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E-Learning and Education for Sustainable Development in the Digital Age: A Bibliometric Analysis of Contributions to the SDGs

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Abstract:
The implementation of the Sustainable Development Goals (SDGs) by the United Nations in 2015 positioned education as a key element in achieving these global objectives, particularly SDG 4, which focuses on quality education. This study explores the role of e-learning in supporting Education for Sustainable Development (ESD) and its alignment with the Sustainable Development Goals (SDGs). Using a bibliometric analysis of 421 publications from 2010 to 2023 sourced from the Scopus database, the research identifies publication trends, international collaboration, and thematic developments in e-learning related to SDGs. The findings indicate significant growth in e-learning research following the adoption of the SDGs in 2015, with the most substantial increase occurring post-COVID-19 due to accelerated digital education needs. China, Spain, and the United States are highlighted as leading contributors to this field. Key topics identified include the integration of sustainability principles in digital education and the use of emerging technologies such as artificial intelligence (AI) and augmented reality (AR). These insights emphasize the potential of e-learning as a vehicle for advancing SDG 4 (Quality Education) and contributing to other goals like SDG 13 (Climate Action). The analysis also underscores challenges, such as digital inequalities, that must be addressed to enhance the reach and impact of e-learning in sustainable education.
Keywords: *e-learning, online learning, education for sustainable development, ESD, sustainable development goals, SDGs, bibliometric analysis, digital learning, technology-enhanced learning*

INTRODUCTION

A global call to action, the Sustainable Development Goals (SDGs), launched by the United Nations in 2015, represent a visionary framework for addressing the world's most pressing challenges. Encompassing issues such as poverty, inequality, climate change, and environmental degradation, the 17 SDGs aim to guide global efforts toward a sustainable and equitable future by 2030 [1]. Among these, SDG 4 is pivotal, aiming to "ensure inclusive and equitable quality education and promote lifelong learning opportunities for all." Education underpins not only its own standalone goal but also serves as a foundation for advancing other SDGs, including SDG 5 (Gender Equality), SDG 13 (Climate Action), and SDG 8 (Decent Work and Economic Growth). In this context, Education for Sustainable Development (ESD) is essential for realizing SDG 4 by equipping learners with the knowledge, skills, and values needed to make informed, responsible decisions on environmental, economic, and social issues [2]. With the advancement of digital technology, e-learning has emerged as a powerful medium for delivering ESD, providing flexible and accessible learning experiences that extend educational opportunities globally [3,4]. Through online courses, Massive Open Online Courses (MOOCs), virtual classrooms, and mobile learning applications, e-learning platforms are overcoming geographic, financial, and social barriers, democratizing educational access for underserved and remote communities [5,6]. E-learning also offers a platform for integrating sustainability principles across a wide range of subjects. By leveraging online tools, learners can explore topics such as environmental science, sustainable energy, and climate change mitigation strategies. This contributes to SDG 13 by reducing the carbon footprint associated with traditional educational infrastructure [7]. The COVID-19 pandemic underscored the vital role of e-learning in maintaining educational continuity during crises. As schools and universities worldwide closed, millions of students transitioned to online learning [8], accelerating the adoption of digital platforms and highlighting the necessity of robust digital infrastructure to sustain educational access [9]. However, the pandemic also revealed significant digital divides, particularly in low- and middle-income countries, where access to the

internet and technological resources is often limited [10]. Despite these challenges, the rapid expansion of e-learning during the pandemic demonstrated its potential to enhance educational resilience and contribute to sustainable development in the long term [11]. Given its broad reach, e-learning is an ideal tool for advancing SDG 4, particularly in promoting lifelong learning for marginalized populations and learners in resource-limited settings [12].

Prior studies on e-learning, including those by Djeki et al. [13], Tibaná-Herrera et al. [14], Martins et al. [15], Chiang et al. [16], Hung [17], and Fauzi [18], have primarily focused on trends, collaboration patterns, productivity, and thematic developments in e-learning. These studies, many of which employed bibliometric approaches, have explored topics such as e-learning adoption, international collaboration, and key influencers in the field. However, they have largely centered on adoption patterns and research trends, leaving a significant gap in understanding the connection between e-learning and the SDGs, particularly through ESD. To date, limited research has investigated how e-learning directly supports SDG 4 and enhances sustainability competencies. Furthermore, the role of e-learning in advancing other critical goals such as SDG 5 (Gender Equality) and SDG 13 (Climate Action) remains underexplored. This gap highlights the need for a focused bibliometric analysis to uncover the contributions of e-learning to ESD and its alignment with global SDG efforts, including international collaboration and the conceptual structure of related research.

This study, titled "E-Learning and Education for Sustainable Development in the Digital Age: A Bibliometric Analysis of Contributions to the SDGs," aims to fill this gap by conducting a bibliometric analysis specifically focused on e-learning's contributions to the SDGs through ESD. This research will explore how e-learning has evolved as a tool supporting ESD, examining international collaboration, research trends, and the conceptual links between e-learning and the SDGs. Specifically, this study seeks to answer the following research questions:

RQ1. How has research on e-learning and ESD evolved in the digital age?

RQ2. Which countries and institutions have significantly contributed to research on e-learning and ESD related to SDGs?

RQ3. What are the most influential journals and authors in this field?

RQ4. What are the collaboration patterns and intellectual structure of research on e-learning and ESD in the SDGs context?

RQ5. What is the conceptual structure of research on e-learning and ESD concerning SDGs?

By addressing these questions, this study aims to provide valuable insights for educators, policymakers, and researchers seeking to integrate e-learning into global efforts for sustainable development. By employing a bibliometric approach centered on the SDGs, this research will contribute to a more holistic understanding of the role of e-learning in achieving sustainable education goals while fostering international collaboration in this critical field.

METHODS AND METHODOLOGY:

Data Collection

Data for this bibliometric study were extracted from Scopus, a comprehensive and widely recognized academic database [19–21]. As of 2023, Scopus includes over 97.3 million scientific records from 25,300 peer-reviewed journals, 1,200 book series, and 12.5 million conference papers across diverse fields [22]. The search was conducted using keywords related to "e-learning," "Education for Sustainable Development (ESD)," and "SDGs" to capture relevant literature. Primary keywords included terms such as "e-learning," "digital learning," "online learning," and "technology-enhanced learning" alongside sustainability terms like "Education for Sustainable Development," "SDGs," and "green education." This query was designed to retrieve publications from 2010 to 2023, focusing on recent literature following the 2015 adoption of the SDGs. The search was limited to original research and review articles written in English.

