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Sustainability in Digital Education Systems: A PRISMA Systematic Review of Online Learning Innovations

Adelia Utari*
University of Bengkulu, INDONESIA

YELIZA
University of Bengkulu, INDONESIA

*** Corresponding author:**
Adelia Utari, University of Bengkulu, INDONESIA. ✉ adelliautari17@gmail

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Abstract

Purpose of the study: This study aims to map global research trends on sustainability in digital education systems and identify major themes, collaboration patterns, methodological characteristics, and future research directions related to Sustainable Development Goal 4 (SDG 4).

Methodology: A PRISMA-based Systematic Literature Review (SLR) combined with bibliometric analysis was conducted. Bibliographic data were retrieved from the Scopus database covering publications from 2016 to 2026. Bibliometrix/Biblioshiny and VOSviewer software were used for data analysis, including thematic mapping, collaboration analysis, and research trend identification.

Main Findings: The findings show increasing publications after 2019, with sustainability, digital transformation, innovation, artificial intelligence, and SDG 4 as dominant themes. Technology integration, learning effectiveness, user readiness, and implementation challenges were the main research focuses. Systematic reviews were the most frequently used research design, while empirical validation, longitudinal studies, and policy-oriented research remain important future directions.

Novelty/Originality of this study: This study provides a comprehensive integration of bibliometric analysis and PRISMA-based systematic review to reveal the intellectual structure, thematic evolution, methodological characteristics, and future directions of sustainability research in digital education systems. The findings extend existing knowledge by identifying research gaps and supporting sustainable, inclusive, and evidence-based digital education development.

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INTRODUCTION

The rapid advancement of digital technologies has fundamentally transformed the global education landscape, particularly in the context of sustainability and digital learning systems. The integration of digital technologies into education has been significantly accelerated by global disruptions such as the COVID-19 pandemic, which forced institutions worldwide to adopt online learning modalities in a relatively short period (Adedoyin & Soykan, 2023; Bozkurt et al., 2020) . This sudden transition highlighted both the potential and limitations of digital education systems, emphasizing the need for more resilient, inclusive, and sustainable learning environments(Crawford et al., 2020). Moreover, the pandemic revealed structural inequalities in

access to digital infrastructure, further stressing the importance of equitable technology integration in education(Viner et al., 2020; World Bank, 2022).

In response to these challenges, higher education institutions have increasingly embraced digital transformation as a strategic approach to improve learning accessibility, flexibility, and quality (Castro Benavides et al., 2020) . Digital learning environments enable students to access educational resources beyond traditional classroom boundaries, fostering more inclusive and lifelong learning opportunities.However, the effectiveness of these systems depends not only on technological availability but also on pedagogical innovation and institutional readiness. The distinction between emergency remote teaching and well-designed online learning further illustrates the importance of systematic planning in digital education implementation (Hodges et al., 2020).

The emergence of advanced technologies such as artificial intelligence (AI) has further expanded the potential of digital education systems. AI-driven tools enable personalized learning experiences by analyzing students' performance data and adapting instructional content accordingly (Chen et al., 2020; Holmes & Porayska-Pomsta, 2022). These technologies support self-paced learning, enhance student engagement, and provide real-time feedback, thereby improving learning outcomes (Bond et al., 2020). Furthermore, AI has the potential to democratize education by making high-quality learning resources more accessible to diverse populations (Bulathwela et al., 2021).

However, despite these advantages, concerns related to ethical implications, data privacy, and algorithmic bias remain significant challenges in the adoption of AI in education (Pragya Mishara, 2024) . Algorithmic bias, in particular, poses a serious threat to fairness and equity in education systems. AI models often rely on historical data that may contain inherent biases, which can lead to unequal treatment of students from different socio-economic or cultural backgrounds (Obed Boateng & Bright Boateng, 2025). This issue is further compounded by the lack of diversity in training datasets, potentially reinforcing existing inequalities in educational outcomes. Consequently, the implementation of AI in education requires careful consideration of ethical principles and the development of fair and transparent algorithms (Holmes & Porayska-Pomsta, 2022).

Beyond technological aspects, sustainability in education encompasses broader dimensions, including social inclusion, equity, and long-term systemic resilience. Sustainability-oriented education aims to equip learners with the knowledge and skills necessary to address complex global challenges (Brundiers et al., 2010) . Higher education institutions play a crucial role in promoting sustainability initiatives and integrating sustainable development principles into curricula and research activities (Filho et al., 2019). In this context, digital education serves as a key enabler for achieving Sustainable Development Goals (SDGs), particularly SDG 4, which focuses on quality education.

The integration of sustainability into digital education also requires innovative pedagogical approaches. Research has shown that technology-enhanced learning designs can significantly improve student engagement and learning effectiveness when aligned with appropriate instructional strategies (Choi-Lundberg et al., 2023) . Similarly, the concept of Education 4.0 emphasizes the use of advanced technologies to create more flexible, personalized, and learner-centered education systems. However, the successful implementation of these innovations depends on teachers' digital competencies, beliefs, and institutional support systems (Ertmer & Ottenbreit-Leftwich, 2010).

Teacher readiness and professional development are critical factors in ensuring the effectiveness of digital education. Educators must possess not only technical skills but also pedagogical knowledge to effectively integrate technology into teaching practices (Philipsen et al., 2019) . Frameworks such as the European Digital Competence Framework for Educators (DigCompEdu) provide guidelines for enhancing teachers' digital capabilities (Redecker & Punie, 2017). In addition, teacher satisfaction and adaptability have been identified as key determinants of successful digital learning (Li & Yu, 2022).

From a policy perspective, the digital transformation of education is influenced by global and institutional strategies aimed at fostering innovation and inclusivity. The evolving digital education policy landscape reflects a shift from traditional education systems toward platform-

based ecosystems that integrate various digital tools and services (Cobo & Rivas, 2023) . Public-private partnerships have also been recognized as important drivers of digital transformation, enabling the development of scalable and sustainable educational solutions (Tanveer et al., 2025).

Furthermore, the role of digital education in supporting sustainability extends beyond formal education systems. Digital platforms facilitate knowledge sharing, collaboration, and community engagement, which are essential for achieving sustainable development (Guandalini, 2022) .Localized approaches to sustainability, such as community-based education initiatives, highlight the importance of contextualizing digital learning within specific socio-cultural environments (Pathak & Deshkar, 2023).

Despite the growing body of research on digital education and sustainability, several challenges remain. Issues related to digital inequality, access to resources, and technological infrastructure continue to hinder the effective implementation of digital learning systems (Hu & Raman, 2024) Additionally, the increasing reliance on technology raises concerns about the human dimension of education, including student engagement, motivation, and interaction (Almela-Baeza et al., 2023) . Maintaining a balance between technological innovation and human-centered pedagogy is therefore essential.

Recent studies also emphasize the importance of inclusive and culturally responsive digital education frameworks. Personalized learning approaches that consider students' diverse backgrounds and learning needs can enhance educational equity and effectiveness (Ober et al., 2023) . Inclusive digital education practices aim to ensure that all learners, regardless of their socio-economic status, have equal opportunities to benefit from technological advancements (Mintz et al., 2024).

