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# MAPPING THE GLOBAL ECOSYSTEM OF INTERACTIVE DIGITAL TECHNOLOGIES IN SUSTAINABILITY EDUCATION: A BIBLIOMETRIC ANALYSIS

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## ABSTRACT

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| Aim/Purpose | This study aims to systematically map the intellectual structure, research evolution, and emerging hotspots of Interactive Digital Technologies (IDTs) in Education for Sustainable Development (ESD). It specifically addresses the fragmentation and uneven technological integration within this field. |
| Background | As education systems face accelerating digital transformation and urgent sustainability challenges, understanding how digital technologies support ESD has become increasingly important. Although research in this area has grown rapidly, it remains fragmented across technologies, educational levels, and regions. A comprehensive bibliometric synthesis is therefore needed to clarify the field's development, key contributors, and emerging directions. |
| Methodology | This study used a bibliometric design to analyze 377 journal articles indexed in Scopus and published between 2000 and October 2025. Using standard screen- |

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| | ing and science-mapping techniques, the study examined publication growth, citation impact, collaboration patterns, keyword networks, and thematic evolution. |
| Contribution | This study provides a novel integrative perspective by reconceptualizing interactive digital technologies as components of digitally enabled sustainability learning ecosystems, moving beyond fragmented and technology-specific approaches, and advancing theory by suggesting an emerging shift from isolated instructional tools toward ecosystem-based sustainability learning. |
| Findings | Results show rapid growth in publications after 2016, peaking in 2024, indicating increasing global attention to this field. Five major themes emerged: AI-enabled learning, green digital curricula, game-based and mobile sustainability learning, institutional digital governance, and interdisciplinary competence development. The findings reveal a transition toward integrated digital sustainability ecosystems, while persistent challenges remain in ethics, equity, and institutional readiness. |
| Recommendations for Practitioners | Educational institutions and policymakers should adopt ethically grounded, inclusive, and system-oriented digital strategies that align technological innovation with sustainability competencies, teacher capacity development, and equitable access frameworks. |
| Recommendations for Researchers | Future studies should integrate multi-database analyses, multilingual sources, and mixed-method approaches to capture contextual diversity and examine the pedagogical effectiveness of IDTs in fostering measurable sustainability competencies. |
| Impact on Society | By mapping the global research landscape, this study informs the development of inclusive and digitally enabled sustainability education systems that support SDG 4 and strengthen long-term societal resilience. |
| Future Research | Future research should employ longitudinal, comparative, and empirical designs to examine how AI-driven, immersive, and governance-oriented digital ecosystems influence learning outcomes, ethical practice, and sustainable behavioral transformation across diverse sociocultural contexts. |



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| Keywords | interactive digital technologies, education for sustainable development, artificial intelligence, sustainability education, bibliometric analysis |


## INTRODUCTION

The transition toward sustainable societies has strengthened the strategic role of education in developing learners' competencies, values, and decision-making capacities. Accordingly, Sustainable Development Goal (SDG) 4 identifies quality education as a key enabler of broader sustainability transformation. Education for Sustainable Development (ESD) is increasingly recognized as essential for preparing learners to address environmental, social, and economic challenges. It promotes critical and reflective thinking, problem-solving, and ethical decision-making capacities needed for sustainable societies (Carrión-Martínez et al., 2020).

At the same time, rapid digital transformation has fundamentally reshaped educational systems, redefining how learning is accessed, delivered, and experienced. Within this context, Interactive Digital Technologies (IDTs), including artificial intelligence (AI), virtual reality (VR), augmented reality (AR),

and mobile learning, have emerged as key enablers of more interactive, learner-centered, and inclusive educational environments (Chiu, 2021; Damaševičius & Sidekerskienė, 2024). While these technologies offer significant pedagogical potential, including enhanced engagement, experiential learning, and expanded access, their integration within ESD remains uneven and fragmented across educational levels, regions, and technological domains (Okoye et al., 2025; Yakobi & Yakobi, 2025). This fragmentation limits a comprehensive understanding of how diverse IDTs collectively contribute to the development of sustainability-oriented learning systems.

Despite the rapid growth of research on digital technologies and sustainability education, the field remains conceptually fragmented, particularly in explaining how diverse interactive digital technologies collectively shape the intellectual structure and global development of ESD. To address this gap, this study employs a comprehensive bibliometric analysis of Scopus-indexed publications from 2000 to 2025 to systematically map the intellectual structure, research evolution, and emerging hotspots of IDTs in ESD. Specifically, the study examines publication trends, citation patterns, collaboration networks, and thematic development across this interdisciplinary domain.

By doing so, this research moves beyond fragmented and technology-specific perspectives and reconceptualizes IDTs as interconnected components of digitally enabled sustainability learning ecosystems. In doing so, it provides an integrated and evidence-based foundation for advancing theory, informing policy, and guiding future research in sustainability-oriented digital education.

## LITERATURE REVIEW

### *THEORETICAL FOUNDATIONS OF DIGITAL SUSTAINABILITY LEARNING*

The integration of IDTs into sustainability education can be understood through several complementary theoretical perspectives. First, Transformative Learning Theory explains that meaningful learning occurs when individuals critically reflect on prior assumptions and revise their perspectives through dialogue and experience (Mezirow, 1997). This perspective is highly relevant to ESD, which seeks not only knowledge acquisition but also changes in values, responsibility, and sustainable behavior (UNESCO, 2020). Immersive and participatory technologies such as virtual reality, simulations, and collaborative platforms may therefore support transformative sustainability learning by enabling learners to engage directly with complex environmental and social challenges (Damaševičius & Sidekerskienė, 2024; Fadillah, Syafrijon, Siregar, & Usmeldi, 2025).

Technology adoption perspectives, particularly the Technology Acceptance Model (TAM), further explain how perceived usefulness and ease of use shape teachers' and learners' willingness to adopt digital tools (Davis, 1989). In educational contexts, these factors remain important in shaping teachers' readiness to integrate digital tools into classroom practice, particularly when supported by institutional training and infrastructure (Dzinoreva et al., 2024; Okoye et al., 2025; Shambare & Jita, 2025).

Third, the Technological Pedagogical Content Knowledge (TPACK) framework emphasizes that effective technology integration requires alignment among technological, pedagogical, and subject-matter knowledge (Mishra & Koehler, 2006). This is particularly important in sustainability education, where interdisciplinary topics such as climate change, ethical consumption, and systems thinking require carefully designed teaching approaches.

Taken together, these frameworks suggest that the educational value of IDTs depends not merely on technological availability but on pedagogical design, user acceptance, institutional readiness, and alignment with transformative sustainability learning goals.

### *THE IMPORTANCE OF INTERACTIVE DIGITAL TECHNOLOGIES IN EDUCATION*

IDTs have transformed traditional education into a more learner-centered and experiential process, where students construct knowledge through digital interactions, simulations, and collaborations. By

providing immersive experiences, these technologies foster engagement, motivation, and creativity, which are essential attributes for 21st-century learning and sustainable development (Beheshti et al., 2024). While augmented and virtual reality tools are widely reported to support visualization, experimentation, and contextual exploration, existing studies largely emphasize short-term engagement and conceptual understanding, with limited evidence regarding their long-term impact on sustainability competencies or behavioral change (Asrizal et al., 2023; Schmidt & Stumpe, 2025; Simon et al., 2025; Wang et al., 2025). This highlights a critical gap between technological affordances and empirically validated long-term learning outcomes in sustainability education. Nevertheless, these studies collectively suggest that interactive digital technologies have the potential to enhance students' conceptual understanding, along with their engagement, collaboration, and contextual awareness in sustainability-related learning; however, this evidence remains largely focused on short-term, context-specific outcomes. Rather than functioning as isolated tools, these technologies increasingly support integrated, participatory, and experience-based learning environments aligned with the core principles of ESD.

This interactivity fosters digital literacy, cooperation, inclusivity, and a sense of community, which are central to sustainability-oriented education. However, Okoye et al. (2025) highlighted that the "digital divide" remains a major barrier to the equitable use of digital tools, especially in rural or under-resourced contexts where access to technology and reliable internet connectivity is limited. Such disparities emphasize the need for comprehensive strategies that integrate technological infrastructure, teacher training, and digital inclusion policies to ensure that the benefits of interactive technologies are shared equitably across diverse educational settings.

## *Interactive Digital Technologies and Education for Sustainable Development*

ESD prepares learners to make responsible decisions and take informed actions for environmental integrity, social well-being, and economic viability. Integrating IDTs into ESD has the potential to enrich teaching and learning processes by connecting knowledge with real-world sustainability challenges. Virtual and augmented learning environments allow learners to explore ecological systems, simulate climate change scenarios, and analyze sustainable solutions in interactive ways (Damaševičius & Sidekerskienė, 2024). Through these experiences, learners develop critical thinking, creativity, and empathy, which are essential for fostering sustainability competencies. For example, Y. Zhang et al. (2025) demonstrated that virtual reality supports sustainable and responsible pedagogy by promoting motivation, digital leadership, and ethical awareness among art and design students. Similarly, Simon et al. (2025) argued that augmented reality can increase students' environmental awareness when incorporated into well-designed educational frameworks.

Furthermore, digital tools offer new possibilities for interdisciplinary collaboration and innovation in sustainability education. Suwanprapha et al. (2024) emphasized that environmental schools and programs integrating digital technologies are better positioned to address complex global issues by linking environmental science with entrepreneurship, technology, and design. However, several studies have noted that implementing IDTs within sustainability education is often hindered by inadequate teacher training, lack of institutional readiness, and limited pedagogical models. Martini et al. (2024) reported that while teachers in early education acknowledge the importance of information and communication technology (ICT) in fostering environmental awareness, many lack the confidence and resources to integrate these tools effectively. X. Zhang et al. (2025) also highlighted the need for more inclusive approaches to teacher preparation, particularly in underrepresented regions of the Global South. Thus, to fully realize the transformative power of interactive technologies in ESD, educational systems must align digital innovation with equity, ethics, and sustainability-driven learning goals.