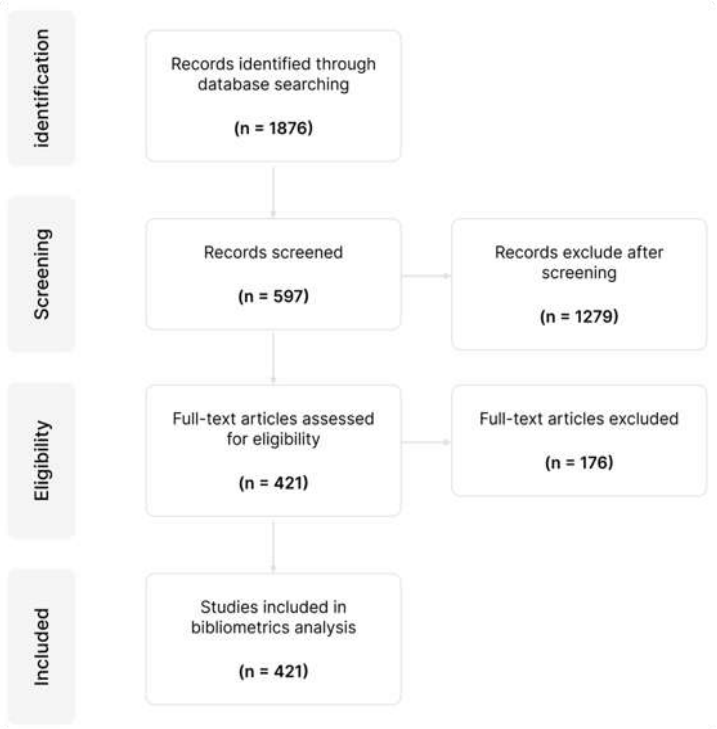

Figure 1. PRISMA flowchart of the study

Data Extraction and Screening

The initial search in Scopus yielded 1,876 documents, including articles, reviews, and conference papers. To ensure data quality and relevance, a thorough screening was conducted using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [23]. Titles and abstracts were reviewed to confirm alignment with the study's focus on e-learning, ESD, and SDGs, and irrelevant documents were excluded. Duplicate entries and non-peer-reviewed content, such as editorials and brief communications, were removed. Full texts of the remaining documents were assessed to ensure they addressed e-learning's role in promoting sustainability or its contributions to the SDGs. This process resulted in a final dataset of 421 documents for analysis (see Fig. 1 PRISMA flowchart).

Data Analysis

The final dataset was analyzed using VOSviewer and Bibliometrix R-Tool, software tools developed for bibliometric analysis and network visualization. Several key areas were analyzed. First, co-authorship analysis identified collaboration patterns among authors and institutions, highlighting the research network's structure and geographic productivity in this field. Second, co-citation analysis identified foundational works shaping current research on e-learning and sustainable development by examining frequently co-cited publications. Third, keyword co-occurrence analysis uncovered dominant research themes by analyzing keyword frequencies in the literature, identifying major research areas such as the role of e-learning in supporting quality education (SDG 4) and climate action (SDG 13). Additionally, citation analysis was used to pinpoint the most cited publications and authors, indicating influential contributions to the field.

Results

Evolution of Research on E-Learning and Education for Sustainable Development in the Digital Age

Research on e-learning's role in Education for Sustainable Development (ESD) has experienced considerable growth over the past decade, especially since the adoption of the United Nations Sustainable Development Goals (SDGs) in 2015. Specifically, SDG 4, which advocates for inclusive, equitable, and quality education, has inspired substantial academic interest in how digital learning technologies can contribute to achieving sustainable development objectives worldwide.

Table 1. Publication Overview

Description	Results
Timespan	2010-2023
Total Sources (Journals, Books, etc.)	199
Total Documents	421
Annual Growth Rate (%)	19.38

Average Document Age (Years)	0,18888889
Average Citations per Document	15.31
Total References	21,65
Keywords Plus (ID)	1,434
Author's Keywords (DE)	1,384
Total Authors	1,324
Single-Authored Documents	74
Average Authors per Document	03.33
International Co-authorship (%)	25.42.00
Document Type: Articles	405
Document Type: Reviews	16

Table 2. Number of Citations of The Publication Collection

Number of Citations	Number of Documents	Percentage
0	47	11,16%
1 to 10	213	50,59%
11 to 20	74	17,58%
21 to 54	67	15,91%
55 to 100	14	3,33%
>100	6	1,43%

A bibliometric analysis of 421 publications from 2010 to 2023 reveals a distinct upward trend in research activity, with an annual growth rate of 19.38% (see Table 1). This trend demonstrates increasing recognition of digital education as a valuable tool for promoting sustainable development. The research progression can be divided into three main phases:

Initial phase (2010–2015): During this phase, research on e-learning and ESD was in its early stages, with 49 articles published, representing 12.4% of the total publications over the study period. Publication rates remained relatively low, with an average of 9 to 14 articles per year. Research interest was building gradually, laying the foundation for future exploration into the potential of digital learning to address educational and sustainability goals.

Expansion phase (2016–2020): This period saw a notable increase in research output, with 108 publications, or 27.4% of the total. This phase aligns with the global adoption of the SDGs, as researchers increasingly explored how e-learning could support these ambitious goals. The expansion phase reflects the growing global emphasis on the importance of digital education in promoting sustainable practices and reaching underserved populations. Increased funding and attention from educational institutions and policymakers likely contributed to this surge in research activity.

Rapid growth phase (2021–2023): The most substantial growth occurred during this phase, with 259 articles published, accounting for 60.2% of the total research output. Annual publications peaked at 98 articles in 2022, indicating a robust academic response to the demand for sustainable educational solutions. This rapid growth phase corresponds with the post-pandemic era, during which the role of digital learning expanded dramatically due to widespread school closures and the need for remote education solutions. E-learning emerged as a crucial component of educational systems worldwide, fueling research into its applications for sustainable development.The most productive period was between 2021 and 2023, when over half (56.1%) of all publications were produced. During these years, annual publication numbers remained high, with no fewer than 71 articles each year. The peak publication volume in 2022 underscores a widespread recognition of e-learning's role in achieving the SDGs, particularly in the context of global challenges that have amplified the need for accessible, flexible, and sustainable educational practices.