In addition, the ethical implications of digital education technologies require careful consideration. Issues such as data privacy, algorithmic transparency, and accountability must be addressed to ensure the responsible use of technology in education (Pragya Mishara, 2024). The development of ethical guidelines and regulatory frameworks is therefore essential to mitigate potential risks associated with digital learning systems.

Previous bibliometric studies have investigated several dimensions of digital education, including artificial intelligence, online learning, digital transformation, and sustainability, by examining publication trends, citation performance, collaboration networks, and thematic development (Bond et al., 2020). These studies have successfully identified influential authors, journals, countries, and emerging research themes within their respective domains. However, most bibliometric analyses have focused on specific technologies or educational contexts and have primarily provided quantitative mapping of scientific publications without integrating a systematic synthesis of empirical findings.

Likewise, previous systematic literature reviews have synthesized evidence regarding digital learning, sustainability, and technology-enhanced education, providing valuable insights into educational practices and implementation outcomes (García-Hernández et al., 2023). Nevertheless, these reviews have rarely combined bibliometric analysis with a PRISMA-guided systematic literature review to simultaneously examine publication trends, collaboration networks, thematic evolution, methodological characteristics, implementation challenges, and future research directions. Consequently, a comprehensive understanding of the intellectual structure and evolution of sustainability in digital education systems remains limited.

Therefore, this study addresses this research gap by integrating bibliometric analysis with a PRISMA-guided systematic literature review. Unlike previous studies, this research combines quantitative bibliometric mapping with qualitative evidence synthesis to provide a comprehensive overview of publication growth, influential authors, journals, countries, collaboration networks, thematic evolution, research methodologies, implementation challenges, and future research opportunities related to sustainability in digital education systems. By offering both quantitative and qualitative perspectives, this study contributes new insights into the development of sustainable digital education and provides evidence-based implications for researchers, educators, and policymakers in supporting the achievement of Sustainable Development Goal 4 (SDG 4).

METHOD

This study employed a Systematic Literature Review (SLR) integrated with bibliometric analysis to comprehensively investigate research trends, thematic evolution, collaboration networks, and scientific contributions related to sustainability in digital education systems. The review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure methodological transparency, systematic reporting, and reproducibility throughout the literature selection process (Guandalini, 2022). Bibliometric analysis complemented the systematic review by quantitatively mapping publication trends, citation patterns, collaboration networks, and keyword evolution using Bibliometrix/Biblioshiny and VOSviewer, thereby providing a comprehensive overview of the intellectual structure of the research field (Bond et al., 2020).

The bibliographic data were primarily retrieved from the Scopus database because of its extensive coverage of peer-reviewed international publications and standardized bibliographic metadata. To minimize the possibility of overlooking relevant publications, an additional search was conducted using Google Scholar as a supplementary source. The literature search covered publications published between 2016 and 2026 and employed Boolean operators combining keywords related to sustainability, Sustainable Development Goals (SDGs), digital education systems, online learning, digital transformation, educational technology, and artificial intelligence (Alotaibi, 2022; García-Hernández et al., 2023).

The search process initially identified 232 records, consisting of 222 records from Scopus and 10 records from Google Scholar. All retrieved records were exported in CSV format, merged into a single dataset, and preprocessed using OpenRefine to remove duplicate records, standardize author names, normalize keywords, and correct metadata inconsistencies before bibliometric analysis.

The literature selection followed the four stages of the PRISMA 2020 framework, namely identification, screening, eligibility, and inclusion. During the screening stage, publications were assessed according to predefined inclusion and exclusion criteria. The inclusion criteria consisted of (1) journal articles published between 2016 and 2026, (2) publications written in English, (3) studies focusing on sustainability, digital education, online learning, educational technology, artificial intelligence, or digital transformation, and (4) publications containing complete bibliographic metadata. Meanwhile, the exclusion criteria included conference papers, book chapters, editorials, notes, duplicate records, publications outside the scope of the study, inaccessible full-text articles, and publications with incomplete bibliographic metadata.

Following the initial screening, 102 publications satisfied the inclusion criteria and proceeded to the eligibility assessment. Subsequently, 43 publications were excluded because they did not meet the research objectives or eligibility criteria. Among the remaining 59 reports, 8 reports could not be retrieved in full text and were therefore excluded from further review. An additional 2 reports were excluded because of incomplete bibliographic metadata that prevented reliable bibliometric processing. Consequently, 49 publications were included in the final bibliometric and systematic literature review analyses.

The finalized dataset was analyzed using Bibliometrix/Biblioshiny to generate descriptive bibliometric indicators, including annual scientific production, annual citation trends, source productivity, author productivity, keyword occurrence, thematic evolution, Three-Field Plot (Countries–Authors–Keywords), and Bradford's Law for identifying core publication sources (Bond et al., 2020). To complement these analyses, VOSviewer was employed to visualize co-authorship networks, keyword co-occurrence, institutional collaboration, and thematic clusters through Network Visualization and Overlay Visualization, thereby identifying major research themes related to sustainability, digital transformation, online learning, artificial intelligence, educational innovation, and policy development (Chen et al., 2020; Choi-Lundberg et al., 2023). Finally, the selected publications were synthesized qualitatively following the SLR protocol to identify research objectives, methodologies, principal findings, implementation challenges, and future research directions. The integration of bibliometric analysis with a PRISMA-guided systematic literature review provides a comprehensive, transparent, and reproducible framework for understanding the current state and future development of sustainability in digital education systems (Castro Benavides et al., 2020; Hu & Raman, 2024). Figure 1 is a bobliometrix research flow diagram.

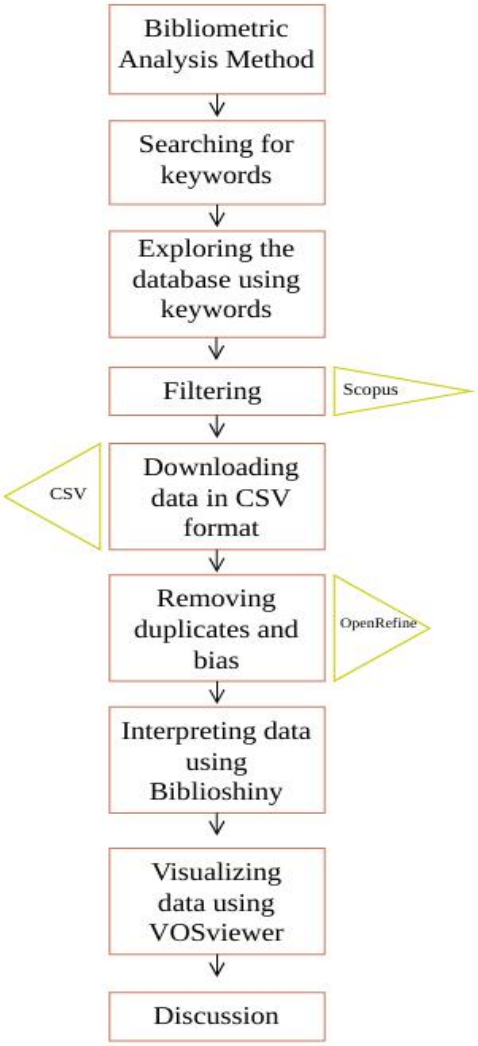

Figure 1. Research Method Flow Diagram.

