, the investigation reports that the learners were able to express the synesthesia in their multimodal productions, which signifies an improvement in learning outcomes through the application of the different semiotic modes, including technological tools. - Overall, even though the document delves into the technology integration in environmental education teaching, it does not provide comprehensive information on the teacher training processes and the specific technology knowledge requirements.

Table A2 (Continued). Synthesis of findings

Reference	Code	Synthesis of findings
Khurvalieva (2020)	A14	- The study points out the significant role of information and communication technologies (ICT) in preschoolers' environmental education up, stating that computers can actively engage the kids in learning process and support a people-oriented educational approach. - It indicates that the embedding of ICT in teaching can bring about the excellent quality of environmental education, filling up the gaps in the existing practices. - The research uncovers a lack of methodological conditions and appropriate technologies for the use of computers in environmental education, thus pointing out the necessity of teacher training in those areas. - Furthermore, it also proposes that through the development of a model for the electronic textbook usage, the formation of the environmental concepts in little kids can be made easier - teachers' training is thus underscoring the point that their use of the technologies has to be very effective. - To sum up, the implications of the research are that the technological knowledge and teacher training need to be improved in order for the students' learning outcomes in environmental education to be positively affected by the technology used.
Díaz et al. (2020)	A15	- The research highlights the necessity of integrating ICT in environmental education, emphasizing that the sustainable use of technological resources can raise the consciousness of eco-friendliness among the students. - It points out the effective use of ICTs not only to underpin the teaching of theoretical content but also to be an environmental management case in practice. - The study shows a satisfactory level of digital competence among environmental sciences teachers as very important for the improvement of students' learning outcomes, since it indirectly helps the development of students' digital skills. - In addition, the article addresses the issue of teacher training in technology and claims that the tech-upskilling of educators is one of the foundations of 21st century education. - In general, the conclusions imply a positive relationship between the use of ICT in the teaching of environmental education and the enhancement of student learning, along with the ever-increasing demand for the technology skill training of teachers.
Fernández (2020)	A16	- The research investigates the connection between ICT and various educational aspects, including environmental education, but it does not explicitly discuss the direct link between the teaching of environmental education and technologies. It underlines the significance of ICT for the coordination and communication among the teachers which can indirectly support the efforts of environmental education. - The research indicates the necessity to train teachers in the use of ICT and also claims that knowledge of neuroscience and cultural studies can help in understanding students with functional diversity, which can be linked to the improvement of environmental education teaching practices. - Notwithstanding, the paper fails to deliver detailed information on the ways by which technology directly boosts the learning of students in environmental education nor the technological expertise that the teachers need for an effective training in this area. The restrictions of the research also suggest that it concentrates on a particular sample which might not completely represent the educational contexts that are wider.
Miyaji and Fukui (2020)	A17	- The study highlights the incorporation of ICT tools in environmental education, stressing that the lessons merge research-based learning with the experimental one, which is vital for teacher training processes in environmental education. - It was found that the computer skills of the students improved, which points out a positive relationship between the technology use and the student learning outcomes in environmental education. - The lessons aimed at cultivating a local viewpoint and at the same time, developing a global one, illustrating the dual benefit of the technology to enhance the local and global environmental awareness. - The research indicates that the use of ICT tools not only assists in knowledge acquisition but also develops the students' practical skills and confidence, which are the essential components of an effective teacher training. - To sum up, the results reveal a considerable increase in the students' awareness of their capabilities and their confidence to participate in environmental education through the technology use.
Thysiadou et al. (2019)	A18	- Research highlights the significant impact that ICT have on educational processes change, particularly in the area of environmental education, through metamorphosis of the teaching and learning multimedia interactive and supporting environments that escalate the student participation and learning outcomes. - The alignment of the ICT with teaching methods is associated with an increase in students' interest in learning, along collaboration encouragement and the development of research culture, all of which are vital for the effective environmental education. - The research points out the need for training of teachers in the effective use of these technologies and suggests that the educators should be very well acquainted with the technological knowledge in order to facilitate the integration of ICT in their teaching practices. - The results show that through the use of educational technology, not only the students get to understand the environmental concepts but also their critical thinking and interpersonal skills are enhanced, which are extremely important for students' overall growth in environmental education. In the end, the paper stresses the need for teacher training in ICT as a way to enhance student learning in environmental education.