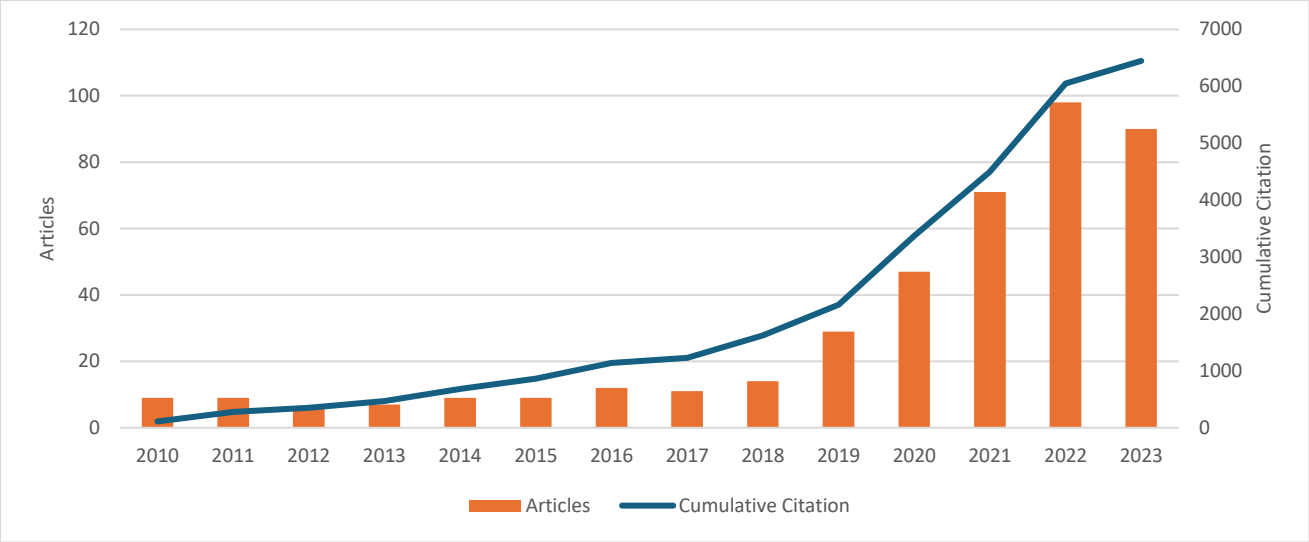

Figure 2. Bar chat illustrates annual number of publications and its cumulative citations

The cumulative citation count also reflects this growth, with 6,449 total citations over the study period (see Table 2) and an average of 15.31 citations per document, suggesting that key publications have significantly influenced the field. Certain milestone publications likely reinforced the role of e-learning in advancing ESD and contributed to shaping the academic discourse. Citation counts rose significantly from one phase to the next, highlighting the growing influence of this research area. In the initial phase (2010–2015), 863 citations were recorded, comprising 13.4% of the total. The expansion phase (2016–2020) saw a marked increase with 3,370 citations, representing 52.3% of the cumulative total. Finally, in the rapid growth phase (2021–2023), citations continued to rise, reaching 2,217, or 34.4% of the total.

On an annual basis, citation activity peaked in 2022, when 1,551 citations were recorded, accounting for 24.1% of the cumulative citations. Articles remain the most influential document type, as evidenced by their substantial contribution to the overall citation count, while other document types, such as reviews and proceedings papers, received relatively fewer citations. The average citation rate per document was 15.31, underscoring the impact and relevance of key publications in advancing understanding of e-learning's role in sustainable development (see Figure 2).

Geographic and Institutional Contributions to Research on E-Learning and ESD

Over the past decade, research on e-learning and Education for Sustainable Development (ESD) has seen significant growth, with an increasing number of countries and institutions contributing to the field. Initially, only a limited number of countries, such as the United States and the United Kingdom, were actively publishing in this area. However, between 2010 and 2023, this focus expanded considerably, with a total of 84 countries now involved in advancing e-learning and ESD research. This broad participation highlights the rising global importance of integrating sustainable development principles within digital learning environments.

China leads the global contributions with 66 publications, representing 11.40% of the total output. Spain follows with 45 publications (7.77%), while the United States has produced 37 publications (6.39%). The prominence of these countries underscores a shift in academic leadership, with Asian and European nations emerging as key players. Other major contributors include the United Kingdom with 32 publications (5.53%), Germany with 22 publications (3.80%), and Malaysia with 21 publications (3.63%). Australia, India, South Africa, and Taiwan are also significant contributors, each publishing between 16 and 17 articles (Table 3). Collectively, these top ten countries account for a large portion of the research output, demonstrating that e-learning and ESD are shared global priorities.

On the institutional level, a diverse array of 322 universities and research organizations worldwide have contributed to e-learning and ESD research. As illustrated in Table 4, Tecnológico de Monterrey in Mexico is the most productive institution, with 6 publications, accounting for 1.43% of the total output in this field. It is followed closely by University of Crete in Greece and Universidad de Extremadura in Spain, each contributing 5 publications (1.19%). Other notable institutions include Universiti Kebangsaan Malaysia, University of South Africa, Universitat Politècnica de València (Spain), The Open University (UK), Universidade Aberta (Portugal), and Universitatea Babeş-Bolyai (Romania), each with 4 publications (0.95%).

Table 3. Top 10 countries with the highest number of publications

Rank	Country	Number of Documents	Percentage (%)	Citations
1	China	66	11,40	1127
2	Spain	45	7,77	918
3	United States	37	6,39	491
4	United Kingdom	32	5,53	603
5	Germany	22	3,80	225
6	Malaysia	21	3,63	308
7	Australia	17	2,94	313
8	India	17	2,94	780
9	South Africa	17	2,94	223
10	Taiwan	16	2,76	470

Table 4. Top 10 most productive institutions publishing based on total number of publications

Rank	Institutions	Country	Number of Documents	Percentage (%)
1	Tecnológico de Monterrey	Mexico	6	1,43
2	University of Crete	Greece	5	1,19
3	Universidad de Extremadura	Spain	5	1,19
4	Universiti Sains Malaysia	Malaysia	4	0,95
5	Universiti Kebangsaan Malaysia	Malaysia	4	0,95
6	University of South Africa	South Africa	4	0,95
7	Universitat Politècnica de València	Spain	4	0,95
8	The Open University	UK	4	0,95
9	Universidade Aberta	Portugal	4	0,95
10	Universitatea Babeş-Bolyai	Romania	4	0,95

Leading Journals, Articles, and Authors

The analysis of journal productivity reveals that a limited number of journals are responsible for publishing a substantial portion of research related to e-learning and ESD. Table 5 presents the six most active journals in this area. *Sustainability (Switzerland)*, published by MDPI, ranks as the most productive journal, with 104 articles (24.7% of the dataset) and 1,806 citations. This high volume of publications and citations solidifies *Sustainability* as a core outlet for research on integrating digital education and sustainability. With a CiteScore of 6.8 and a Q1 ranking in Scopus, this journal provides a prominent platform for studies on sustainable education practices, policy frameworks, and technology-enhanced learning initiatives. Other key journals include the *International Journal of Sustainability in Higher Education* (Emerald Publishing), *Education Sciences* (MDPI), and *Journal of Cleaner Production* (Elsevier). Although these journals published fewer articles than *Sustainability*, they also play a significant role in advancing research on sustainable education and digital learning methods. Notably, the *Journal of Cleaner Production*, while contributing only eight articles, boasts a high CiteScore of 20.4, suggesting that it focuses on fewer but high-impact studies that appeal to a broader audience beyond academia, including policy-makers and industry practitioners.

The top six journals collectively published over 35% of the analyzed articles, illustrating their central role in disseminating knowledge on sustainable education practices. This concentration of research in a few high-impact journals highlights their influence in setting the agenda and standards for research at the intersection of digital education and sustainability. By publishing seminal studies, these journals contribute to shaping educational strategies, curriculum designs, and policy development aimed at integrating sustainability in digital learning environments.