Prism Method

This research also applies the PRISMA method which aims to present the article selection process in a systematic, transparent, and structured way. This process includes steps ranging from identification, screening, to selection of relevant studies. This diagram serves to ensure that the search and selection of literature is carried out in a valid manner, avoid duplication, and assist readers in following the steps taken in the preparation of the literature review. Here are the steps implemented in the PRISMA method, which can be seen in Figure 2:

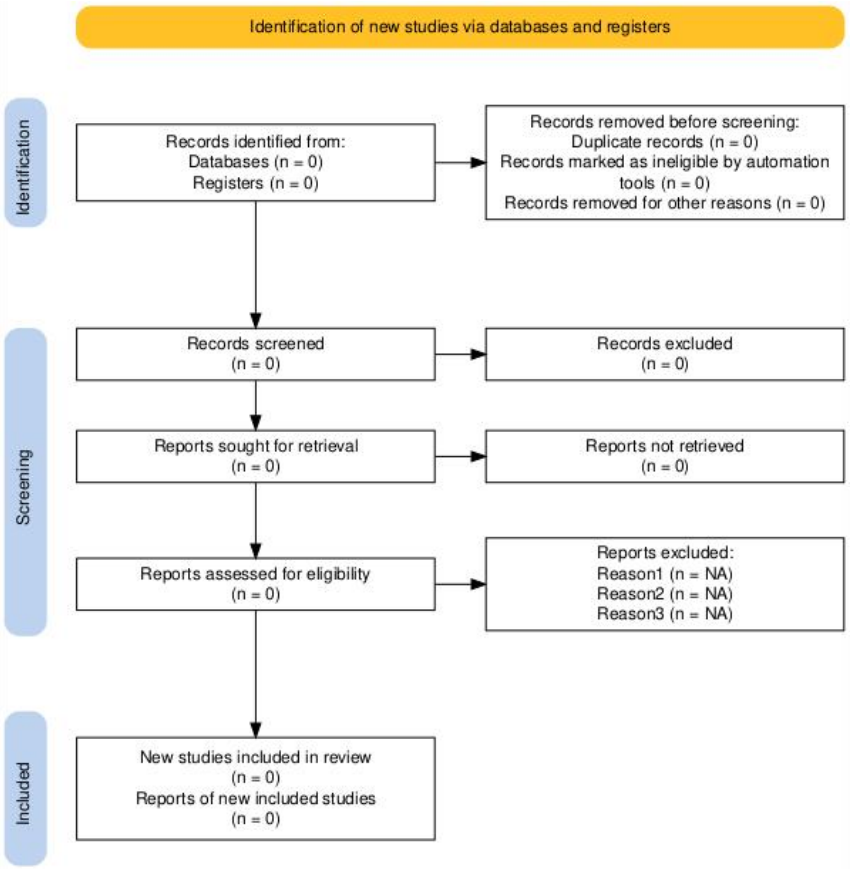

Figure 2. Prism Method Diagram.

RESULTS AND DISCUSSION

Bibliometric Studies

In bibliometric analysis, the data search strategy was carried out using the Scopus database which is relevant to the research theme Sustainability in Digital Education Systems. The search focused on the linkage between sustainability, digital education systems, and technology integration in online learning innovations. The keyword combinations used in the search process are as follows:

("sustainability" OR "sustainable development goals" OR SDGs)
AND
("education systems" OR "digital learning systems")
AND
("technology integration" OR "innovation")

Based on the search strategy, 222 initial documents were obtained. Furthermore, a filtering process is carried out with certain criteria, including: the type of document (articles, reviews, and conference papers), the year of publication, open access, and the use of English. After going through this stage, the number of documents was reduced to 49 documents that were considered relevant to the focus of the research. The next stage is the data cleanup process using the OpenRefine application to identify and remove duplicate data. The results of this process show that there is one duplicate data, so that the final number of documents used in the analysis is 48 documents. Thus, the entire data selection process is carried out starting from initial identification, screening based on inclusion criteria, to data cleansing, resulting in a collection of valid and relevant literature to be further analyzed in a systematic study based on the PRISMA method. This curated data is then used

as a basis for exploring research trends, collaboration patterns, and innovation developments in a sustainable digital education system.

Reducing Duplicate Data

The process of reducing duplicate data is carried out by utilizing the results of the literature search that has been obtained previously. All documents resulting from the initial selection of 49 articles were exported in CSV format, then compressed in the form of .zip files before being imported into the OpenRefine application.The use of OpenRefine aims to carry out data cleaning, especially in identifying and removing duplicate data and ensuring the consistency of keyword writing. In addition, this application also helps to minimize keyword bias that may arise due to differences in writing or indexing in source databases such as Scopus.Based on the results of this process, it is found that there is duplicate data in the literature collection that has been filtered. The number of documents that was originally 49 articles was reduced to 48 articles after the data cleaning process was carried out. Thus, the final data used in this study is data that has been validated, free of duplication, and is ready for further analysis in a systematic study based on the PRISMA method, as seen in Figure 3.

Completeness of metadata -- **48** docs from **Scopus**

Metadata	Description	Missing Counts	Missing %	Status
AB	Abstract	0	0.00	Excellent
C1	Affiliation	0	0.00	Excellent
AU	Author	0	0.00	Excellent
CR	Cited References	0	0.00	Excellent
DT	Document Type	0	0.00	Excellent
SO	Journal	0	0.00	Excellent
DE	Keywords	0	0.00	Excellent
PY	Publication Year	0	0.00	Excellent
TI	Title	0	0.00	Excellent
TC	Total Citation	0	0.00	Excellent
DI	DOI	1	2.08	Good
ID	Keywords Plus	19	39.58	Poor
RP	Corresponding Author	48	100.00	Completely missing
LA	Language	48	100.00	Completely missing
WC	Science Categories	48	100.00	Completely missing

Figure 3. Meta data on DE/Keword is good.

Furthermore, the process of interpreting bilometric data can be carried out using the Bibliosiny application as follows. The main information data as a whole is the information obtained is seen in the image. Table 1 provides the main information on the data as a whole.

Table 1. Main information on the data sheet

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2016:2026

Sources (Journals, Books, etc)	28
Documents	48
Annual Growth Rate %	17.46
Document Average Age	3.58
Average citations per doc	17.23
References	6351
DOCUMENT CONTENTS	
Keywords Plus (ID)	180
Author's Keywords (DE)	233
AUTHORS	
Authors	163
Authors of single-authored docs	5
AUTHORS COLLABORATION	
Single-authored docs	5
Co-Authors per Doc	3.4
International co-authorships %	37.5
DOCUMENT TYPES	
article	48

Table 1 summarizes the principal bibliometric characteristics of the 48 publications included in this study. The dataset spans the period from 2016 to 2026 and comprises articles published across 28 scientific sources, indicating that research on sustainability in digital education systems is disseminated through a diverse range of academic journals rather than being concentrated within a limited number of publication outlets. This distribution reflects the interdisciplinary nature of the field, which integrates perspectives from education, educational technology, sustainability, digital transformation, and information systems.