Table A2 (Continued). Synthesis of findings

Reference	Code	Synthesis of findings
Paredes-Labra et al. (2018)	A19	- The research highlights the role of ICT as powerful pedagogical instruments that can raise awareness about sustainability issues, which is a prerequisite for environmental education teaching. It emphasizes the incorporation of ICT in the curriculum content related to renewables and environmental education and suggests a direct link between technology and environmental education. - The paper discusses the importance of teacher training for effective use of ICT, and signals that the introduction of ICT-related projects entails a rethink of the role of higher education institutions and their connection with the educational entities. - It also points out that teachers need to devote themselves to new teaching methods that involve the exploration of knowledge through ICT, which implies the need for them to be equipped with technological skills. - The text states that the project will have a wide range of stakeholders, including universities and local authorities, which implies a collaborative approach towards improving environmental education through ICT. - On the whole, the document suggests a strong association between ICT and environmental education and emphasizes the necessity of training teachers in technology in order to facilitate students' learning outcomes.
Midoro (2017)	A20	- The research paper analyzes the integration of ICT in teacher training processes, emphasizing the need for teachers to develop competences that include technological knowledge in order to improve their teaching practices, especially in environmental education. - The importance of online courses is stressed, such as the "Medea" program, which aims to train teachers in the effective use of ICT to create learning communities and improve the learning outcomes of students. - The article suggests that the teachers' ICT competencies should cover not only personal productivity but also the pedagogical tools for facilitating children learning, which reflects a direct connection between the technology use and the educational practices improvement. - In addition, it points out that the teachers need to adjust themselves to the new environments and learning methodologies brought about by ICT, which may greatly affect the teaching of environmental education. - Overall, the findings imply that the effective training of teachers in ICT is a determining factor for the quality of environmental education and the learning outcomes of students to improve.
Sangiorgio et al. (2017)	A21	- The research paper examines the incorporation of ICT into education, emphasizing their contribution to the enhancement of creativity and innovation, which are crucial for the effectiveness of the environmental education systems in Europe. - It points out the necessity of understanding scientific methods and improving the students' skills in ICT and argues that these competencies can be a vehicle for the development of scientific knowledge, particularly in the area of environmental education. - The paper also refers to the development of a serious game for pupils which integrates scientific research and technology for the students to get interested in the ecological and Earth sciences topics thus improving their technological skills. Additionally, teacher and student training materials produced are aimed at boosting their comprehension of scientific research methodologies, which implies an emphasis on teacher training in the context of technology use. - Overall, the paper indicates that the adoption of technology in the teaching of environmental education could lead to a significant improvement in the students' learning outcomes and he/she/it/they/noun emphasizes the continuous training of teachers in these technologies as a need.
Ugolini et al. (2016)	A22	- The research highlights the integration of ICT in environmental education, stressing that the students are familiar with these technologies, which can improve their learning experiences. - The methodology developed in the Involven and Raise projects fosters a participatory approach, where teachers and facilitators team up with students and experts, which signals the need to train the teachers in ICT-related skills to effectively the learning process. - The use of serious games and nature-based research activities is suggested as the way to engage the students, meet the needs of the digital natives' generation, and boost the motivation and learning outcomes. - Moreover, intergenerational sharing of experiences through ICT has proven to enhance communication and knowledge transfer, thus pointing to the necessity of technology literacy among the teachers. - All in all, the findings imply that proper technology training for teachers, in particular, is to a great extent responsible for the improvement of students' learning in the field of environmental education.
Fauville et al. (2014)	A23	- The review emphasizes the potential of ICT to enhance EE by offering new learning experiences which can surpass the traditional obstacles such as restrictions of budgets and time, thus allowing the students the interaction with the complex environmental systems through virtual media. - It points out that it is necessary to train the teachers for the effective integration of ICT in EE and adds that even though there is a fast rising of ICT resources, there is an urgent need for studies which would model productive teaching and learning practices using these technologies. - The literature expresses that ICT can play a role to lessen the reliance of students on teachers thereby creating a more independent learning atmosphere. - Yet, the educators' concern is the possible disaffection towards nature that may result from the over-reliance on technology in artificial education, thus, it is crucial to balance the usage of ICT with real-world experiences. - Overall, the use of ICT in environmental education is regarded as a promising strategy for the enhancement of student learning but it will require proper teacher training and a reflective approach to its adoption.