Table 5. Top 6 most active journals publishing based on total number of publications

Rank	Journals	Publishing House	Articles	%	Citations	CiteScore 2023	Scopus Quartil
1	Sustainability (Switzerland)	Multidisciplinary Digital Publishing Institute (MDPI)	104	24,70	1806	6,8	Q1
2	International Journal of Sustainability in Higher Education	Emerald Group Publishing Ltd.	11	2,61	187	6,6	Q1

3	Education Sciences	Multidisciplinary Digital Publishing Institute (MDPI)	9	2,14	111	4,8	Q2
4	Journal Of Cleaner Production	Elsevier Ltd	8	1,90	190	20,4	Q1
5	International Journal of Environmental Research and Public Health	Multidisciplinary Digital Publishing Institute (MDPI)	7	1,66	70	7,3	Q2
6	Journal Of Teacher Education for Sustainability	De Gruyter Open Ltd.	7	1,66	67	4,1	Q2

Table 6. Top 10 most prolific authors based on total number of publications

Rank	Authors	Institution	Country	Articles	%	Citations	H-Index
1	González-Gómez, D.	Universidad de Extremadura	Spain	5	1,19	91	4
1	Jeong, J.S.	Universidad de Extremadura	Spain	5	1,19	91	4
3	Aksela, M.	Helsingin Yliopisto	Finland	3	0,71	51	3
3	Breaz, T.O.	Universitatea 1 Decembrie 1918 din Alba Iulia	Romania	3	0,7%	59	3
3	Fülöp, M.T.	Universitatea Babeş-Bolyai	Romania	3	0,71	59	3
6	Harizan, S.H.M.	Universiti Sains Malaysia	Malaysia	3	0,71	6	2
6	Makrakis, V.	University of Crete	Greece	3	0,71	53	3
6	Teixeira, A.	Universidade Aberta	Portugal	3	0,71	36	3
9	Adarkwah, M.A.	Beijing Normal University	China	2	0,48	209	2
9	Al-Okaily, M.	Jadara University	Jordan	2	0,48	76	2

Table 7 lists the ten most cited articles on e-learning and sustainable development, which together reflect some of the foundational work that continues to shape the field. The top-cited article, *"Understanding the role of digital technologies in education: A review"* by Haleem et al. (2022), published in *Sustainable Operations and Computers*, has accumulated 562 citations. This study provides an extensive review of digital technologies and their applications in educational contexts, positioning it as a pivotal reference for researchers and practitioners exploring the integration of digital tools in sustainable education.The second most cited article, *"I'm not against online teaching, but what about us?": ICT in Ghana post-COVID-19* by Adarkwah (2021), published in *Education and Information Technologies*, addresses the impact of the COVID-19 pandemic on education in developing countries. With 205 citations, it highlights the importance of digital literacy and access to technology in promoting equitable and sustainable education. This theme is further explored in other highly cited works, such as Chang et al.'s (2011) study on WebQuest and mobile learning for environmental education, and Daniela et al.'s (2018) research on sustainable higher education and technology-enhanced learning.These top ten articles collectively account for a significant portion of citations within the dataset, emphasizing their lasting impact and relevance in shaping both research and practice. They cover a range of themes, from self-regulated learning and ICT literacy to financing models for sustainable education, all of which are critical for achieving the SDGs in educational settings. The recurrence of themes related to technology-enhanced learning and sustainable practices underscores the sector's focus on innovation and adaptability, especially in the wake of global disruptions like the COVID-19 pandemic. Notably, *Sustainability* published several articles in this top-cited list, reinforcing its status as a primary source for impactful research on sustainable education.

Table 7. Top 10 most cited articles

Rank	Document Title	Author	Journal	Number of Citations

1	Understanding the role of digital technologies in education: A review	Haleem et al. [24]	Sustainable Operations and Computers	562
2	"I'm not against online teaching, but what about us?": ICT in Ghana post Covid-19	Adarkwah [25]	Education and Information Technologies	205
3	The study on integrating WebQuest with mobile learning for environmental education	Chang et al. [26]	Computers & Education	128
4	Self-regulated learning strategies in higher education: Fostering digital literacy for sustainable lifelong learning	Anthonysamy et al. [27]	Education and Information Technologies	110
5	Critical success factors for the continuation of e-learning initiatives	McGill et al. [28]	The Internet and Higher Education	105
6	Sustainable Higher Education and Technology-Enhanced Learning (TEL)	Daniela et al. [29]	Sustainability	97
7	Systematic Review of Good Teaching Practices with ICT in Spanish Higher Education. Trends and Challenges for Sustainability	Alonso-García et al. [30]	Sustainability	92
8	E-Learning Financing Models in Russia for Sustainable Development	Nie et al. [31]	Sustainability	87
9	Challenge Based Learning: Innovative Pedagogy for Sustainability through e-Learning in Higher Education	Portuguez Castro & Gómez Zermeño [32]	Sustainability	83
10	Applied Model of E-Learning in the Framework of Education for Sustainable Development	Zhang et al. [33]	Sustainability	78

Table 6 highlights the top authors contributing to e-learning and sustainable development research. This analysis identifies researchers who have published multiple influential articles, making substantial contributions to the academic and practical knowledge base in this domain. *González-Gómez, D.* and *Jenea, J.S.*, both from European institutions, lead with five articles each, contributing 1.19% to the overall dataset. Their research, often affiliated with universities in Spain and Romania, respectively, spans various facets of sustainable digital education, from curriculum development to policy impact analysis.Other prolific authors include *Asikainen, M.T.* from Finland and *Brez, T.O.* from Romania, with three articles each. These researchers, along with others in the top ten list, are actively engaged in exploring how digital education can support sustainable development, with research topics covering e-learning accessibility, environmental literacy, and pedagogical innovations. The contributions of these authors are frequently cited, reflecting their influence and the recognition of their work within the academic community.The geographical diversity of these leading researchers highlights the global relevance of sustainable education. Researchers from Europe, Asia, and the Middle East are represented, showcasing an international effort toward understanding and promoting sustainable development through digital learning. Many of these authors have also developed partnerships across institutions and countries, further enhancing the collaborative and interdisciplinary nature of research in this field. The H-Index values associated with these authors suggest that their contributions have not only been prolific but have also achieved significant impact, as reflected in their citation counts.

Collaboration Networks and Intellectual Structure of E-Learning and ESD Research

The analysis of collaboration networks at both the author and country levels, alongside a co-citation examination of influential authors, provides insights into the collaborative dynamics and intellectual underpinnings of research in e-learning and Education for Sustainable Development (ESD).