The dataset exhibits an annual publication growth rate of 17.46%, suggesting a substantial increase in scholarly attention to sustainable digital education during the last decade. Rather than representing a stable research area, this growth indicates that the topic has emerged as an expanding field of inquiry, particularly following the acceleration of digital transformation in education driven by technological innovation and global educational disruption. The relatively low average document age (3.58 years) further demonstrates that the literature is dominated by recent publications, implying that sustainable digital education remains an active and evolving research area with continuing scholarly interest.

The average citation rate of 17.23 citations per document indicates that the publications included in the dataset have received considerable academic attention. Although citation counts vary among individual studies, this average suggests that many of the selected publications have contributed to shaping current discussions on digital education, sustainability, online learning, and educational technology. Furthermore, the presence of 6,351 cited references demonstrates that the field builds upon a broad and well-established knowledge base, reflecting continuous integration of previous theoretical and empirical studies.

The metadata also reveal substantial thematic diversity. A total of 233 Author Keywords (DE) and 180 Keywords Plus (ID) were identified, indicating that researchers employ a wide range of concepts to investigate sustainability in digital education systems. The larger number of author-defined keywords compared with Keywords Plus suggests that researchers continue to introduce new concepts and specialized terminology, reflecting the dynamic development of the field and the emergence of new research themes associated with digital transformation, artificial intelligence, and sustainable education.

Regarding authorship patterns, the dataset consists of 163 authors, whereas only five publications were written by a single author. The average of 3.4 co-authors per document indicates that collaborative research has become the dominant approach within this field. Such collaboration is consistent with the interdisciplinary nature of sustainable digital education, which frequently requires expertise from multiple disciplines, including education, computer science, engineering, and sustainability studies.

In addition, the 37.5% international co-authorship rate demonstrates a moderate level of global research collaboration. While international cooperation has become increasingly important in addressing worldwide educational challenges, this percentage also suggests that opportunities remain for strengthening cross-country collaboration, particularly among institutions from developing and developed countries.

Finally, all publications included in the analysis are journal articles, ensuring consistency in publication quality and facilitating reliable bibliometric comparisons across the dataset. Collectively, these bibliometric indicators characterize sustainability in digital education systems as a rapidly developing, interdisciplinary, and collaborative research field that continues to expand in both thematic scope and international scholarly engagement. The annual publication trend presented in Figure 4 further illustrates how this growth has evolved throughout the study period.

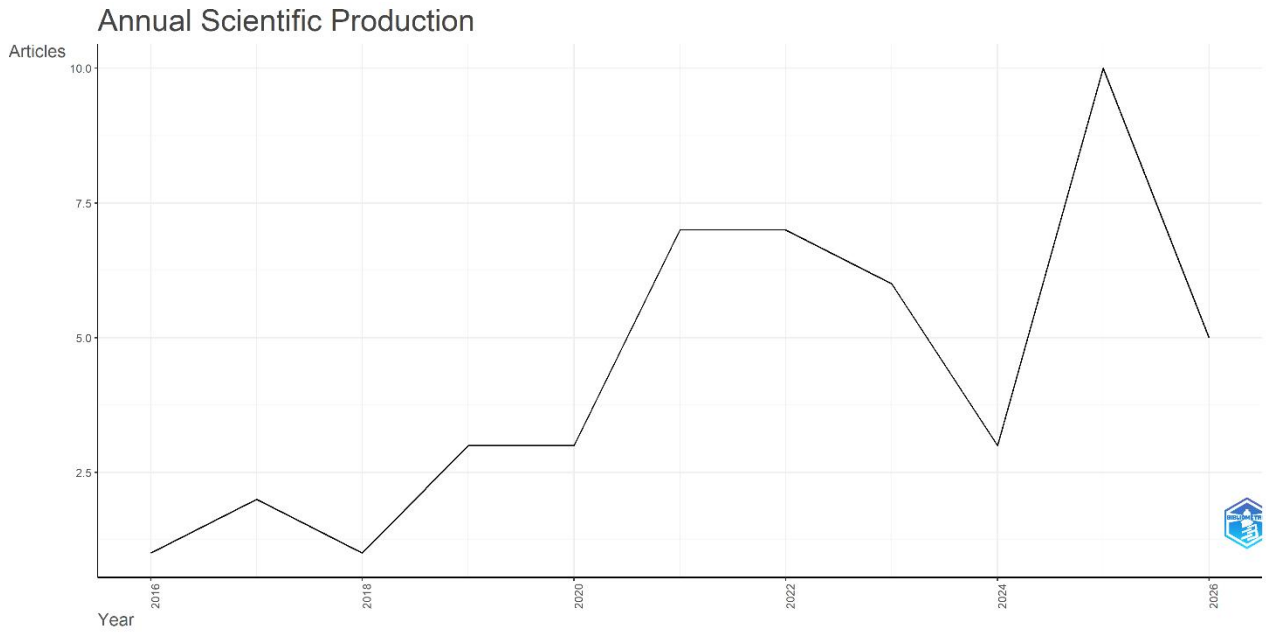

Figure 4. Year-over-year growth chart.

It can be shown by the distribution of the data in Table 2.

Table 2. Yearly Growth

Year	Articles
2016	1
2017	2
2018	1
2019	3
2020	3
2021	7
2022	7
2023	6
2024	3
2025	10
2026	5

Figure 4 and Table 2 illustrate the annual scientific production of publications related to sustainability in digital education systems between 2016 and 2026. Overall, the dataset demonstrates a clear upward trajectory in publication output despite several short-term fluctuations, indicating that the topic has evolved from an emerging research area into an

increasingly established field of scholarly inquiry. The observed growth is consistent with the reported 17.46% annual growth rate (Table 1), suggesting sustained academic interest in the intersection of sustainability, digital transformation, and educational innovation.

During the initial period (2016–2018), publication output remained relatively limited, with only one or two articles published annually. Rather than indicating low research importance, this pattern reflects the early developmental stage of the field, when sustainability and digital education were generally investigated as separate research domains. At that time, studies primarily focused on educational technology adoption or sustainability initiatives independently, while research integrating both perspectives remained relatively scarce (Guandalini, 2022; García-Hernández et al., 2023).

A gradual increase became evident in 2019–2020, when annual publications reached three articles. This period coincided with growing international interest in digital transformation within higher education, which had already begun before the COVID-19 pandemic through the expansion of online learning platforms, educational technologies, and institutional digitalization strategies (Castro Benavides et al., 2020). Consequently, sustainability in digital education started to receive greater scholarly attention as researchers increasingly examined technology-enhanced learning from broader institutional and societal perspectives.

A more pronounced increase occurred during 2021 and 2022, with seven publications recorded in each year. This pattern is consistent with the substantial expansion of research on online learning and digital education following the COVID-19 pandemic, which accelerated the adoption of digital technologies across educational institutions worldwide (Adedoyin & Soykan, 2023; Crawford et al., 2020). Importantly, the sustained publication level across two consecutive years suggests that scholarly interest extended beyond emergency remote teaching toward longer-term issues such as sustainable digital learning environments, educational resilience, and technology-supported pedagogical innovation.