## *PREVIOUS STUDIES*

Bibliometric analysis has increasingly been employed to map the intellectual structure, thematic evolution, and global dynamics of research at the intersection of education, sustainability, and digital transformation. Over the past decade, numerous studies have examined sustainability education, digital innovation, and pedagogical transformation using quantitative mapping techniques such as citation analysis, co-authorship networks, topic modeling, and keyword co-occurrence. Although prior bibliometric studies have mapped aspects of sustainability education or digital transformation separately, few studies have integrated both domains systematically. Existing reviews often privilege publication patterns while giving less attention to pedagogical effectiveness, learning outcomes, or theoretical explanations of technology adoption. As synthesized in Table 1, most existing bibliometric and systematic reviews either concentrate broadly on ESD without systematically analyzing the technological dimension or examine digital transformation in education without explicitly anchoring it within the sustainability framework.

For example, Carrión-Martínez et al. (2020) conducted one of the earliest bibliometric analyses of ICT in ESD and identified mobile learning and distance education as dominant strategies supporting sustainability objectives. Although their findings illuminate technological trends within ESD, ICT was treated as a broad category, leaving the evolving intellectual structure of immersive and interactive technologies unexplored. Similarly, Grosseck et al. (2019) documented, through a longitudinal mapping of nearly three decades of ESD research, a transition from theoretical discourse to more implementation-oriented approaches.

However, digital technologies were not conceptualized as structural drivers of sustainability transformation but rather as complementary instructional tools. In contrast, Okoye et al. (2025) analyzed digitalized education through a combined systematic and bibliometric synthesis, highlighting pedagogical opportunities alongside structural inequalities, such as the digital divide. Yet, their work did not explicitly situate digital transformation within sustainability competencies or the broader ESD policy agenda. Likewise, Bathla et al. (2025) identified thematic clusters, including digital pedagogy, STEAM, and future-oriented learning, using bibliometric and text-mining techniques, but sustainability was treated indirectly rather than as a central analytical lens.

Meanwhile, technology-specific investigations, such as studies on augmented reality (Simon et al., 2025) and virtual reality for responsible pedagogy (Y. Zhang et al., 2025), demonstrate the pedagogical potential of immersive tools in enhancing environmental awareness, ethical reasoning, and digital leadership. Nevertheless, these contributions remain limited to particular technologies and lack macro-level bibliometric mapping of how IDTs collectively influence the evolution of ESD scholarship. As reflected in Table 1, none of the prior bibliometric analyses systematically integrates immersive and interactive technologies, including VR, AR, AI, mobile learning, virtual worlds, and collaborative platforms, within the conceptual, institutional, and global discourse of Education for Sustainable Development.

Taken together, prior studies reveal a conceptually dispersed and insufficiently integrated body of knowledge, where digital technologies are frequently examined in isolation and sustainability education is seldom analyzed through a unified technological lens. As a result, the broader intellectual structure, thematic evolution, and global research dynamics linking IDTs and ESD remain insufficiently understood. Addressing this gap requires a systematic, large-scale bibliometric synthesis capable of capturing the field as a coherent, evolving research domain.

**Table 1. Summary of previous bibliometric and systematic studies related to digital technologies and sustainability education**

| Authors | Scope and dataset | Analytical approach | Main focus | Key findings | Limitations relative to IDTs–ESD focus |
|---|---|---|---|---|---|
| Carrión-Martínez et al. (2020) | ICT in ESD (WoS/Scopus) | Bibliometric analysis | ICT integration in ESD | Mobile learning and distance education prominent in advancing sustainability goals | Focused broadly on ICT; did not examine interactive/immersive IDTs or intellectual structure evolution |
| Grosseck et al. (2019) | 30 years of ESD research | Bibliometric mapping | Evolution of ESD research | Shift from conceptual discourse to implementation-oriented research | Limited emphasis on digital technologies as structural drivers |
| Bathla et al. (2025) | Design thinking in education (1986–2022) | Bibliometric + text mining | Innovation & creative pedagogy | Clusters: digital pedagogy, STEAM, future education | Sustainability dimension indirect; not grounded in ESD framework |
| Okoye et al. (2025) | Digitalized education research | Systematic + bibliometric | Digital transformation in education | Identified opportunities and digital divide challenges | Did not explicitly connect digitalization with ESD competencies |
| Ninh and Hue (2025) | Sustainable entrepreneurial ecosystems | Bibliometric analysis | Sustainability & digital ecosystems | Education and digital technologies key in sustainable innovation systems | Focused on entrepreneurship, not formal ESD |
| Weng et al. (2024) | Peer interaction in online/mobile learning | Topic modeling | Online and mobile learning | Sustainability & inclusivity emerging themes | Sustainability treated as sub-theme; not central analytical focus |
| Simon et al. (2025) | Augmented reality in education | Empirical review | AR for environmental education | AR enhances environmental awareness | Technology-specific; not bibliometric nor mapped within broader ESD landscape |
| Y. Zhang et al. (2025) | VR and sustainable pedagogy | Empirical study | VR in responsible education | VR supports ethical awareness & digital leadership | Single-technology scope; lacks macro-level bibliometric mapping |

### *Research Gap and Positioning of the Present Study*

Despite the growing body of research at the intersection of digital technologies and sustainability education, critical gaps remain that limit a comprehensive understanding of this field.

First, existing studies are fragmented across specific technologies such as virtual reality, augmented reality, mobile learning, or artificial intelligence, with limited efforts to examine these tools collectively as an integrated research domain (Carrión-Martínez et al., 2020; Simon et al., 2025; Y. Zhang et al., 2025). Second, many empirical studies focus on short-term outcomes such as motivation, engagement, or awareness, while fewer examine measurable sustainability competencies, systems thinking, or long-term behavioral change (Damaševičius & Sidekerskienė, 2024; UNESCO, 2020). Third, previous bibliometric studies have often examined sustainability education or digital transformation separately, resulting in a limited understanding of the global intellectual structure connecting IDTs with ESD (Grosseck et al., 2019; Okoye et al., 2025).

In addition, insufficient attention has been given to how publication trends, collaboration networks, influential contributors, and thematic evolution have developed across this interdisciplinary field over time. Consequently, a comprehensive bibliometric synthesis is needed to clarify how IDTs are shaping sustainability education research worldwide.

Positioned within these gaps, the present study provides a systematic bibliometric analysis of Scopus-indexed publications from 2000 to 2025. By mapping publication growth, citation patterns, leading contributors, keyword evolution, and emerging hotspots, this study offers an integrated evidence base for future research, educational practice, and policy development in digitally enabled sustainability education. Building on this foundation, the study is guided by a set of research questions designed to systematically examine the structure and development of this field.

### *Research Focus*

This study provides a comprehensive bibliometric mapping of the research landscape at the intersection of IDTs and ESD. By analyzing data from major scientific databases, it examines structural patterns, thematic evolution, and global knowledge networks shaping this interdisciplinary domain. Specifically, the study addresses the following research questions (RQs):

RQ1. What are the publication and citation trends in this research field?

RQ2. What are the most frequently used index and author keywords, and how have these keywords evolved over time?

RQ3. Who are the most influential authors, sources, affiliations, and countries contributing to this field?

RQ4. What are the main research hotspots emerging at the convergence of IDTs and ESD?

## METHODS

### *Data Source*

This study employed a bibliometric design to map the research landscape of IDTs in ESD. All bibliographic records were retrieved from the Scopus database (Elsevier), selected for its comprehensive multidisciplinary coverage and robust citation indexing across educational, technological, and environmental studies. Scopus is widely recognized for its reliability and representativeness in bibliometric analyses (AlRyalat et al., 2019; Falagas et al., 2008; Singh et al., 2021). Beyond its widespread use, Scopus was selected for its high consistency in metadata structure, comprehensive citation indexing, and robust author affiliation disambiguation, all of which are essential for accurate bibliometric mapping. Compared to other databases, it offers broader interdisciplinary coverage across education, technology, and sustainability, making it particularly well-suited to capturing the complex intersection

of IDTs and ESD. Thus, its selection is based on methodological robustness rather than convenience.

Scopus indexes journals, conference proceedings, and book chapters from major publishers such as Elsevier, Springer, IEEE, and Wiley. However, only peer-reviewed journal articles were included in the present study to ensure consistency in document type and bibliometric comparison. Despite its broad coverage, reliance on a single database may introduce selection bias due to the exclusion of relevant publications indexed in other databases with different journal inclusion criteria, regional coverage, and disciplinary focus. For example, Web of Science tends to prioritize high-impact journals, while ERIC provides stronger coverage of education-specific and pedagogical research. Consequently, the dataset represents a comprehensive but not exhaustive mapping of global research on IDTs in ESD. However, using a single, standardized database ensured consistency in metadata structure, citation format, and analytical comparability, consistent with established bibliometric standards (Fadillah, Syafrijon, Sulandari, et al., 2025; Festiyed et al., 2024; Maral, 2026; Siregar et al., 2026).

## *Search Strategy*

To retrieve relevant literature, a systematic search strategy was formulated using a conceptual block model comprising three domains to capture literature at the intersection of digital interactivity, sustainability, and education. The Scopus search was conducted on October 28, 2025, and retrieved publications indexed between 2000 and October 2025. Boolean operators ("AND" and "OR") were applied to link these conceptual blocks and ensure both precision and comprehensiveness. Searches were conducted in the TITLE–ABS–KEY fields (title, abstract, and author keywords) to maximize conceptual relevance and minimize retrieval bias. Table 2 summarizes the conceptual structure of the search string applied in Scopus, showing each block's focus and keywords.