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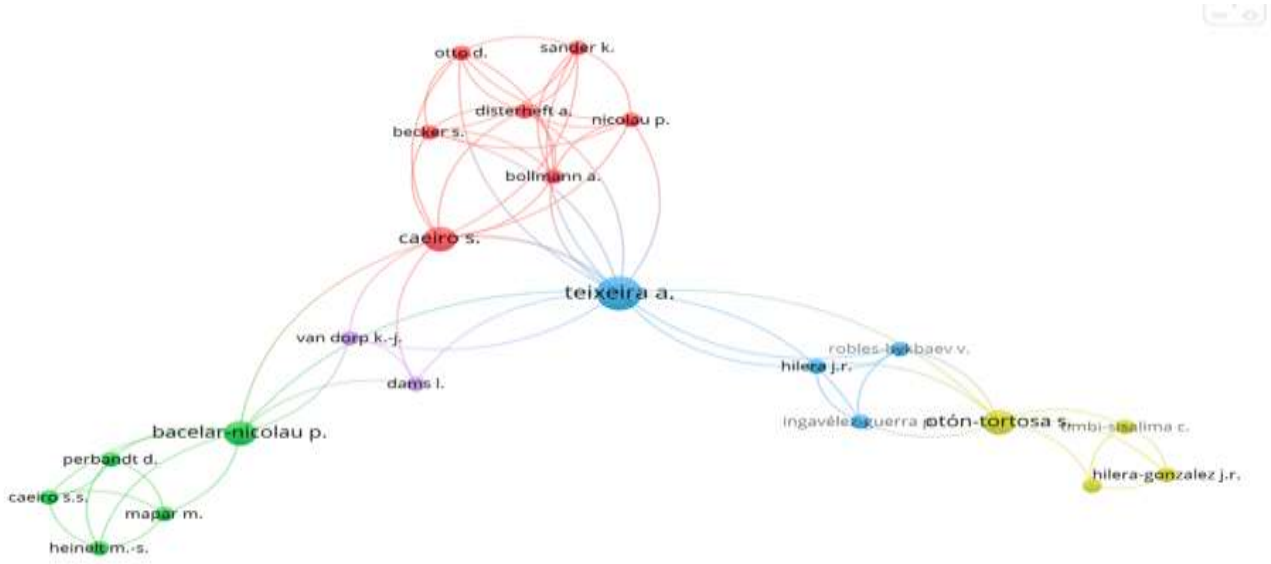

Figure 3. Network of co-authorship, authors level (minimum number of documents for each author, 1, n = 22)

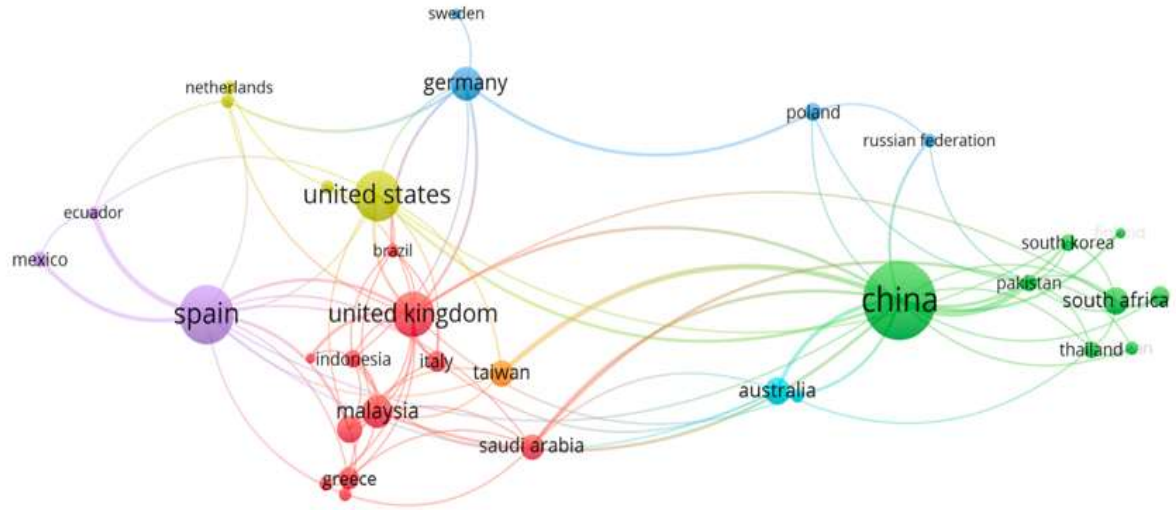

Figure 4. Network of co-authorship, countries level (minimum number of documents for each country, 5, n = 33)

The author-level co-authorship network (Figure 3) illustrates the connections between individual researchers in e-learning and ESD. This network highlights key figures whose work connects various clusters of researchers, establishing them as influential in this field. For instance, Teixeira A. is prominently positioned at the center of the network, with multiple strong collaborative links to other authors. This centrality suggests Teixeira A.'s prominent role in fostering collaborative research and influencing research directions within the field. Within this network, distinct clusters of authors emerge, representing specialized communities or research groups with frequent collaboration. Cluster 2, for example, includes Bacelar-Nicolau P., who holds a moderate relationship strength of 8, contributes to two publications, and has a normalized citation score of 0.5261, with an average of 3.5 citations per publication. This indicates moderate impact but a strong collaborative presence in their subgroup. Cluster 1, on the other hand, features authors like Becker S. and Bollmann A., who have established significant influence, each achieving an average of 26 citations per document and a normalized citation score of 1.4041. Their publications, mostly from 2019, demonstrate sustained relevance and high impact within the community. Furthermore, Caeiro S., another notable researcher in Cluster 1, has a relationship strength of 10 and a total of 11 connections, with 31 total citations. Caeiro's high level of engagement and collaboration reflects their substantial role in advancing research within their subgroup, contributing influential work that resonates across the broader research community. This clustering of authors based on shared themes or methodologies reveals the diversity and depth of research interests within e-learning and ESD, with each cluster contributing unique insights to the field.

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Figure 4 expands the collaboration network analysis to the country level, emphasizing the global nature of e-learning and ESD research. This network underscores how international partnerships are crucial in advancing understanding and implementing sustainable education practices across different regions. China stands out with the highest metrics for collaboration, evidenced by a relationship strength of 34, contributions to 66 documents, and an impressive average of 17.06 citations per document. The average publication year of 2021 indicates that China is at the forefront of recent developments in e-learning and ESD, suggesting its commitment to driving contemporary research in these areas. India also demonstrates significant collaborative activity, with a relationship strength of 9 and 17 publications, and boasts a high normalized citation score of 3.0103. This score signifies that Indian research contributions are particularly impactful, with a large number of citations per document, underscoring India's role as an influential player in the field. Other countries such as Spain and the United Kingdom are also central to this network. Spain, for example, achieves an average of 20.4 citations per document, which highlights the substantial influence Spanish researchers have in ESD. Meanwhile, smaller nations such as Latvia and Thailand participate actively through partnerships with larger countries, adding diverse perspectives and expanding the scope of sustainable education initiatives. The country-level analysis reveals that while certain nations lead in research output and influence, smaller or developing countries contribute meaningfully through strategic collaborations, enriching the research landscape with a variety of approaches and insights.