Although publication output declined slightly in 2023 and 2024, the decrease should not necessarily be interpreted as a reduction in research interest. Instead, it may reflect a transition from the rapid publication phase observed during the pandemic toward a more stable stage of scientific production, where research increasingly emphasizes the quality and sustainability of digital education rather than immediate responses to global educational disruption (Hu & Raman, 2024). Such fluctuations are common in emerging interdisciplinary research fields and do not alter the overall upward trajectory observed throughout the study period.

The highest publication output was recorded in 2025, with 10 articles, indicating continued expansion of research on sustainable digital education. This peak suggests that the research focus has gradually shifted from short-term digital learning implementation toward broader themes, including sustainability integration, artificial intelligence, digital transformation, and institutional innovation in higher education (Alotaibi, 2022; Choi-Lundberg et al., 2023). These developments indicate that sustainable digital education is increasingly being recognized as a strategic research area rather than solely as a response to the pandemic.

The lower publication count observed in 2026 should be interpreted with caution because the bibliographic search was conducted before the completion of the publication year. Consequently, publications indexed after the data collection period were not included in the dataset, which may partially explain the reduced number of articles. Therefore, the 2026 value should not be considered indicative of a declining research trend.

Overall, the annual publication pattern demonstrates that research on sustainability in digital education systems has experienced continuous long-term growth, with temporary fluctuations reflecting changes in global educational priorities rather than a decline in scholarly interest. The findings suggest that the field is transitioning from an emerging research topic into a mature interdisciplinary domain characterized by increasing attention to sustainable digital transformation, educational innovation, and technology-enhanced learning. The scholarly impact of these publications is further examined through the annual citation analysis presented in Figure 5.

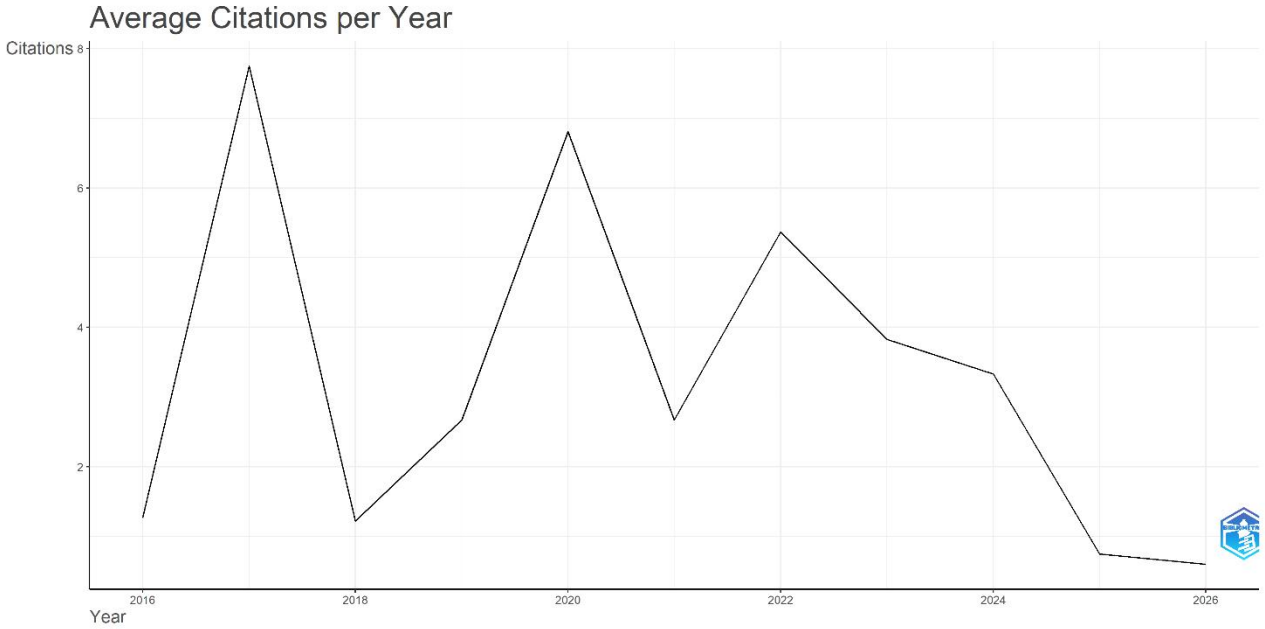

Figure 5. Annual Citation Chart

This can be explained in the form of Table 3.

Table 3. Annual Citation

Year	MeanTCperArt	N	MeanTCperYear	CitableYears
2016	14.00	1	1.27	11
2017	77.50	2	7.75	10
2018	11.00	1	1.22	9
2019	21.33	3	2.67	8
2020	47.67	3	6.81	7
2021	16.00	7	2.67	6
2022	26.86	7	5.37	5
2023	15.33	6	3.83	4
2024	10.00	3	3.33	3
2025	1.50	10	0.75	2
2026	0.60	5	0.60	1

Figure 5 and Table 3 present the annual citation performance of the publications included in the dataset. Unlike publication productivity, which reflects research output, citation indicators provide insight into the scholarly influence and visibility of publications over time. The results reveal that citation performance does not necessarily follow the same pattern as publication growth, indicating that an increase in publication volume is not always accompanied by an immediate increase in scientific impact.

The highest Mean Total Citations per Article (MeanTCperArt) was recorded in 2017, reaching 77.50 citations per article, followed by 2020 with 47.67 citations per article. These findings indicate that publications produced during these years attracted substantial attention from the academic community and became influential references within the field.

In contrast, although publication output increased considerably after 2021, the average citation rate per article gradually declined. This pattern should not be interpreted as a reduction in the scholarly value of more recent studies. Instead, it primarily reflects the cumulative nature of citation accumulation, whereby older publications have had a longer period to be discovered, read, and cited by subsequent research.

This interpretation is further supported by the Mean Total Citations per Year (MeanTCperYear) indicator, which normalizes citation counts according to the number of years

since publication. Publications from 2017 and 2020 continue to demonstrate the highest annual citation rates, suggesting that their influence remains relatively strong even after accounting for differences in publication age. These years correspond to periods in which digital transformation and technology-enhanced learning became increasingly important topics within educational research, particularly before and during the COVID-19 pandemic, thereby increasing the visibility and relevance of studies published during that period (Adedoyin & Soykan, 2023; Crawford et al., 2020).

Conversely, publications from 2025 and 2026 exhibit substantially lower citation values. However, this observation should be interpreted cautiously because these publications have experienced a much shorter citation window, as indicated by their Citable Years values of only two and one years, respectively. Citation accumulation is inherently time-dependent, and recently published articles generally require several years before their scientific influence becomes fully reflected in bibliometric indicators. Therefore, the lower citation counts observed for recent publications are more appropriately attributed to limited exposure time rather than reduced academic relevance (Bond et al., 2020).

The comparison between publication productivity (Figure 4) and citation performance (Figure 5) also highlights an important characteristic of the field. While the number of publications has increased substantially in recent years, influential studies remain concentrated in earlier publication periods that have accumulated citations over a longer timeframe. This pattern suggests that the field of sustainability in digital education systems is expanding rapidly, whereas the long-term scientific influence of recently published studies is still evolving and cannot yet be fully evaluated using citation-based indicators alone.