Table A2 (Continued). Synthesis of findings

Reference	Code	Synthesis of findings
Gutiérrez-Perez and Perales (2014)	A24	- The research shows that environmental educators see the ICT as a potent tool that can be used for confidence building and making education proposals in a green way, thus implying a positive relationship between ICT and EE. - It is pointed out that the educators consider the computer training courses as very valuable, since 70% of them assess the training as either very or fairly useful for the development of their personal skills, which indicates the need for technology training for teachers. - The study also mentions that, although the teachers do not regularly apply the ICT in their work, they all agree that it is necessary to use the ICT in the teaching methods in order to get better learning results for the students. - Furthermore, the paper stresses the need to integrate traditional and constructive methodologies, which might be quite tricky in the case of the ICT, hence it suggests that there should be very effective teacher training programs in these technologies. Altogether, the results indicate a significant correlation between ICT and environmental education, alongside an evident necessity for technological skill enhancement of the teachers.
Pontes-Pedrajas and Varo-Martínez (2014)	A25	- The research underlines the crucial role of the ICT in environmental education, pointing out the potential of the ICT to really great extent the information and knowledge about sustainability therefore, make the public aware of the development of the planet more sustainable. - The use of conceptual mapping which is made easy by the application of ICT tools like CMapTools is one of the suggestions made by the research as the way to enhance the motivation of the environmental educators and to make the learning process of the students reflective and collaborative. - It also mentions that the teachers possessing a firm knowledge of the key concepts are more productive, which implies the integration of ICT into training of teacher can raise the teaching power and communication skill of the educators. - The educational experience presented in the paper involved among other things the use of a number of ICT tools to support the development of environmental education as a cross-curricular topic, thus indicating a clear connection of technology and teacher education processes. - All in all, the findings indicate that the proper use of technology in the teaching of environmental education can not only enhance the learning outcome of the students but also cater to the technology-related training needs of the teachers in the first place.
Leppisaari and Lee (2012)	A26	- The research shows that ICTs are an important part of young students' lives, who are referred to as digital natives, and who are very well equipped to use social media for learning purposes. Nevertheless, the use of international virtual learning projects particularly in environmental education continues to be limited, thus reflecting a gap in the effective use of technology in this area. - The study emphasizes the need to improve teacher training processes so that the integration of ICT in education can become more widespread. It points out organizational, linguistic, technical and collaborative barriers as the main obstacles that block the way to effective teacher practices in environmental education. - Besides, the paper argues that the establishment of school practices that are in line with modern learning concepts can have a considerable impact on the technological requirements of teaching, thus implying the necessity of continuous teacher training in ICT for the purpose of enhancing student learning outcomes. - The findings suggest that greater interactivity and genuine commitment among teachers from partner countries during the planning phase are paramount to fostering technology-aided effective learning environments in environmental education. Generally, the connection between ICTs and environmental education is emphasized by the necessity of improving teacher training and the effective use of technology for the purpose of enhancing student learning outcome.
Ojeda et al. (2012)	A27	- The study emphasizes the potential of ICT as a tool for EE support, stressing its role in the training of teachers and the enhancement of environmental literacy among the citizens. It suggests that ICT can play an important role in the strategies of pedagogy used by educators in EE, mainly through the integration of the online resources and the virtual tools. - The paper reviews the development of the collaborative program, ECOUR-BAN 3, which provides tools for cooperative work and aims to enhance the teaching of environmental education in urban settings that signifies the need for the teachers to be trained on using the technologies efficiently. - It also points out the fact that teachers are increasingly using the Internet, blogs, and other digital platforms for communication and resource acquisition, which indicates a shift towards technology integration in the teaching practices. - Furthermore, the study recognizes the need for a continuous assessment of the educational tools and resources, which is pivotal for the learners to advance in the field of technology-enhanced education through better learned outcomes. All in all, the results highlight the necessity of the teachers' ICT training as a condition for the improvement of the environmental education effectiveness.