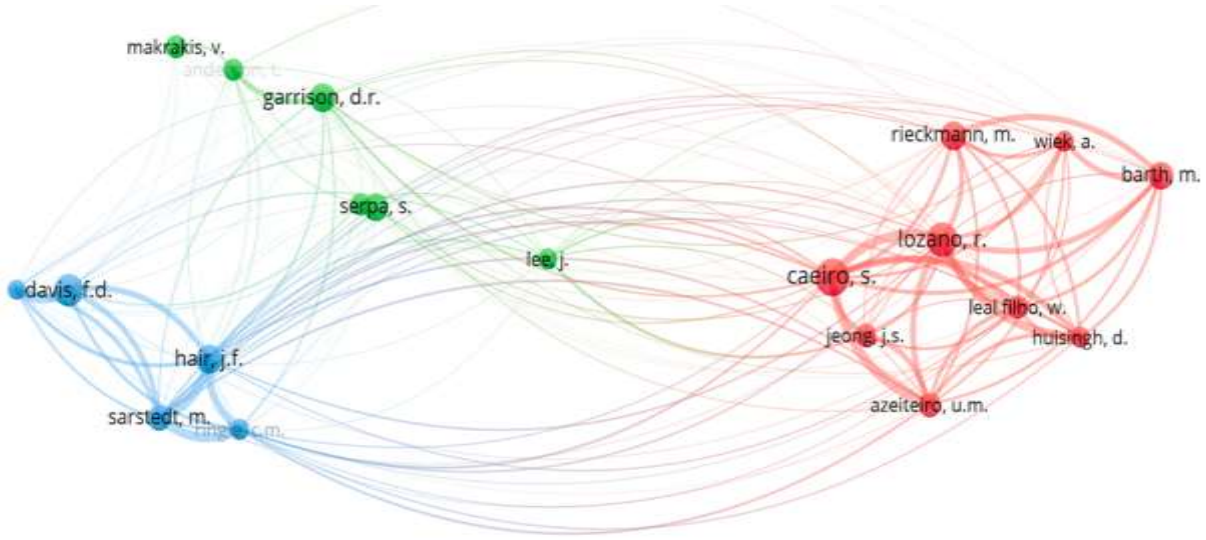

Figure 5. Network of co-citations-cited authors (minimum number of citations of an author, 28, n = 20)

The co-citation network (Figure 5) provides an overview of the intellectual foundation of e-learning and ESD by identifying authors frequently cited together. This network serves as a map of thematic connections, highlighting authors whose works are often used as foundational references across multiple studies, thereby shaping the theoretical and methodological frameworks within the field. Anderson T. and Davis F.D. emerge as foundational authors in this network, with relationship strengths of 15 and substantial citation counts (33 and 51, respectively). Their contributions are essential in establishing digital learning frameworks, which form the backbone of many e-learning methodologies in ESD. These authors' works on learning theories and technological applications in education are widely regarded as pivotal references, influencing a range of studies aimed at integrating digital tools into sustainable education. Caeiro S. and Lozano R. also hold prominent positions in the co-citation network, with relationship strengths of 17 and citation counts of 64 and 56, respectively. Their research focuses on incorporating sustainability principles within educational frameworks, aligning closely with the objectives of ESD. The prominence of Caeiro and Lozano indicates that their work has significantly impacted how sustainability is conceptualized and implemented in educational settings. Additionally, Leal Filho W. and Azeiteiro U.M. are influential contributors with relationship strengths of 17 and 15, and citation counts of 35 and 36, respectively. Their research encompasses sustainable practices within academic institutions, supporting e-learning methodologies tailored to ESD objectives. By emphasizing practical applications of sustainable education, Leal Filho and Azeiteiro's work provides actionable frameworks that are frequently referenced by researchers and educators alike.

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(a) The conceptual structure of E-Learning and ESD Research

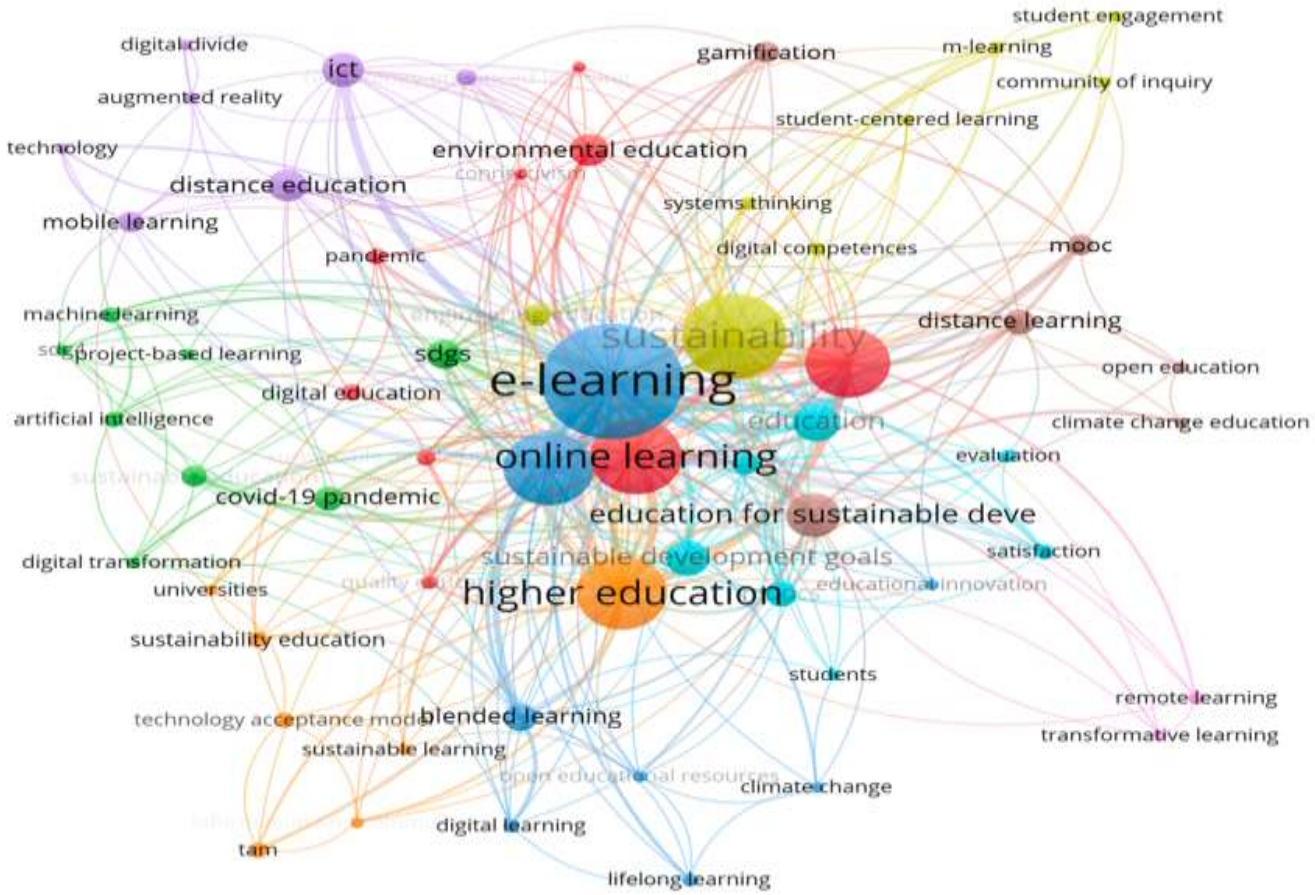

Figure 5. Co-occurrence of author keywords. Minimum number of occurrences of a keyword, 4 (n = 62)