Overall, the citation analysis demonstrates that scientific influence within this research field is determined not only by publication volume but also by publication age and the cumulative process of knowledge dissemination. Consequently, citation indicators should be interpreted together with publication trends and citation windows to obtain a more balanced understanding of the development and maturity of research on sustainability in digital education systems. The intellectual relationships among authors, cited references, and research themes are further explored through the Three-Field Plot analysis presented in Figure 6.

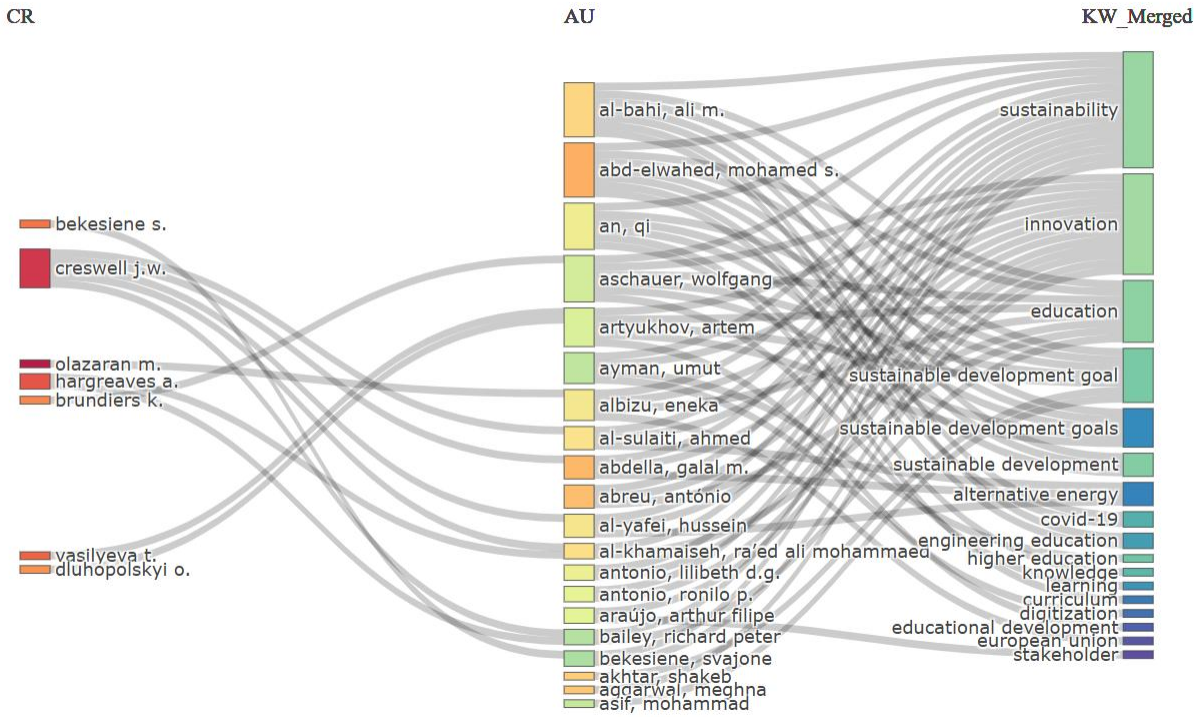

Figure 6. Three-Field Plot Diagram.

Figure 6 presents a Three-Field Plot illustrating the intellectual relationships among cited references (CR), authors (AU), and merged author keywords (KW_Merged) within the selected literature. Unlike simple frequency analysis, this visualization reveals how influential references shape the work of individual researchers and how these researchers contribute to the development of major research themes. The flow connections indicate the strength of associations between references, authors, and keywords, thereby providing an overview of the intellectual structure of sustainability research in digital education systems (García-Hernández et al., 2023; Guandalini, 2022).

The cited-reference field demonstrates that several foundational publications function as the principal knowledge base for subsequent studies. For example, Creswell J.W. occupies a central position because methodological references are widely adopted across empirical and review-based educational research. Likewise, works by Brundiers, Hargreaves, Olazaran, and Vasilyeva indicate that the field has evolved by integrating perspectives from sustainability education, educational innovation, and organizational transformation. This pattern suggests that research on sustainable digital education is built upon multiple complementary theoretical traditions rather than a single disciplinary perspective, reflecting the interdisciplinary nature of sustainability research in higher education (Brundiers et al., 2010; Filho et al., 2019).

The author field illustrates that several researchers including Al-Bahi Ali M., Abd-Elwahed Mohamed S., An Qi, Aschauer Wolfgang, and Artyukhov Artem are connected to multiple references and research themes. Rather than indicating productivity alone, these multiple connections suggest that their studies integrate diverse theoretical foundations and contribute to different aspects of digital education. Such a pattern is consistent with the increasing convergence of educational technology, sustainability, and digital transformation reported in previous systematic reviews (Castro Benavides et al., 2020; Hu & Raman, 2024).

The keyword field further highlights the thematic orientation of the literature. The dominant keywords sustainability, innovation, education, and sustainable development goal(s) receive the largest number of connections from contributing authors, indicating that these concepts constitute the intellectual core of the research field. Their prominence suggests that digital education is increasingly investigated not only as a technological innovation but also as a strategic approach to supporting sustainable educational development and achieving Sustainable Development Goal 4 (Quality Education) (Alotaibi, 2022; García-Hernández et al., 2023). The appearance of both sustainable development goal and sustainable development goals mainly reflects differences in keyword indexing across publications rather than distinct conceptual themes.

Beyond these dominant themes, several complementary keywords including engineering education, higher education, curriculum, digitization, knowledge, European Union, and alternative energy illustrate the broadening scope of research. These terms indicate that sustainability is increasingly examined across different educational sectors, policy contexts, and disciplinary applications. The diversity of keywords demonstrates that digital education research has gradually shifted from technology adoption toward curriculum innovation, institutional transformation, and policy implementation, consistent with recent discussions on Education 4.0 and technology-enhanced learning (Anaelka, 2018; Choi-Lundberg et al., 2023; Cobo & Rivas, 2023).

Overall, the Three-Field Plot reveals a well-connected intellectual ecosystem in which foundational references, multidisciplinary researchers, and evolving research themes reinforce one another. The observed relationships indicate that future studies should continue integrating perspectives from educational technology, sustainability science, artificial intelligence, and digital policy to develop more comprehensive and inclusive digital education systems. Such interdisciplinary integration is increasingly recognized as essential for supporting long-term educational sustainability and responding to emerging challenges in digital learning environments (Holmes & Porayska-Pomsta, 2022; Mintz et al., 2024; Teräs, 2022).