Table A2 (Continued). Synthesis of findings

Reference	Code	Synthesis of findings
Roy et al. (2012)	A28	- The research highlights the use of ICT media to link local environmental officials with school pupils, thus making it easier to carry out project-based learning activities aimed at solving local environmental conservation problems. This approach has proved that technology has the power to enhance the students' learning in the field of environmental education. - The CASC model, which stands for "children as agents of social change," is introduced as a framework that employs the ICT to support learning without assuming the availability of a ICT infrastructure, thus tackling the limitations that developing countries often face. - The study states that teacher training in ICT is very important, since many developing countries face such issues as limited educational budgets and a shortage of qualified teachers, which, in turn, can hinder the effective integration of technology into teaching. - The findings imply that models like CASC could be advantageous for educational and NGO agencies and underscore the need to train teachers in technology in order to improve the educational outcomes in the area of environmental education. On the whole, the paper emphasizes the necessity of incorporating technology into the teaching of environmental education while at the same time addressing the ICT teachers' training needs.
Davies et al. (2012)	A29	- The project highlighted the importance of integrating technology, particularly data recording linked to position, in environmental education, thereby demonstrating its potential to improve the scientific research skills of primary school students. About 480 children were engaged in this technology, which made possible the collection and interpretation of the local environment data through the Google Earth visualizations, thus indicating a positive impact on their learning experiences in environmental sciences. - Teacher training processes were identified as essential for the effective integration of ICT into the science curriculum. The study emphasized the need for a continuous professional development (CPD) program that incorporates regular teaching and practical classroom tasks, thereby ensuring that teachers are well-equipped to apply the new technologies in their teaching. - The findings suggest that while data recording became a routine feature of practicing science, the sustainability of position-linked recording was not fully reached, thus indicating the need for ongoing support and training for teachers in order to avail of the technology's full potential in environmental education.
Papastergiou et al. (2011)	A30	- The study emphasizes the potential of online learning communities (OLC) to facilitate the implementation of EE projects and eventually recommends that these platforms are capable of doing so by providing the technology integration of the ICT into the learning process effectively. The above-mentioned integration is especially beneficial for secondary education as it enables the learners to get involved in the collective projects irrespective of their limited free time, thus their learning experiences are enhanced. - It was found that the students' active involvement in the OLC has a positive impact on their ICT skills, which suggests that the use of technology in the teaching of physical education can lead to considerable improvements in students' learning outcomes. - The research also highlights the necessity to train teachers for the effective use of ICT in the physical education programs, since teachers have a key role in promoting these technological integrations. - Overall, the findings imply that the connection between ICT and advanced education is indispensable for increasing the involvement of students in learning and for their learning, and at the same time, they strengthen the argument for continuous training of teachers in technology use.
Obara et al. (2009)	A31	- The research brings forward the integration of ICT in environmental education, highlighting their role in the change of teaching methodologies and the improvement of learning experiences for both teachers and students. The employment of ICT has made it easier to establish new ways of knowledge building and collaborating, which are the most important for an effective environmental education. - Teachers were involved in pedagogical workshops focused on environmental education, which consequently improved their ability to use computer resources and participate in cooperative projects. This training is of utmost importance for the enhancement of their technological knowledge and the upgrading of their teaching practices. - The action research methodology used in the projects has allowed teachers to reflect on their pedagogical practices, innovate and create more meaningful learning experiences for students, thereby improving students' learning outcomes. - The projects aimed at collaboration between educators and researchers have also been focused on creating methodological ways to integrate environmental education into the curriculum, with the emphasis on the importance of teacher training for the effective use of technology. Overall, the paper highlights the significant connection between ICT and environmental education, especially concerning teacher training and student learning improvement.

Table A2 (Continued). Synthesis of findings

Reference	Code	Synthesis of findings
Zoakou et al. (2007)	A32	- The research paper investigates the development of e-learning scenarios within the UNITE project, which makes use of several educational contexts, i.e. environmental education, and is built on technology to enhance learning experiences. These scenarios facilitate problem-based learning and support the integration of knowledge from different subject areas, thus corresponding to STEAM and STEM education principles. - The developed scenarios aim at bridging the gap between formal and informal learning environments, by making use of ICT tools that will allow communication and collaboration between students, thereby improving their learning outcomes in environmental education. - Teacher training is highlighted as a critical component, since teachers are engaged in the actively designing process of the scenarios, giving feedback and using manuals which guide them in the making of customized e-learning scenarios. This indicates the need for continuous professional development in the integration of technology and the pedagogical approaches related to environmental education. - The paper points out that teacher's tech knowledge and his/her capacity to implement innovative e-learning scenarios effectively are key factors for the students' technology-based learning to be enhanced. Overall, the ICT integration in environmental education is proposed as a tool for increasing student participation and learning outcomes while at the same time teacher training needs to be emphasized.
Vrasidas et al. (2007)	A33	- The paper looks into the role of ICT as a teacher's power to promote peace and mutual understanding through environmental education, thus pointing to the importance of integrating technology into the teaching practices. - It underlines that merely adding ICT to the curricula is not enough; a comprehensive overhaul that considers the social and economic conditions, as well as the teachers' skills and commitment to technology, is needed for effective teaching. - The study reveals that teachers' professional development is a vital factor for technology's successful impregnation in education, leading to the assumption that teachers usually lack the right training and support for the incorporation of ICT. - The summary strengthens the argument that ICT can be facilitators of communication and participation besides making possible the classroom and community interrelationship in the area of environmental education which is a necessity for peace building. - All in all, the paper argues that the teaching of technology to the teachers needs to be improved in order for the student learning outcomes in the field of environmental education to be positively affected.

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