In recent years, research on E-Learning and Education for Sustainable Development (ESD) has expanded significantly, with various themes and trends emerging in the literature. A keyword analysis of publications from 2010 to 2023 provides insights into the evolving conceptual structure of this research area. By examining the co-occurrence of keywords, thematic clusters, and their respective citation scores, we can better understand the dominant themes, emerging trends, and their relevance to the Sustainable Development Goals (SDGs).

The research surrounding E-Learning and Education for Sustainable Development (ESD) has seen a significant surge, with certain themes taking center stage in recent years. The key themes that frequently appear in publications include "digital learning," "e-learning," "online education," and "distance education." These terms show high co-occurrence, indicating their prominence in the field. For instance, "e-learning" has been identified with the highest total link strength of 130 and an occurrence of 84, with an average publication year of 2019.86, which demonstrates its central role over time. Similarly, "distance education" (20 links, 16 occurrences) and "online learning" (85 links, 48 occurrences) are also pivotal, showcasing their widespread scholarly discussion and relevance to the field of education during the digital age. The rise of themes related to sustainability is also significant, with keywords like "sustainable development" (33 links, 47 occurrences, average publication year: 2020) and "education for sustainable development" (ESD) (18 links, 24 occurrences) gaining increasing prominence. The growing frequency of these terms reflects the intersection between digital education and global sustainability efforts. As the world becomes more interconnected and aware of environmental challenges, the role of education, particularly digital education, in promoting sustainability has become more critical. In Figure 5, the co-occurrence network of author keywords emphasizes the core themes in the literature. The term "e-learning" emerges as the most prominent, represented by the largest blue node in the visualization. This central node connects with other significant themes such as "online learning," "higher education," and "education for sustainable development (ESD)." These terms

indicate the growing integration of digital learning platforms with educational initiatives aimed at promoting sustainability. Moreover, the keyword "sustainability" itself is highlighted as a key node, connecting terms like "sustainable development goals (SDGs)" and "sustainability education." The frequent co-occurrence of these keywords suggests that digital learning is increasingly being aligned with global sustainability targets, including SDG 4 (Quality Education) and SDG 13 (Climate Action).

The nine clusters resulting from the keyword analysis reveal several topics of interest in the field of E-Learning and Education for Sustainable Development. The first cluster addresses *digital learning in the pandemic context* and includes keywords like “connectivism,” “pandemic,” and “online learning.” A prominent term in this cluster is “COVID-19,” which appears 43 times with a total link strength of 56 and an average publication year of 2021.86, underscoring the rapid shift to digital education due to the pandemic. The second cluster indicates the rising role of *emerging technologies in education*, with terms such as “artificial intelligence” and “augmented reality,” where “artificial intelligence” appears 6 times with a link strength of 10 and an average publication year of 2022.17. Another topic emerging from the third cluster is *blended learning and educational innovation*, represented by terms like “blended learning,” which is cited 13 times (link strength 25), indicating a post-2020 trend in combining in-person and online teaching. The fourth cluster highlights *community-based learning*, with key terms like “community of inquiry” appearing 4 times (link strength 6) and an average publication year of 2020.5. The fifth cluster focuses on *digital literacy and access*, addressing issues such as the “digital divide” and “ICT,” with “ICT” recorded 17 times (link strength 22, average year 2019.24). The sixth cluster centers on *educational assessment and standards*, with “quality education” mentioned 5 times (link strength 10) and an average publication year of 2021.8, signaling a focus on quality and satisfaction in education. The seventh cluster focuses on *sustainable development and education*, with terms like “SDGs” appearing 14 times (link strength 28, average year 2021.5), emphasizing the role of education in global sustainability efforts. An eighth cluster addresses *open education and resources*, with terms such as “MOOCs” (9 occurrences, link strength 18), reflecting the popularity of open-access learning since 2019.33. The final cluster, *transformative and lifelong learning*, features keywords like “lifelong learning,” which appears 5 times (link strength 8) with an average publication year of 2017.8, highlighting the importance of continuous, adaptive learning. The analysis of these clusters suggests a diverse range of research themes, with varying levels of emphasis on each area.

DISCUSSION

This study’s bibliometric analysis highlights significant advancements in e-learning research, revealing its pivotal role in supporting Education for Sustainable Development (ESD) and advancing Sustainable Development Goals (SDGs), particularly SDG 4, which focuses on inclusive and equitable quality education. Our findings indicate an expanding focus on integrating sustainability competencies, adaptive technologies, and international collaboration in e-learning systems, marking a transformative shift in educational practices. In this section, we discuss these findings in detail, contextualizing them within current research, and addressing both the opportunities and challenges associated with e-learning in fostering sustainable education globally.The data reveal a rapid increase in e-learning research post-2015, which aligns with the adoption of the SDGs and global emphasis on accessible education. E-learning has demonstrated significant potential in advancing SDG 4 by providing flexible learning opportunities across diverse regions and socio-economic backgrounds. Digital platforms, particularly Massive Open Online Courses (MOOCs) and mobile-based applications, have emerged as crucial tools for overcoming traditional educational barriers, such as geographic isolation and economic constraints. Sangrà et al. [34] and Bozkurt et al. [9] corroborate these findings, showing that e-learning can effectively democratize educational access and support lifelong learning opportunities, which are essential for sustainable development. Moreover, the COVID-19 pandemic has catalyzed digital transformation in education systems, highlighting the role of e-learning as a resilient and adaptable solution during crises [12]. The rapid shift to online learning allowed millions of students to continue their education, underscoring the scalability and adaptability of digital platforms. This finding aligns with studies by Daniel [8] and Bozkurt et al. [9], which underscore the necessity of digital preparedness in educational institutions to mitigate disruptions and ensure continuity of learning . The adaptability of e-learning thus supports not only SDG 4 but also aligns with SDG 10 on reducing inequalities, as it reaches underserved populations who might otherwise lack access to quality education.The keyword analysis indicates a strong intersection between e-learning and environmental education,