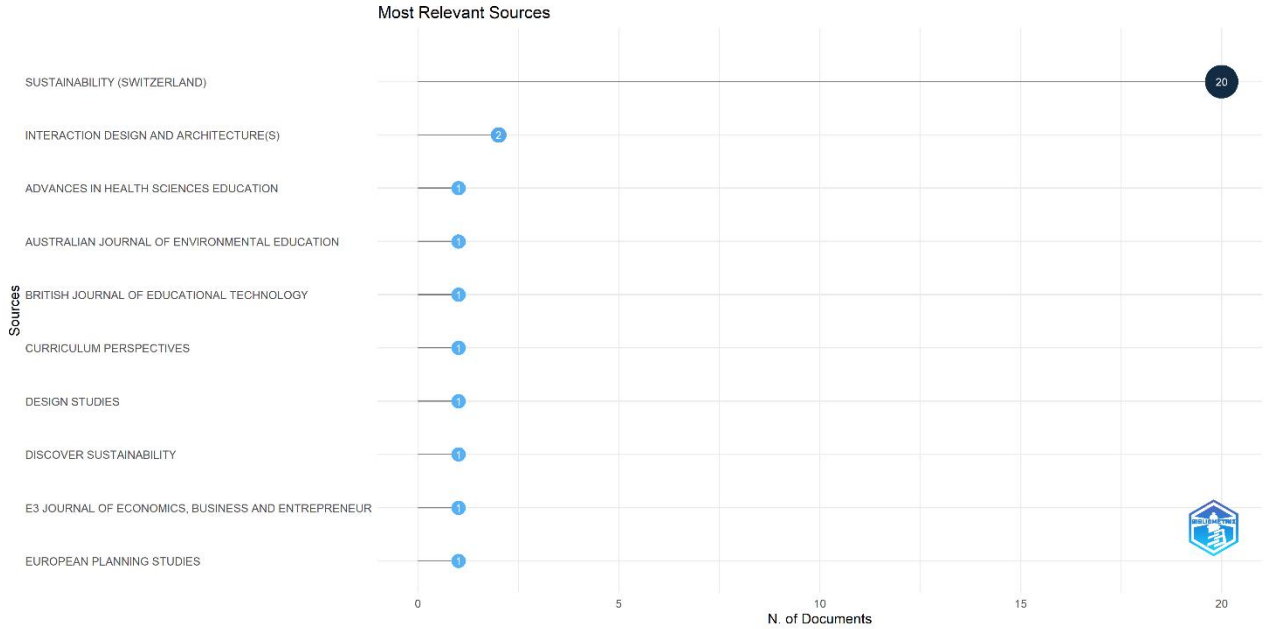

Figure 7. Most Relevant Source.

Figure 7 presents the most relevant publication sources represented in the final dataset. Rather than indicating the most frequently cited journals, this figure identifies the journals that contributed the largest number of publications included in the bibliometric analysis. Consequently, it provides an overview of the publication outlets that have become the primary venues for research on sustainability in digital education systems.

The results demonstrate a highly concentrated publication pattern. Sustainability (Switzerland) overwhelmingly dominates the dataset with 20 publications, whereas Interaction Design and Architecture(s) contributes only two publications, and the remaining journals each contribute a single article. This distribution indicates that research in this field is strongly centered within a limited number of specialized journals, while a broader range of journals provides complementary contributions. Such a publication pattern is consistent with Bradford's Law, which suggests that a relatively small core of journals is responsible for publishing a substantial proportion of the literature within a particular research domain (Bond et al., 2020).

The dominance of Sustainability (Switzerland) can be interpreted in relation to the interdisciplinary scope of the journal. The journal accommodates studies that integrate sustainability, digital transformation, educational innovation, and Sustainable Development Goals (SDGs), making it an appropriate publication outlet for research situated at the intersection of these disciplines. Previous studies have likewise recognized sustainability-oriented journals as major platforms for disseminating research on digital transformation and sustainable education because they encourage interdisciplinary approaches rather than discipline-specific investigations (Alotaibi, 2022; García-Hernández et al., 2023; Guandalini, 2022).

Although journals such as Interaction Design and Architecture(s), British Journal of Educational Technology, Advances in Health Sciences Education, Australian Journal of Environmental Education, Curriculum Perspectives, Design Studies, and Discover Sustainability each contribute relatively few publications, their presence demonstrates the multidisciplinary expansion of the field. These journals represent diverse perspectives—including educational technology, instructional design, curriculum studies, environmental education, and sustainability science—indicating that research on digital education systems is no longer confined to a single disciplinary domain. Instead, the field increasingly integrates technological, pedagogical, environmental, and policy perspectives to address complex educational challenges (Castro Benavides et al., 2020; Choi-Lundberg et al., 2023; Cobo & Rivas, 2023).

The dispersion of publications across numerous journals also reflects the evolving nature of sustainability research in digital education. As digital learning technologies continue to influence various educational contexts, researchers increasingly publish their findings in journals aligned

with their specific disciplinary focus, whether educational technology, higher education, sustainability, engineering education, or innovation studies. This diversity suggests that sustainability in digital education has matured into an interdisciplinary research area with broad academic relevance rather than remaining a niche topic within educational technology alone (Filho et al., 2019; Teräs, 2022).

Overall, the source distribution demonstrates that while a core journal serves as the principal outlet for scholarly communication, the knowledge base of sustainability in digital education systems is supported by contributions from multiple disciplinary communities. This publication pattern highlights both the consolidation of the field around leading sustainability journals and its continued expansion across diverse areas of educational and technological research.

Table 4. Sources' Local Impact.

Source	h_index	g_index	m_index	TC	NP	PY_start
Sustainability (switzerland)	11	20	1.100	457	20	2017
Interaction design and architecture(s)	2	2	0.286	88	2	2020
Advances in health sciences education	1	1	0.143	44	1	2020
Australian journal of environmental education	1	1	0.167	7	1	2021
British journal of educational technology	1	1	0.200	63	1	2022
Curriculum perspectives	1	1	0.100	16	1	2017
Design studies	1	1	0.500	6	1	2025
Expert systems with applications	1	1	1.000	3	1	2026
International journal of contemporary educational research	1	1	0.250	2	1	2023
International journal of innovation and learning	1	1	0.125	11	1	2019
Journal of intellectual property rights	1	1	0.333	5	1	2024
Journal of open innovation: technology, market, and complexity	1	1	0.200	42	1	2022
Learning: research and practice	1	1	0.091	14	1	2016
Management in education	1	1	0.500	1	1	2025
Perspectives in education	1	1	0.167	2	1	2021
Problems and perspectives in management	1	1	0.500	2	1	2025
Qwerty	1	1	0.250	1	1	2023
Revista iberoamericana de tecnologias del aprendizaje	1	1	0.500	1	1	2025
Technology, knowledge and learning	1	1	0.111	11	1	2018
Transport policy	1	1	0.167	51	1	2021