To ensure full transparency and reproducibility, the complete search query applied in Scopus is presented below:

> *TITLE-ABS-KEY (("interactive digital technology" OR "interactive technology" OR "digital technology" OR "interactive multimedia" OR "educational technology" OR "ICT" OR "digital media" OR "e-learning" OR "virtual learning environment" OR "immersive technology" OR "digital learning" OR "digital pedagogy" OR "digital innovation" OR "learning technology") AND ("education for sustainable development" OR "ESD" OR "sustainability education" OR "sustainable education" OR "environmental education" OR "SDG education" OR "climate education" OR "green education") AND ("teacher" OR "student" OR "classroom" OR "curriculum" OR "pedagogy" OR "school" OR "higher education"))*

The bibliometric analysis was conducted using VOSviewer (version 1.6.19) and the Bibliometrix package with its Biblioshiny web interface (version 4.3.2), operating in the R environment (version 4.3.3). In VOSviewer, co-occurrence analysis was performed using the full-counting method with a minimum threshold of five occurrences. In Bibliometrix/Biblioshiny, standard parameters were applied for performance analysis, collaboration networks, and thematic mapping to ensure consistency and replicability.

The Boolean combination of these blocks was applied to refine the dataset conceptually and eliminate irrelevant records from purely technical or non-educational domains. Only documents indexed as articles were retrieved, consistent with prior bibliometric mappings emphasizing peer-reviewed journal outputs (Zyoud et al., 2023). In addition, the selection of keywords and the restriction to TITLE–ABS–KEY fields may introduce conceptual bias. While this approach enhances precision and relevance, it may exclude studies that address IDTs or ESD implicitly without explicitly using the selected terms. Conversely, some retrieved documents may include only peripheral references to these concepts. Therefore, the results should be interpreted as reflecting dominant, explicitly articulated research trends rather than the field as a whole.

The retrieved records were subsequently processed and screened using a PRISMA-guided (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach to enhance transparency and

reproducibility in dataset selection (Page et al., 2021). Figure 1 presents the PRISMA flow diagram summarizing the identification, screening, and inclusion stages of the document selection process.

**Table 2. Conceptual structure of the search string used in Scopus**

| Block | Domain focus | Conceptual purpose | Keywords (Title–Abstract–Keywords) |
|---|---|---|---|
| Block 1 | Interactive Digital Technology | Capture all variations describing interactive, digital, and media-based learning technologies | "interactive digital technology" OR "interactive technology" OR "digital technology" OR "interactive multimedia" OR "educational technology" OR "ICT" OR "digital media" OR "e-learning" OR "virtual learning environment" OR "immersive technology" OR "digital learning" OR "digital pedagogy" OR "digital innovation" OR "learning technology" |
| Block 2 | Education for Sustainable Development (ESD) | Identify studies focusing on education as a driver of sustainability | "education for sustainable development" OR "ESD" OR "sustainability education" OR "sustainable education" OR "environmental education" OR "SDG education" OR "climate education" OR "green education" |
| Block 3 | Educational Context and Learning Practice | Filter results to focus on formal and non-formal education, excluding purely technical or engineering-oriented works | "teacher" OR "student" OR "classroom" OR "curriculum" OR "pedagogy" OR "school" OR "higher education" |

## *Screening Process and Eligibility Criteria*

The document selection followed a three-stage PRISMA-guided process: identification, screening, and inclusion. The initial identification stage yielded 784 records from the Scopus database, with no duplicates detected because a single data source was used. During screening, documents were filtered by type and language to ensure methodological rigor and analytical consistency. Only peer-reviewed journal articles were retained, while non-article document types, such as conference papers, book chapters, reviews, and notes, were excluded (N = 391). In addition, 16 non-English publications were removed to maintain interpretive clarity and consistency in keyword and thematic analyses, resulting in 377 articles eligible for further evaluation.

The inclusion and exclusion criteria were applied to ensure conceptual alignment with the study's focus on IDTs in ESD. Articles were included if they were peer-reviewed journal publications indexed in Scopus, written in English, published between 2000 and October 2025, and explicitly addressed the use of digital, interactive, or immersive technologies within educational contexts linked to sustainability or ESD frameworks. Conversely, studies were excluded if they focused solely on technical system design without educational application, originated from non-educational or industrial domains, or lacked explicit connections to sustainability or ESD. After applying these criteria, 377 articles were retained for final analysis, forming a conceptually coherent and comprehensive corpus of literature, with the full selection process summarized in the PRISMA flow diagram presented in Figure 1.

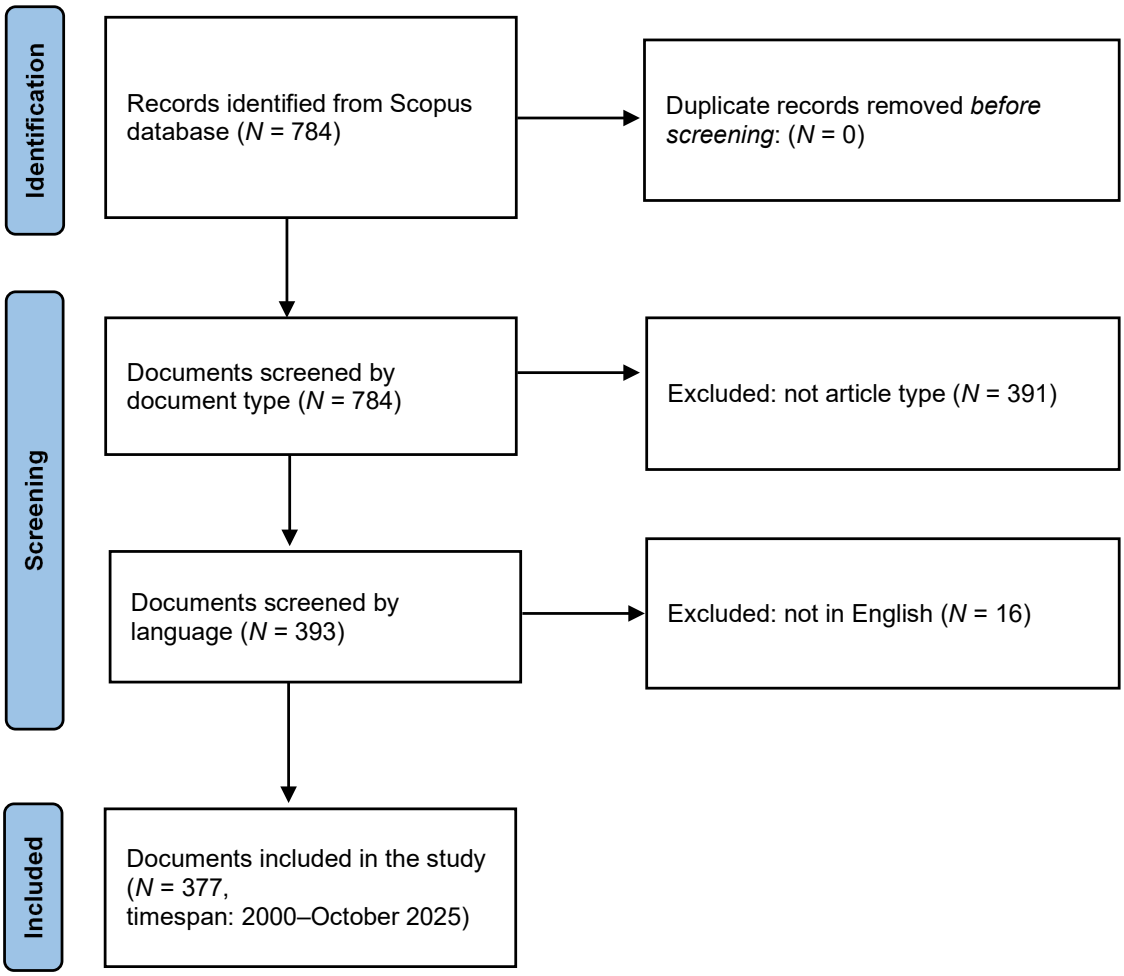


**Figure 1. PRISMA flow diagram of document selection**

## *Data Analysis*

Following dataset refinement, the bibliometric analysis was conducted in two main phases: dynamic and structural. The dynamic analysis examined the temporal and quantitative aspects of the dataset, including publication growth, citation patterns, author productivity, institutional output, and international collaboration. These indicators provided an overview of the evolution of research on IDTs in ESD over the past 25 years.

Keyword analyses employed a minimum co-occurrence threshold of five to identify significant thematic nodes. Author, institutional, and country-level collaborations, as well as impact indicators, were analyzed using the Bibliometrix R-package to ensure consistency and replicability across datasets. To deepen the interpretive dimension of the analysis, the study also identified research hotspots highlighted in the fifteen most-cited articles in the dataset. These top-cited papers were examined to capture dominant conceptual themes, methodological approaches, and implementation challenges shaping the intersection between IDTs and ESD.

This combined approach of quantitative mapping and thematic synthesis enabled detailed visualization of the field's development, highlighting how interactive and digital technologies have been integrated into educational systems to advance sustainability objectives. The methodological framework, integrating Scopus-based data retrieval, PRISMA-guided screening, and dual-tool bibliometric visuali-

zation, ensures reproducibility and analytical rigor. Collectively, these steps provide a robust foundation for understanding how IDTs have evolved within the ESD discourse, revealing emerging trends, dominant contributors, and intellectual trajectories over the past quarter century.