with terms such as "sustainable learning," "digital learning," and "climate action" frequently co-occurring. E-learning has been shown to effectively integrate environmental sustainability topics into curricula, fostering the development of critical competencies necessary to address climate change (SDG 13). Digital platforms offer interactive and flexible learning formats that allow students to engage with complex sustainability issues through simulations, virtual field trips, and problem-based learning activities. Studies by Daniela et al. [29] and Haleem et al. [24] highlight that these digital tools not only make sustainability education accessible but also enhance student engagement and comprehension by providing real-world applications of theoretical knowledge. In alignment with Wiek et al. [35] , our findings suggest that e-learning supports the development of sustainability competencies, such as systems thinking, anticipatory skills, and strategic problem-solving, which are essential for fostering a more sustainable society. For example, virtual laboratories and simulation-based modules allow students to explore and address issues such as renewable energy, waste management, and environmental conservation in an immersive learning environment. Such hands-on experiences in digital learning spaces help cultivate critical thinking and ethical reasoning, preparing students to engage with and resolve sustainability challenges.Our analysis underscores the rising importance of artificial intelligence (AI) and augmented reality (AR) in e-learning research, particularly in the context of sustainable education. AI, cited frequently with an average publication year of 2022.16, plays a transformative role by enabling personalized and adaptive learning. AI's application in analyzing learner behavior and delivering customized content has been shown to improve engagement and retention, which is critical in sustainability education where complex concepts often require tailored learning approaches [36].Personalized AI-based learning can cater to individual learning speeds and preferences, helping students navigate intricate sustainability topics at their own pace. This approach aligns with the findings of Weng et al. [37], who emphasize the importance of AI in creating learner-centered environments that enhance understanding and foster a deeper connection with environmental content. Augmented reality (AR), with a citation score of 31.5 in our study, provides immersive learning experiences by merging digital and physical environments. In sustainability education, AR's potential for simulating real-world scenarios allows students to interact with ecosystems, conduct virtual experiments, and visualize environmental impacts firsthand. This hands-on approach aligns with experiential learning theories [38], which posit that direct interaction with learning materials enhances retention and application of knowledge. AR's capacity to simulate fieldwork and environmental processes supports research by Ibáñez and Delgado-Kloos [39], who found that AR-based e-learning promotes active learning and can significantly improve outcomes in environmental and technical subjects .The geographic and institutional distribution of e-learning research highlights a global commitment to integrating ESD across educational systems. Leading countries, such as China, the United States, and Spain, play prominent roles in advancing research on e-learning and sustainable development, as evidenced by their substantial output and collaborative networks. International partnerships, as illustrated by this study's co-authorship analysis, facilitate the exchange of resources, expertise, and innovative practices, which are crucial for addressing the multi-faceted challenges of sustainable education. Our findings resonate with the observations of Filho et al. [40], who argue that global collaborations are essential for achieving SDG 17 on partnerships for the goals, as they allow institutions from different regions to pool resources, share expertise, and overcome regional limitations . For instance, partnerships between institutions in high-income and low-income countries create opportunities to bridge digital divides and promote sustainable practices across diverse contexts. Collaborative projects involving countries with strong digital infrastructure, such as China and Spain, have been shown to enable capacity-building efforts, particularly in resource-limited settings, as they foster knowledge transfer and the development of context-appropriate e-learning models.While e-learning offers significant benefits, our study also reveals persistent digital inequalities that restrict access to digital education for marginalized populations. The digital divide, especially prevalent in low- and middle-income countries, limits e-learning's reach and undermines its potential as an equitable educational solution. Studies by Meinck et al. [10] and Van Dijk [41] emphasize that without equitable access to digital infrastructure, including reliable internet and learning devices, the benefits of e-learning cannot be fully realized, as many students remain excluded from online educational opportunities. To address this divide, targeted policies and investments are essential. Public-private partnerships, such as those facilitated by organizations like UNESCO, have shown promise in providing affordable internet access and digital devices in underserved areas, thereby supporting SDG 4's goal of inclusive education for all [42]. Additionally, research on low-bandwidth and offline e-learning platforms suggests potential solutions for students in

regions with limited connectivity, as such platforms allow content to be downloaded and accessed without continuous internet access. These innovations are essential for expanding e-learning access and ensuring that digital education contributes to reducing educational inequalities rather than exacerbating them.

The prominence of gamification and student-centered learning models in our analysis underscores a shift toward interactive and adaptable educational frameworks in e-learning for ESD. Gamification, which uses elements like rewards, challenges, and progression tracking, has been shown to increase student motivation and engagement, particularly in online settings where learner interaction may be limited [43]. By incorporating gamified elements, e-learning platforms can enhance the appeal of sustainability education, encouraging students to explore complex topics and engage in problem-solving exercises related to environmental issues. Student-centered learning models, indicated by a high citation score of 143.25, emphasize a shift from traditional, instructor-led approaches to more flexible and adaptable learning environments where students have agency over their learning. This aligns with the constructivist approach to education, which posits that knowledge is actively constructed by learners through engagement and reflection [44]. ICT, which is central to e-learning infrastructure, facilitates the deployment of these adaptive models, as it provides interactive tools and platforms that enable student-centered learning in digital contexts [4].

CONCLUSION

This bibliometric analysis underscores the significant and evolving role of e-learning in advancing Education for Sustainable Development (ESD), particularly within the framework of the United Nations' Sustainable Development Goals (SDGs). The findings from analyzing 421 publications spanning 2010 to 2023 reveal critical insights into the growth and impact of e-learning research. Notably, the research landscape has experienced robust expansion, especially following the adoption of the SDGs in 2015, with an acceleration during the COVID-19 pandemic. This period highlighted the adaptability and scalability of digital learning, emphasizing its capacity to ensure educational continuity and resilience in times of crisis.Geographic and institutional contributions indicate that countries such as China, Spain, and the United States have emerged as leaders in this domain, contributing a substantial share to the global body of knowledge. Collaborative research efforts among various institutions have further enriched the diversity and depth of the field. The key themes identified include the role of digital platforms in promoting educational accessibility and equity (aligned with SDG 4), the incorporation of sustainability into curricula, and the growing use of advanced technologies such as artificial intelligence (AI) and augmented reality (AR). These trends point to a shift toward interactive, student-centered learning models and innovative teaching approaches that align with sustainability goals.However, the analysis also reveals persistent challenges, particularly digital inequalities that limit the reach of e-learning in marginalized and underserved communities. Addressing these disparities is essential to unlocking the full potential of digital education as a tool for achieving SDG 4 and other related goals. This necessitates targeted policy interventions and investments in digital infrastructure to bridge the digital divide and foster inclusive learning environments.Future research should continue to explore the potential of emerging technologies like AI to enhance personalized learning and investigate effective strategies for bridging digital gaps. Additionally, understanding the long-term impact of e-learning on sustainability competencies will be crucial for informing educational policy and best practices. In conclusion, while e-learning has proven to be a transformative approach for sustainable education, realizing its full benefits requires a concerted effort from policymakers, educators, and stakeholders to address existing challenges and leverage its potential to advance global sustainability objectives.

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Conflict of Interest

No potential conflict of interest was reported by the author(s).

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