# RESULTS

## *DESCRIPTIVE OVERVIEW OF THE RESEARCH LANDSCAPE*

As summarized in Table 3, the bibliometric analysis of research on IDTs in ESD from 2000 to October 2025 reveals a rapidly expanding and increasingly mature research landscape. The dataset comprises 377 articles published across 195 sources, with a high annual growth rate of 14.94% and an average document age of 4.14 years, indicating an emerging yet dynamically evolving field. The mean of 16.58 citations per document reflects notable scholarly visibility, while the large volume of references (3,449) and extensive conceptual breadth, as evidenced by 1,299 author keywords and 1,023 keywords plus, highlight the field's intellectual richness and thematic diversity. Authorship patterns further underscore its collaborative and interdisciplinary character, with 1,417 authors, an average of 6.49 co-authors per article, no single-authored publications, and a substantial international co-authorship rate of 23.34%, signaling strong global engagement. Collectively, these indicators portray IDTs in ESD as a vibrant and interconnected research domain that aligns closely with broader agendas of digital transformation and sustainability-oriented pedagogy (UNESCO, 2020).

**Table 3. Descriptive statistics**

| Category | Indicator | Result |
|---|---|---|
| Main Information | Timespan | 2000–October 2025 |
| | Sources (Journals, Books, etc.) | 195 |
| | Documents | 377 |
| | Annual Growth Rate (%) | 14.94 |
| | Document Average Age | 4.14 |
| | Average Citations per Document | 16.58 |
| | References | 3,449 |
| Document Contents | Keywords Plus | 1,023 |
| | Author Keywords | 1,299 |
| Authorship and Collaboration | Authors | 1,417 |
| | Co-Authors per Document | 6.49 |
| | International Co-Authorships (%) | 23.34 |
| Document Type | Article | 377 (100%) |

## *PUBLICATION AND CITATION TRENDS*

The temporal distribution of publications on IDTs in ESD from 2000 to October 2025 demonstrates a distinct pattern of gradual emergence followed by exponential expansion (see Figure 2, green column). During the early years (2000–2009), research activity was sporadic, with fewer than three publications per year, reflecting the nascent stage of inquiry into digital technologies for sustainability-oriented education. Between 2010 and 2015, publication output began to increase modestly, averaging around six papers annually, indicating growing scholarly awareness of the potential of interactive technologies in educational contexts aligned with sustainability goals.

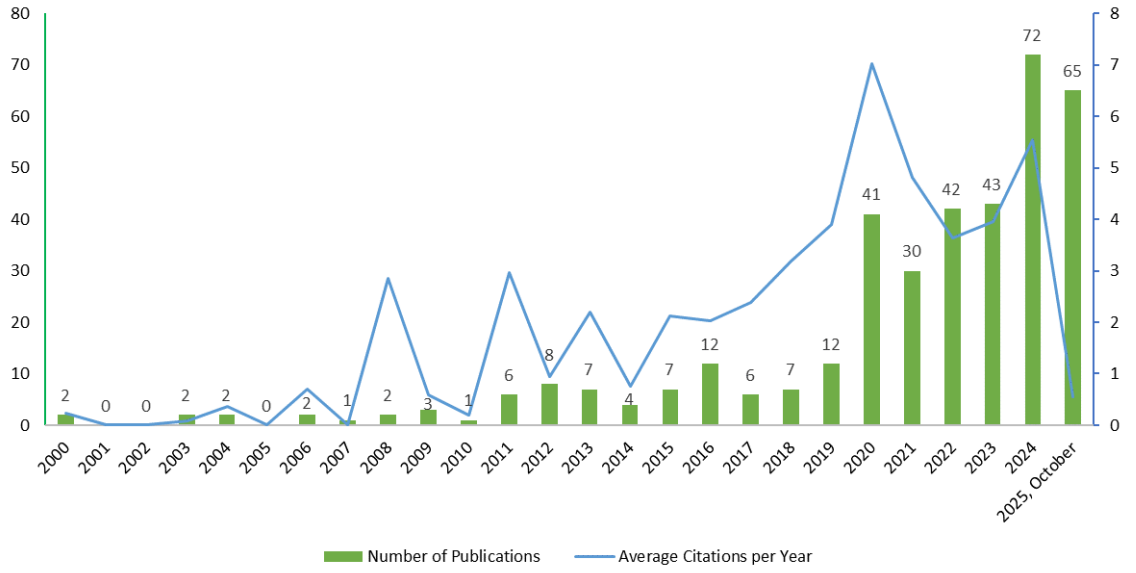


**Figure 2. Trends in annual publications and average citations per year on IDTs for ESD**

A substantial acceleration after 2016 marks a structural turning point in the field, where research on IDTs in ESD shifts from exploratory inquiry to sustained global attention. Rather than merely reflecting increased publication counts, this surge indicates the alignment of digital education research with major global agendas, particularly the SDGs and the rapid digital transformation triggered by the COVID-19 pandemic. This convergence suggests that interactive digital technologies are increasingly being conceptualized in the literature as important components of sustainability-oriented education systems. Following this, the upward trajectory continued, with 42 and 43 publications in 2022 and 2023, respectively. The most dramatic increase occurred in 2024, which recorded 72 publications, the highest annual output in the dataset, followed closely by 65 documents up to October 2025. This steep rise underscores the transformation of IDTs in the ESD domain from a developing field into a mature, rapidly expanding area of scholarly focus.

In terms of scholarly influence, the citation trend (see Figure 2, blue line) mirrors the field's developmental stages. Prior to 2010, average citations per year remained below 1.0, reflecting the limited academic visibility of early works. However, a gradual increase is observable after 2011, when the mean citation rate reached 2.97, indicating that foundational studies began to gain traction. The concentration of citation impact after 2020 reflects more than increased visibility; it signals rapid intellectual consolidation within the field. Rather than dispersed contributions, recent studies appear to be shaping a coherent and shared research agenda, particularly at the intersection of digital pedagogy, artificial intelligence, and sustainability education. This pattern suggests that the field is transitioning toward theoretical and conceptual maturity.

The trends displayed in Figure 2 illustrate a clear evolution: from isolated exploratory studies in the early 2000s toward a vibrant, globally engaged research community after 2020. The parallel rise in publication output and citation impact reflects both expanding scholarly participation and deepening theoretical and empirical contributions to the integration of digital technologies in ESD.

## *Keyword Analysis and Evolution*

Keyword analyses were conducted to identify dominant and emerging themes in IDTs in ESD. Following the principle that co-occurring keywords indicate conceptual relationships, both author keywords and Keywords Plus were examined using VOSviewer (van Eck & Waltman, 2010). A mini-

mum co-occurrence threshold of five was applied to highlight significant thematic nodes. As summarized in Table 3, the dataset includes 377 documents (2000–October 2025) containing 1,299 DE and 1,023 ID, demonstrating the thematic breadth of this field.

The keywords plus co-occurrence network (Figure 3) shows the temporal evolution of research foci, with blue nodes indicating earlier topics (2018–2020) and red/orange nodes representing emerging themes (2023–2024). The evolution of keywords suggests an emerging conceptual shift in the field. Early emphasis on *environmental education* and *e-learning* indicates a focus on content delivery and awareness-building, whereas recent themes such as *artificial intelligence*, *digitalization*, and *global crises (e.g., COVID-19)* signal a transition toward technology-mediated, systems-oriented sustainability learning. This shift suggests that recent publications increasingly frame IDTs as potential drivers of educational transformation rather than solely as supporting instructional tools.

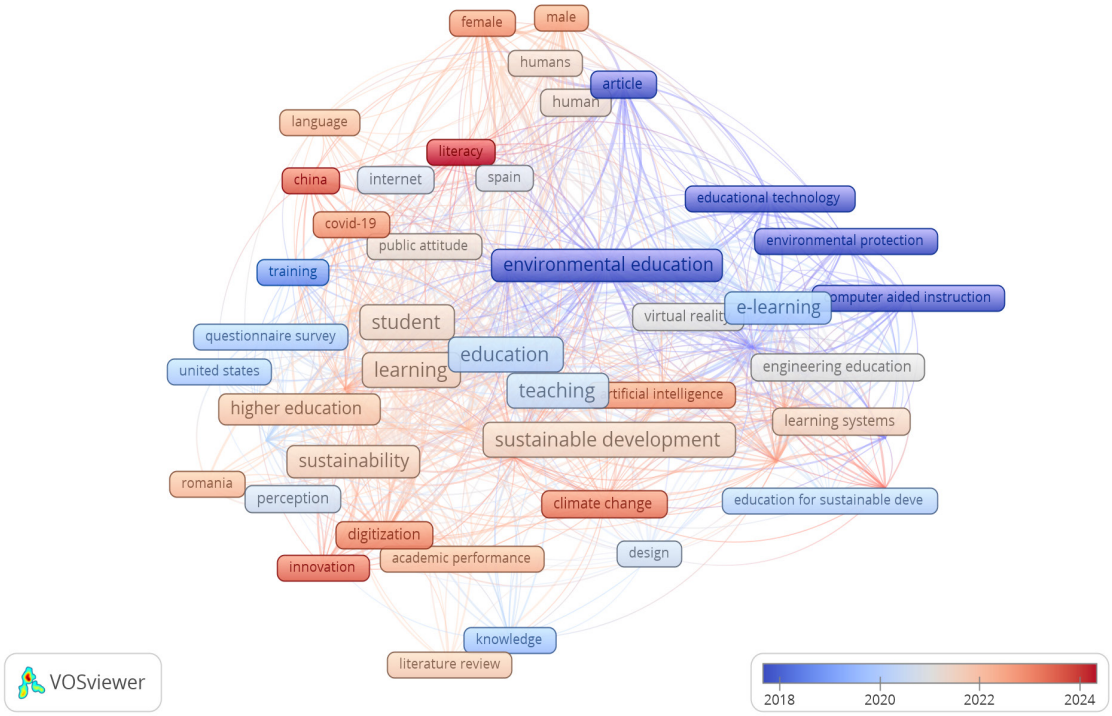


**Figure 3. Keywords plus co-occurrence network in IDTs for ESD**

A comparable but broader pattern appears in the author keywords network (Figure 4). A similar transition is evident in the author keyword network, where the shift from *ICT* and *e-learning* toward *artificial intelligence*, *immersive learning*, and *systems thinking* reflects a reorientation of the field. This progression indicates that sustainability education is increasingly embedded within digitally integrated and interactive learning ecosystems, emphasizing complexity, interactivity, and learner engagement.

Figures 5 and 6 collectively demonstrate a consistent thematic progression from foundational environmental education toward digitally mediated sustainability ecosystems. Rather than isolated thematic shifts, the parallel evolution of author keywords and keywords plus indicates a convergence between digital transformation and sustainability agendas. This convergence highlights the emergence of learner-centered, technology-enabled pedagogies as a defining characteristic of the field.

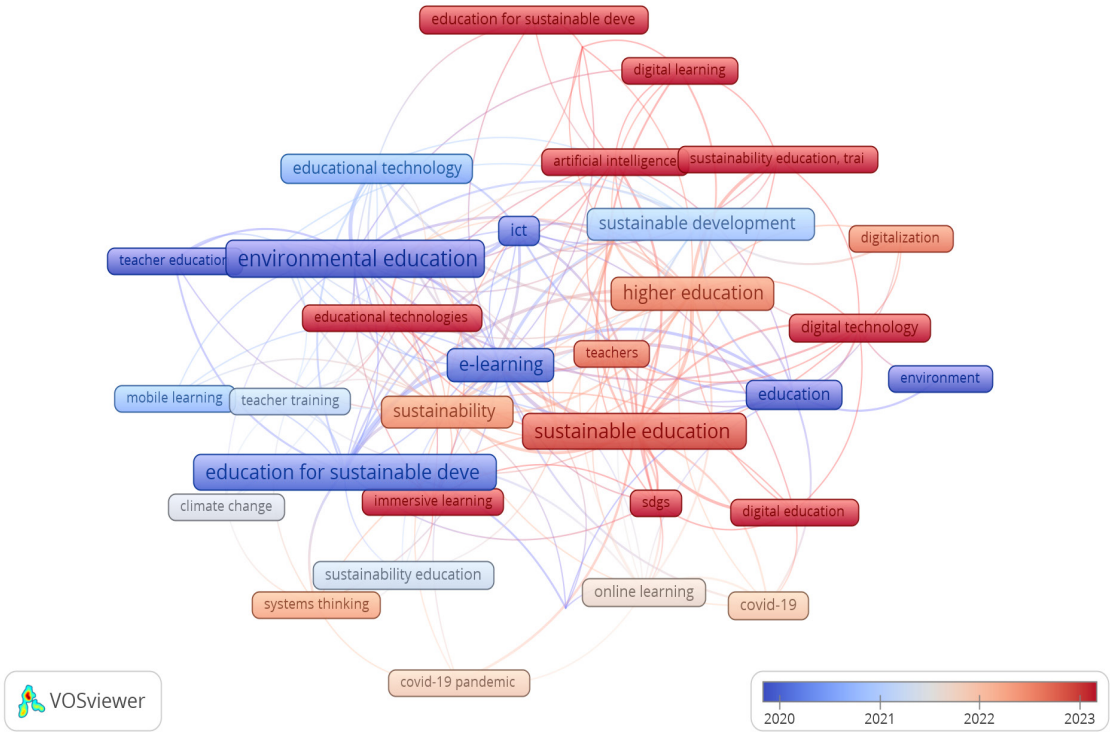


**Figure 4. Author keywords co-occurrence network in IDTs for ESD**

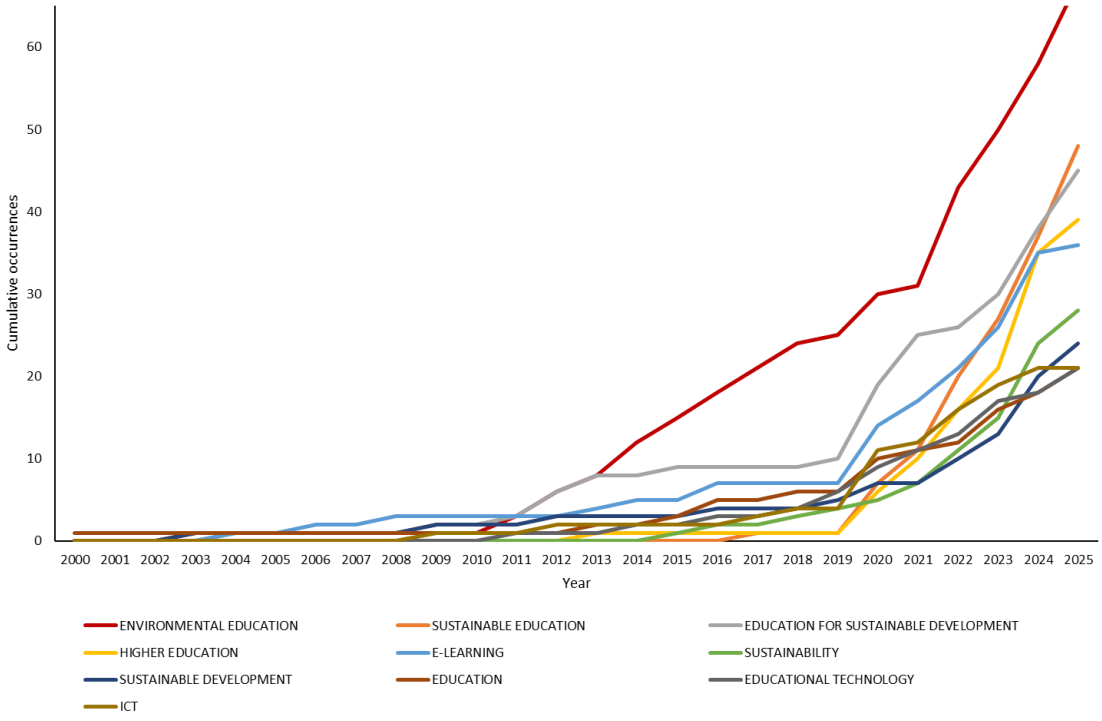


**Figure 5. Trends in author keywords in IDTs for ESD (2000–October 2025)**

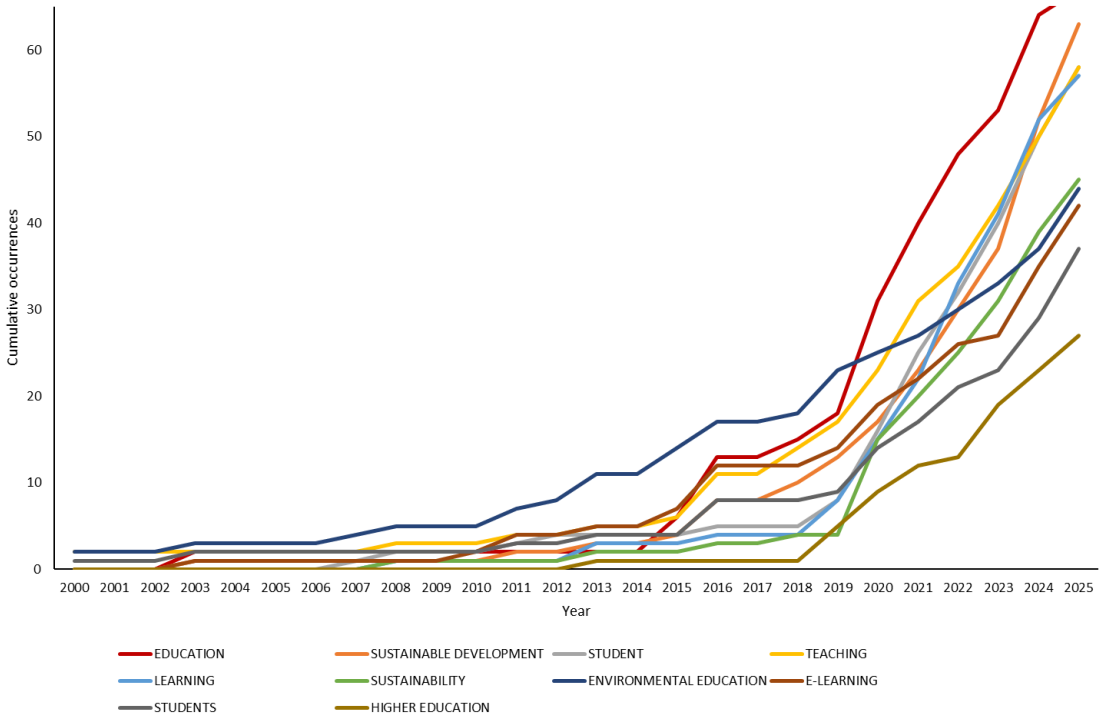


**Figure 6. Trends topics by keywords plus in IDTs for ESD (2000–October 2025)**

## *Influential Authors, Sources, Affiliations, and Countries*

The bibliometric mapping of IDTs in ESD highlights a growing international collaboration among scholars, journals, and institutions dedicated to integrating digital innovation into sustainability-oriented education. Analysis of the author network shows that a limited but influential group of researchers has consistently contributed to this emerging intersection between technology-enhanced learning and ESD. As presented in Table 4, the distribution of publications across authors suggests that the field is shaped by a relatively concentrated network of contributors. This pattern indicates that IDTs in ESD remain an emerging domain, where intellectual leadership is still consolidating among a core group of researchers before broader diffusion.

**Table 4. Most relevant authors in IDTs for ESD**

| Authors | Articles | Articles fractionalized |
|---|---|---|
| Avsec, Stanislav | 3 | 1.33 |
| Eilks, Ingo | 3 | 0.92 |
| González-Gómez, D. | 3 | 1.33 |
| Jeong, Jin Su | 3 | 1.33 |
| Makokotlela, Matlala Violet | 3 | 3.00 |
| Makrakis, Vassilios G. | 3 | 1.17 |
| Aljohani, Naif Radi | 2 | 0.50 |
| Baena-Morales, Salvador | 2 | 0.58 |
| Barragán-Sánchez, Raquel | 2 | 0.50 |
| Bersimis, Fragiskos Gerasimos | 2 | 0.45 |

Temporal analysis of publication and citation impact (see Table 5) reveals that Naif Radi Aljohani stands out as the most influential author, achieving 418 citations from a 2020 publication and maintaining the highest citation rate per year (TCpY = 69.667). It indicates the strong and sustained visibility of his research in digital transformation and ESD frameworks. Similarly, Makrakis V. G., a pioneer in sustainability pedagogy, shows consistent productivity since 2012, with 62 total citations. Meanwhile, González-Gómez, D., and Jeong, J. S., both exhibit parallel productivity and citation trajectories, each securing over 50 citations from their 2020 works focused on interactive digital learning environments. These results indicate a recent yet accelerating concentration of high-impact publications during and after 2020, reflecting a post-pandemic emphasis on integrating digital interactivity into sustainability education.

**Table 5. Authors' production over time in IDTs for ESD**

| Author | Year | Freq | TC | TCpY |
|---|---|---|---|---|
| Aljohani, Naif Radi | 2020 | 1 | 418 | 69.667 |
| Aljohani, Naif Radi | 2019 | 1 | 76 | 10.857 |
| Makrakis, Vassilios G. | 2012 | 3 | 62 | 4.429 |
| González-Gómez, D. | 2020 | 2 | 53 | 8.833 |
| Jeong, Jin Su | 2020 | 2 | 53 | 8.833 |
| Baena-Morales, Salvador | 2020 | 1 | 43 | 7.167 |
| Barragán-Sánchez, Raquel | 2020 | 1 | 38 | 6.333 |
| Baena-Morales, Salvador | 2022 | 1 | 21 | 5.250 |
| Avsec, Stanislav | 2022 | 1 | 20 | 5.000 |
| González-Gómez, D. | 2019 | 1 | 15 | 2.143 |

Further examination of local author impact metrics (see Table 6) shows that González-Gómez D., Jeong J.S., and Makrakis V.G. possess the highest *h*-index values (3), indicating consistent scholarly influence within the field. Although Aljohani N.R. has a lower *h*-index (2), his total citations (TC = 494) far exceed those of others, underscoring a concentrated yet impactful contribution. Emerging scholars such as Baena-Morales S. and Darinskaia L.A. demonstrate promising growth with notable *m*-index scores, reflecting rapid influence since their first publications in 2020 and 2023, respectively. Overall, these author metrics reveal a dynamic interplay between experienced sustainability educators and new contributors leveraging digital technologies to advance ESD goals.

**Table 6. Authors' local impact in IDTs for ESD**

| Author | h_index | g_index | m_index | TC | NP | PY_start |
|---|---|---|---|---|---|---|
| González-Gómez D. | 3 | 3 | 0.429 | 68 | 3 | 2019 |
| Jeong Jin Su | 3 | 3 | 0.429 | 68 | 3 | 2019 |
| Makrakis Vassilios G. | 3 | 3 | 0.214 | 62 | 3 | 2012 |
| Aljohani Naif Radi | 2 | 2 | 0.286 | 494 | 2 | 2019 |
| Avsec Stanislav | 2 | 3 | 0.500 | 23 | 3 | 2022 |
| Baena-Morales Salvador | 2 | 2 | 0.333 | 64 | 2 | 2020 |
| Bucea-Manea-Ţoniş Radu | 2 | 2 | 0.333 | 153 | 2 | 2020 |
| Bucea-Manea-Ţoniş Rocsana | 2 | 2 | 0.333 | 153 | 2 | 2020 |
| Darinskaia Larisa A. | 2 | 2 | 0.667 | 4 | 2 | 2023 |
| Eilks Ingo | 2 | 3 | 0.333 | 16 | 3 | 2020 |

Turning to the sources, *Sustainability (Switzerland)* dominates as the leading outlet for research in this domain with 91 publications (see Table 7). Its strong focus on sustainable education and technology integration has positioned it as the central hub for disseminating studies linking digital pedagogies to sustainability outcomes. The *Journal of Teacher Education for Sustainability* and the *International Journal of Sustainability in Higher Education* follow, reflecting the educational and policy-oriented dimensions of this research area. *Education Sciences* and *Cogent Education* also contribute substantially, publishing interdisciplinary work that bridges digital learning innovation with sustainability literacy. Notably, *Environmental Education Research* and *Journal of Cleaner Production* indicate cross-disciplinary engagement between educational sciences and environmental management research.

**Table 7. Most relevant sources in IDTs for ESD**

| Sources | Articles |
|---|---|
| Sustainability (Switzerland) | 91 |
| Journal of Teacher Education for Sustainability | 11 |
| International Journal of Sustainability in Higher Education | 10 |
| Education Sciences | 9 |
| Cogent Education | 8 |
| Journal of Cleaner Production | 7 |
| Environmental Education Research | 6 |
| Eurasia Journal of Mathematics, Science and Technology Education | 5 |
| Journal of Environmental Education | 5 |
| Australian Journal of Environmental Education | 3 |

Impact analysis of these sources (see Table 8) further confirms the centrality of *Sustainability (Switzerland)*, which has the highest *h*-index (27) and *g*-index (44), with over 2,200 total citations since 2013. The *Journal of Teacher Education for Sustainability* and the *International Journal of Sustainability in Higher Education* also demonstrate consistent citation growth, indicating strong reputations at the intersection of teacher training and sustainability literacy. Meanwhile, journals such as the British Journal of Educational Technology and Education Sciences show rapid increases in m-index, indicating the growing academic recognition of digital approaches to ESD.

**Table 8. Sources' local impact in IDTs for ESD**

| Source | h_index | g_index | m_index | TC | NP | PY_start |
|---|---|---|---|---|---|---|
| Sustainability (Switzerland) | 27 | 44 | 2.077 | 2209 | 91 | 2013 |
| Journal of Teacher Education for Sustainability | 8 | 11 | 0.571 | 129 | 11 | 2012 |
| Journal of Cleaner Production | 6 | 7 | 0.261 | 660 | 7 | 2003 |
| International Journal of Sustainability in Higher Education | 5 | 10 | 1.250 | 174 | 10 | 2022 |
| Education Sciences | 4 | 7 | 0.444 | 59 | 9 | 2017 |
| Environmental Education Research | 4 | 6 | 0.267 | 132 | 6 | 2011 |
| Journal of Environmental Education | 4 | 5 | 0.200 | 110 | 5 | 2006 |
| Australian Journal of Environmental Education | 3 | 3 | 0.600 | 12 | 3 | 2021 |
| British Journal of Educational Technology | 3 | 3 | 0.750 | 63 | 3 | 2022 |
| Eurasia Journal of Mathematics, Science and Technology Education | 3 | 5 | 0.375 | 80 | 5 | 2018 |

Institutional and geographical analysis provides additional insights into the global distribution of research activity. As seen in Table 9, the *Universitat d'Alacant* leads with 16 publications, followed closely by *Universidad de Burgos*, *Chukwuemeka Odumegwu Ojukwu University*, and the *University of Crete* (11 each). European institutions dominate the top affiliations, though universities from Africa and Asia, such as the *University of Calabar* (Nigeria) and *Central China Normal University*, show increasing engagement, reflecting the transnational relevance of ESD-oriented digital learning.

**Table 9. Most relevant affiliations in IDTs for ESD**

| Affiliation | Articles |
|---|---|
| Universitat D'alacant | 16 |
| Universidad de Burgos | 13 |
| Chukwuemeka Odumegwu Ojukwu University | 11 |
| University of Crete | 11 |
| University of Calabar | 10 |
| Universität Bremen | 10 |
| State University "Kyiv Aviation Institute" | 9 |
| Universidad de Sevilla | 9 |
| Central China Normal University | 8 |
| Universidad de Extremadura | 8 |

The geographical distribution of publications reveals an uneven but expanding global landscape (Table 10). The dominance of European and Asian countries suggests strong institutional alignment between sustainability policy and digital innovation, while the growing contributions from the Global South indicate an increasing diversification of perspectives and research contexts within the field.

**Table 10. Countries' scientific production in IDTs for ESD**

| Country | Frequency |
|---|---|
| Spain | 108 |
| China | 82 |
| Usa | 76 |
| Indonesia | 62 |
| Germany | 48 |
| Greece | 48 |
| Romania | 40 |
| Nigeria | 35 |
| Brazil | 34 |
| Italy | 34 |

## *Research Hotspots*

Table 11 presents the fifteen most globally cited articles addressing IDTs in ESD. The distribution of highly cited articles reflects a clear conceptual evolution of the field, moving from early pedagogical experimentation toward integrated digital sustainability ecosystems. This progression indicates that research is no longer focused solely on the effectiveness of individual technologies but is increasingly addressing the systemic, institutional, and ethical dimensions of sustainability-oriented digital education.

**Table 11. Highly cited publications on IDTs for ESD**

| Article (author, year) | Total citations | TC per year | Normalized TC |
|---|---|---|---|
| Waheed et al. (2020) | 418 | 69.67 | 9.91 |
| Abulibdeh et al. (2024) | 393 | 196.50 | 35.41 |
| Mian et al. (2020) | 216 | 36.00 | 5.12 |
| Chang et al. (2011) | 134 | 8.93 | 3.01 |
| Bordoloi et al. (2021) | 133 | 26.60 | 5.53 |
| González-Salamanca et al. (2020) | 116 | 19.33 | 2.75 |
| T. Zhang et al. (2020) | 107 | 17.83 | 2.54 |
| Klimova et al. (2016) | 107 | 10.70 | 5.28 |
| Caniglia et al. (2018) | 103 | 12.88 | 4.05 |
| Baytak and Land (2011) | 98 | 6.53 | 2.20 |
| Cheng et al. (2013) | 90 | 6.92 | 3.17 |
| Kalogiannakis and Papadakis (2017) | 88 | 9.78 | 4.09 |
| Bucea-Manea-Ţoniş et al. (2021) | 85 | 17.00 | 3.54 |
| Mokski et al. (2023) | 84 | 28.00 | 7.08 |
| González-Zamar et al. (2020) | 76 | 12.67 | 1.80 |

Synthesizing the evidence from these 15 influential papers reveals that research on IDTs for ESD has converged into 5 major thematic hotspots. The first hotspot concerns the **emergence of AI and data-driven decision-making** as new pillars for sustainable learning environments. Waheed et al. (2020) demonstrated that deep learning models can identify at-risk students using data from virtual learning environments, enabling early interventions to support educational sustainability. Abulibdeh et al. (2024) expanded this discussion to the ethical, curricular, and governance dimensions of integrating AI tools, particularly large language models such as ChatGPT, within the ESD paradigm.

The second hotspot focuses on **digital and green ICT curricula** that align with institutional transformation in line with Industry 4.0. Klimova et al. (2016) emphasized the establishment of international Master's programs linking pervasive computing to sustainability awareness; Caniglia et al. (2018) introduced the "glocal curriculum," combining digital transnational collaboration with local sustainability engagement; and Mian et al. (2020) applied SWOT–AHP analysis to map university readiness for sustainable digitalization. These studies collectively position green ICT education as a structural enabler of sustainability competencies.

The third hotspot revisits **game-based, mobile, and outdoor learning** for environmental education, representing the pedagogical roots of interactivity in ESD. Chang et al. (2011) and Baytak and Land (2011) demonstrated that inquiry- and constructionist-based learning through digital games foster environmental knowledge and critical thinking, while Cheng et al. (2013) and Kalogiannakis and Papadakis (2017) confirmed the motivational value of mobile and QR-code-based learning experiences in real-world contexts. This cluster underscores the enduring role of engagement and experiential immersion as drivers of behavioral change toward sustainability.

The fourth hotspot involves **ICT management, blockchain, and virtual environments** in sustainable higher education. González-Zamar et al. (2020) identified global research trajectories linking ICT governance with sustainable institutional policy; Bordoloi et al. (2021) described how the COVID-19 crisis accelerated digital adoption and reshaped blended learning culture; Bucea-Manea-Ţoniş et al. (2021) showed that blockchain can enhance student motivation and collaboration; and T. Zhang et al. (2020) proposed a universal e-learning model structured around self-regulation and competence

growth. Together, these works illustrate the systemic dimension of technological integration in sustainability-oriented education.

Finally, the fifth hotspot pertains to **interdisciplinarity and twenty-first-century competences** as the educational core of sustainability transformation. González-Salamanca et al. (2020) argued for active, ICT-mediated pedagogies to cultivate transversal competences, while Mokski et al. (2023) advanced a harmonized model combining stand-alone and integrated curricula supported by digital collaboration. This cluster shifts the discourse from tools to learning ecosystems, advocating a holistic redesign of higher education toward inclusive, cross-disciplinary sustainability outcomes.

Table 12 summarizes these five hotspots, mapping their representative studies, core foci, emerging technologies, and educational implications. The synthesis suggests an emerging conceptual transition from viewing technology primarily as a tool toward understanding it as part of broader sustainability learning ecosystems. Furthermore, interactive digital systems are increasingly discussed in the literature as infrastructures supporting sustainable learning design and governance.

**Table 12. Summary of research hotspots in IDTs for ESD**

| Hotspot | Representative studies | Core focus | Emerging technologies | Educational implications |
|---|---|---|---|---|
| AI and Data-Driven Sustainable Learning | Waheed et al. (2020); Abulibdeh et al. (2024) | Predictive analytics, ethical AI, learning analytics | Deep learning, ChatGPT, NLP | Early intervention, ethical ESD policy |
| Digital & Green ICT Curricula | Klimova et al. (2016); Caniglia et al. (2018); Mian et al. (2020) | Green ICT education, transnational collaboration | IoT, cloud systems, Industry 4.0 | Curriculum modernization, sustainability literacy |
| Game-Based & Mobile Learning | Chang et al. (2011); Baytak and Land (2011); Cheng et al. (2013); Kalogiannakis and Papadakis (2017) | Experiential digital pedagogy | WebQuest, DGBL, mobile apps, QR codes | Active learning, environmental responsibility |
| ICT Management & Blockchain in HEIs | González-Zamar et al. (2020); Bordoloi et al. (2021); Bucea-Manea-Ţoniş et al. (2021); T. Zhang et al. (2020) | ICT governance, online collaboration | Blockchain, MOOCs, VR/AR | Institutional resilience, digital ethics |
| Interdisciplinarity & 21st-Century Competences | González-Salamanca et al. (2020); Mokski et al. (2023) | Competence-based ESD, integrated curricula | LMS, collaborative platforms | Cross-disciplinary sustainability learning |

Complementing the hotspot synthesis, Table 13 distills the principal implementation challenges identified across the fifteen most-cited works. These include: (1) Ethical and governance dilemmas in AI-based personalization and data privacy (Abulibdeh et al., 2024; Waheed et al., 2020); (2) Institutional readiness gaps such as financial constraints, infrastructure, and faculty competence for digital transformation (Klimova et al., 2016; Mian et al., 2020); (3) Digital divide and inclusivity barriers, especially in developing contexts during the COVID-19 transition (Bordoloi et al., 2021); (4) Pedagogical alignment issues, where technology use is prioritized over learning design (Kalogiannakis & Papadakis, 2017); (5) Socio-emotional and cognitive balance, which remains underexplored in blockchain-based or fully online learning environments (Bucea-Manea-Ţoniş et al., 2021); and (6) Coordination challenges in interdisciplinary integration that require new governance models within HEIs (González-Salamanca et al., 2020; Mokski et al., 2023).

**Table 13. Key implementation challenges identified in the top 15 cited articles**

| Challenge category | Illustrative sources | Description |
|---|---|---|
| Ethical and Data Governance | Abulibdeh et al. (2024); Waheed et al. (2020) | Need for regulatory frameworks ensuring privacy, transparency, and fairness in AI-based education. |
| Institutional Readiness | Mian et al. (2020); Klimova et al. (2016) | Limited infrastructure, funding, and digital skills impede the transition toward Industry 4.0 universities. |
| Digital Divide and Access | Bordoloi et al. (2021) | Persistent inequities in connectivity and device access hinder inclusive digital sustainability education. |
| Pedagogical Alignment | Kalogiannakis and Papadakis (2017); Chang et al. (2011) | Overemphasis on tools without pedagogical coherence weakens learning motivation and outcomes. |
| Socio-Emotional and Cognitive Balance | Bucea-Manea-Ţoniş et al. (2021) | Need to integrate emotional and cognitive development in blockchain- and VR-supported learning. |
| Interdisciplinary Coordination | Mokski et al. (2023); González-Salamanca et al. (2020) | Complex governance required to link stand-alone and embedded ESD curricula across disciplines. |

Overall, these challenges delineate the frontier of current ESD research: the movement toward an ethically guided, institutionally coherent, and pedagogically grounded digital sustainability ecosystem. The trajectory revealed by the fifteen most-cited papers confirms that the intersection of AI, green ICT, interactive pedagogy, and interdisciplinary policy frameworks constitutes both the intellectual hotspot and the practical agenda for future scholarship in IDTs for ESD. More broadly, the results indicate a transition from fragmented, technology-specific applications toward an integrated, ecosystem-based understanding of IDTs in sustainability education, reflecting the growing recognition of digital technologies as structural enablers of sustainability learning rather than isolated instructional tools.

## DISCUSSION

Bibliometric evidence indicates that research on IDTs in ESD has undergone clear conceptual development over the past two decades. The sharp growth in publications after 2016 should not be interpreted merely as quantitative expansion, but as a structural reconfiguration of the field. This turning point reflects the convergence between global sustainability agendas (SDGs) and the rapid digital

transformation of education, suggesting that recent literature increasingly conceptualizes IDTs as infrastructures that support the production, mediation, and application of sustainability knowledge. Accordingly, the development of this field is shaped not only by technological innovation but also by global policy agendas (Leal Filho et al., 2024; Ossiannilsson, 2022; UNESCO, 2020). These bibliometric patterns suggest an emerging shift toward conceptualizing IDTs as components of integrated sustainability-oriented education systems rather than solely as supplementary instructional tools.

This transformation can be more deeply interpreted through the lenses of Transformative Learning Theory (Mezirow, 1997), TPACK (Mishra & Koehler, 2006), and TAM (Davis, 1989). From a transformative perspective, IDTs enable experiential and reflective learning processes that are essential for sustainability-oriented mindset shifts. However, TPACK highlights that such transformation depends on the alignment between technology, pedagogy, and content, while TAM suggests that adoption remains contingent upon perceived usefulness, ease of use, and institutional readiness. Therefore, the role of IDTs in ESD is not inherently transformative but becomes effective only when supported by coherent socio-pedagogical integration.

The consolidation of the literature after 2020, reflected in both publication volume and citation intensity, coincides with the diffusion of artificial intelligence, immersive learning environments, and learning analytics within educational research. While prior studies emphasize the potential of digitally mediated and learner-centered pedagogies to support systems thinking and ethical awareness (e.g., Anthonysamy et al., 2020; Carrión-Martínez et al., 2020; Şen & Yildiz Durak, 2022), the present findings call for a more critical interpretation. The growing dominance of AI-related and technology-driven themes suggests a techno-centric orientation in the field, where innovation may be prioritized over pedagogical depth and sustainability outcomes. This raises a fundamental concern that IDTs risk being treated as ends in themselves, rather than as means to foster meaningful sustainability competencies. At the same time, it is important to recognize that bibliometric indicators primarily reflect scholarly visibility and intellectual structure, rather than direct pedagogical effectiveness or learning outcomes.

This study relied exclusively on the Scopus database as the source of bibliographic data. Although Scopus is widely recognized as one of the most comprehensive databases for bibliometric research (Bhatt & Emdad, 2025; Nguyen et al., 2025; Siregar et al., 2026), this choice may influence the structure and interpretation of the findings. The inclusion of additional databases, such as Web of Science and ERIC, could alter results by introducing differences in journal coverage, citation patterns, and thematic emphasis. For instance, ERIC may contribute more education-focused and practice-oriented studies, while Web of Science may shift citation-based impact indicators due to its more selective indexing criteria. Therefore, the findings of this study should be interpreted as a robust but database-dependent representation of the field.

The evolution of keywords indicates an emerging conceptual shift from conventional ICT-based environmental education toward integrated sustainability learning frameworks that emphasize artificial intelligence, digital transformation, and climate-related themes. However, beyond this apparent progression, the findings also reveal a critical imbalance in the field. While technological sophistication continues to advance, relatively limited attention is given to long-term sustainability competencies, behavioral transformation, and sociocultural contextualization (Damaševičius & Sidekerskienė, 2024; UNESCO, 2020). This suggests that research on IDTs in ESD is evolving faster in technological dimensions than in pedagogical and ethical depth, creating a gap between digital capability and actual sustainability impact. Nevertheless, because document retrieval was restricted to the TITLE-ABS-KEY field, the analysis may have captured some publications with peripheral relevance while simultaneously overlooking niche or context-specific studies whose conceptual focus is not explicitly reflected in titles, abstracts, or author keywords (Sweileh, 2021; Zyoud et al., 2023).

The synthesis of highly cited publications identifies five dominant research hotspots that define the intellectual structure of IDTs in ESD, including AI-enabled personalization, green ICT curricula, experiential digital pedagogy, institutional ICT governance, and interdisciplinary competence development (Baytak & Land, 2011; González-Salamanca et al., 2020; González-Zamar et al., 2020; Klimova et al., 2016; Waheed et al., 2020). The analysis was intentionally limited to journal articles in order to ensure methodological consistency and a focus on peer-reviewed scientific contributions. While this approach strengthens internal validity, it may exclude valuable insights from conference proceedings, book chapters, and review papers, which often serve as early indicators of emerging or interdisciplinary research directions.

Geographical patterns indicate increasing contributions from Asia, Africa, and Southeast Asia alongside the continued dominance of European research outputs (Koopman et al., 2025; X. Zhang et al., 2025). Nevertheless, the exclusive focus on English-language publications may underrepresent regional scholarship published in other languages, thereby constraining the visibility of locally grounded perspectives. These limitations highlight the need for future research to integrate multiple databases, multilingual sources, and complementary qualitative approaches to capture the contextual richness and practical enactment of IDTs across diverse ESD settings.

Building on these findings, this study proposes a conceptual shift toward a Digital Sustainability Learning Ecosystem (DSLE) framework. This proposition aligns with emerging perspectives that emphasize the systemic and integrated nature of technology-enhanced sustainability education (e.g., UNESCO, 2020). Within this framework, IDTs are understood not as isolated tools but as interconnected components of a broader ecosystem integrating: (1) technological infrastructures (e.g., AI, VR, data analytics), (2) pedagogical design (transformative, experiential, and inquiry-based learning), (3) institutional governance (policy, ethics, and access), and (4) sustainability competencies (systems thinking, values, and action), situated within broader learning communities and stakeholder contexts. These components form a dynamic, mutually reinforcing ecosystem in which each dimension interacts bidirectionally to support the development of sustainability competencies.

This framework operationalizes the alignment required for IDTs to function as enablers of sustainability competencies, rather than as isolated technological interventions. Each dimension plays a complementary role within the ecosystem, where technological infrastructures provide enabling capabilities, pedagogical design shapes meaningful and transformative learning experiences, and institutional governance ensures ethical, inclusive, and sustainable implementation. To clarify this conceptual integration, the proposed DSLE framework is visually illustrated in Figure 7.

Taken together, the discussion situates this study as an analysis of the field's intellectual configuration, rather than as an empirical assessment of pedagogical effectiveness or sustainability outcomes. These interpretations directly address the research questions of this study. The rapid publication growth (RQ1) reflects structural alignment with global sustainability and digital transformation agendas; the evolution of keywords (RQ2) indicates a paradigmatic shift toward AI-driven and systems-oriented sustainability learning; the concentration of influential contributors (RQ3) highlights uneven global knowledge production; and the identified research hotspots (RQ4) collectively demonstrate the emergence of an integrated digital sustainability ecosystem. Thus, the study moves beyond descriptive mapping to offer a conceptual explanation of how IDTs are actively reshaping ESD's trajectory.

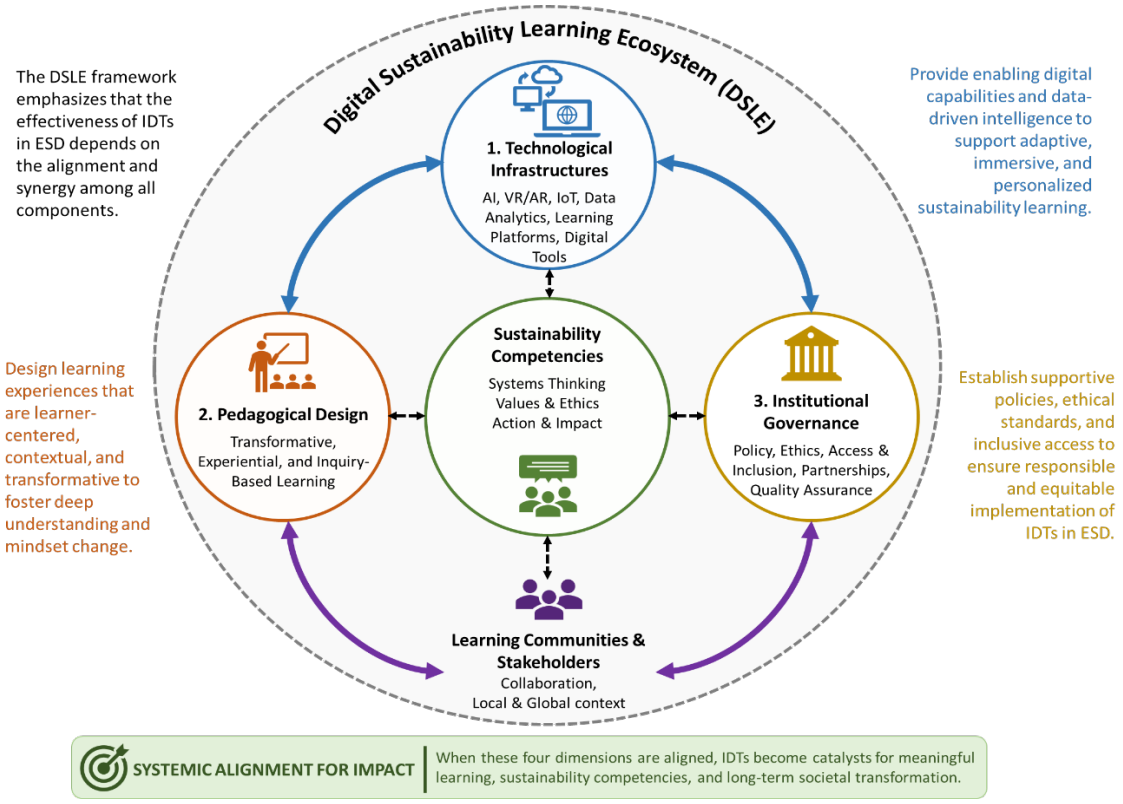


**Figure 7. Conceptual framework of the DSLE**
**The framework shows the alignment among technological, pedagogical, institutional, and sustainability competency dimensions, highlighting that the effectiveness of IDTs in ESD depends on systemic alignment rather than isolated technological adoption.**

## CONCLUSION

This study goes beyond mapping the growth of IDTs in ESD by identifying bibliometric patterns that suggest an evolving conceptualization of digital technologies within sustainability education. Rather than functioning solely as isolated instructional tools, the bibliometric evidence suggests that recent scholarship increasingly frames IDTs as structural enablers of integrated sustainability learning ecosystems, indicating an emerging conceptual shift in the field.

The identification of five major research hotspots suggests that recent research attention is increasingly concentrated on data-driven, system-oriented, and competence-based sustainability education, in which technological, pedagogical, and institutional dimensions are increasingly interdependent.

The originality of this study lies in its integrative perspective, which reconceptualizes the role of IDTs in ESD through a DSLE lens. Unlike prior studies that focus on specific technologies or pedagogical applications, this research positions digital technologies within a systemic framework that connects infrastructure, pedagogy, governance, and sustainability competencies. This contributes to theory by proposing a perspective that extends discussions of technology adoption toward ecosystem alignment.

Practically, the findings highlight the urgent need for educators, institutions, and policymakers to move beyond fragmented technology adoption toward coherent, ethically grounded, and system-level digital strategies. This includes aligning teacher capacity development, digital infrastructure, governance frameworks, and sustainability competencies within unified educational ecosystems.

Future research should move beyond bibliometric mapping to empirically examine how such ecosystems function in practice, particularly in terms of their impact on measurable sustainability competencies, ethical decision-making, and long-term behavioral transformation across diverse sociocultural contexts.

Ultimately, the future of ESD will depend not on the presence of digital technologies, but on how effectively they are orchestrated within integrated ecosystems that transform learning, empower action, and sustain global development.

## DATA AVAILABILITY STATEMENT

The data and analysis files used in this study have been made publicly available on the Open Science Framework (OSF) platform here: https://osf.io/thdv4/overview?view_only=887ed374817d458db0c3a278fae3cb22.

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