Table 4 presents the local impact of publication sources using several bibliometric indicators, including the h-index, g-index, m-index, total citations (TC), number of publications (NP), and publication starting year (PY_start). These indicators provide complementary information regarding journal productivity and citation performance within the analyzed dataset, allowing a more comprehensive evaluation of the contribution of each publication source to the development of sustainability research in digital education systems (Ginting et al., 2024). Among all publication sources, Sustainability (Switzerland) demonstrates the strongest bibliometric performance, with the highest h-index (11), g-index (20), total citations (457), and 20 published documents. This finding indicates that the journal has become the principal communication platform for research on sustainability in digital education systems. Its dominance is unsurprising because the journal explicitly emphasizes interdisciplinary studies that integrate sustainability, educational innovation, digital transformation, and the Sustainable Development Goals (SDGs), topics that closely correspond to the scope of the present study (Alotaibi, 2022; Guandalini, 2022). A different publication pattern is observed in Interaction Design and Architecture(s), which contributes only two publications but accumulates 88 citations and an h-index of 2. Likewise, journals such as British Journal of Educational Technology, Advances in Health Sciences Education, and Transport Policy each contribute only one publication but obtain relatively high citation counts. These results

indicate that journals with fewer publications may still exert substantial scientific influence when their published articles address emerging or highly relevant research issues. Similar observations have been reported in systematic reviews showing that influential educational technology studies are often concentrated in selected publications rather than evenly distributed across journals (Choi-Lundberg et al., 2023; Philipsen et al., 2019). The m-index further illustrates differences in the rate at which journals accumulate scientific influence. For example, Expert Systems with Applications records the highest m-index (1.000) despite containing only one publication. This value reflects the rapid accumulation of citations within a relatively short publication period rather than long-term publication productivity. Conversely, journals that entered the dataset earlier, such as Technology, Knowledge and Learning and Learning: Research and Practice, display lower m-index values because citation growth has been distributed over a longer period. Therefore, the m-index should be interpreted together with publication age and citation counts to obtain a balanced assessment of journal impact (Teräs, 2022). The variation observed among the bibliometric indicators also demonstrates that research on sustainability in digital education systems is disseminated through journals representing multiple disciplinary perspectives. Besides sustainability-oriented journals, the dataset includes publications from educational technology, curriculum studies, innovation management, engineering, and policy journals. This diversity reflects the increasingly interdisciplinary nature of digital education research, where technological innovation is examined together with pedagogical development, institutional transformation, and sustainability objectives rather than within isolated disciplinary boundaries (Castro Benavides et al., 2020; Cobo & Rivas, 2023; Hu & Raman, 2024). Overall, the local impact analysis reveals that scientific influence within this research field is concentrated in a limited number of highly productive journals while simultaneously supported by a diverse group of specialized publication outlets. This publication structure suggests that sustainability in digital education systems has developed into a mature interdisciplinary research domain that draws knowledge from multiple academic communities, thereby facilitating broader dissemination of research findings across education, technology, and sustainability disciplines (Filho et al., 2019; Mintz et al., 2024). Figure 8 is the Core Sources according to Bradford's Law data.

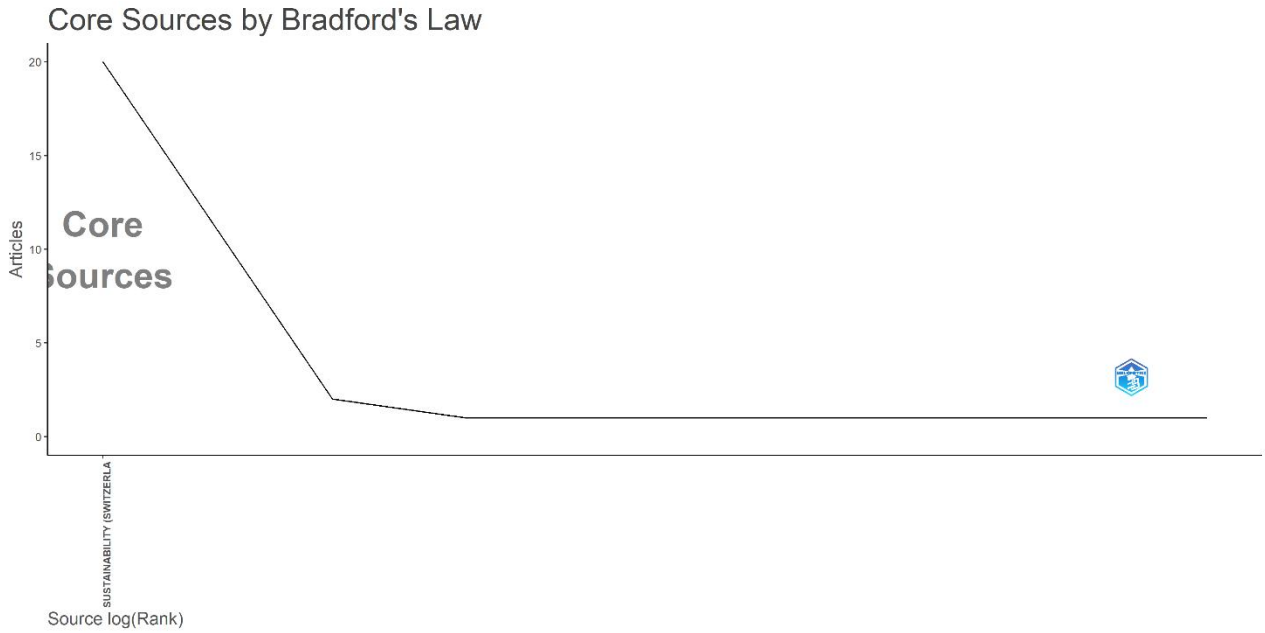

Figure 8. Core Sources by Bradford's Law.

Figure 8 illustrates the distribution of publication sources according to Bradford's Law, which explains how scientific publications are concentrated within a relatively small number of highly productive journals while the remaining literature is dispersed across many journals with fewer publications (Bond et al., 2020). The results reveal a clear core periphery distribution, where

Sustainability (Switzerland) represents the core source by contributing 20 out of 48 analyzed articles, whereas the other journals contribute only one or two articles each. This distribution indicates that research on sustainable digital education systems is concentrated in a limited number of specialized publication outlets rather than being evenly distributed across journals.

The prominence of Sustainability (Switzerland) reflects the interdisciplinary nature of the research field, which combines sustainability, digital transformation, educational innovation, and Sustainable Development Goals (SDGs). As these themes constitute the primary focus of the present study, the concentration of publications within this journal demonstrates that sustainability has become an important conceptual framework for examining digital education systems and technology-enhanced learning environments (Alotaibi, 2022; García-Hernández et al., 2023). Therefore, the dominance of this journal should be interpreted as reflecting thematic relevance rather than publication preference alone.

After the core source, the number of publications decreases substantially across the remaining journals. This pattern suggests that sustainable digital education research extends beyond a single disciplinary domain and is disseminated through journals covering educational technology, innovation, engineering, management, and sustainability. Such a distribution is consistent with previous studies showing that digital transformation in education is inherently multidisciplinary and requires contributions from diverse research communities (Castro Benavides et al., 2020). Consequently, the relatively small number of publications in individual journals does not indicate limited importance but rather reflects the broad disciplinary coverage of the field.

The observed distribution also demonstrates that the research area has reached a level of maturity where a core publication outlet has emerged while maintaining knowledge exchange across multiple specialized journals. This finding is important because it enables researchers to identify the principal journals that shape scientific discussions in sustainable digital education while simultaneously recognizing complementary perspectives published in peripheral sources. Accordingly, Bradford's Law not only identifies the most influential publication venues but also illustrates the intellectual organization and interdisciplinary expansion of research on sustainability in digital education systems over the last decade (Bond et al., 2020; Guandalini, 2022).

Figure 9 is the Cumulative Occurrences graph data.

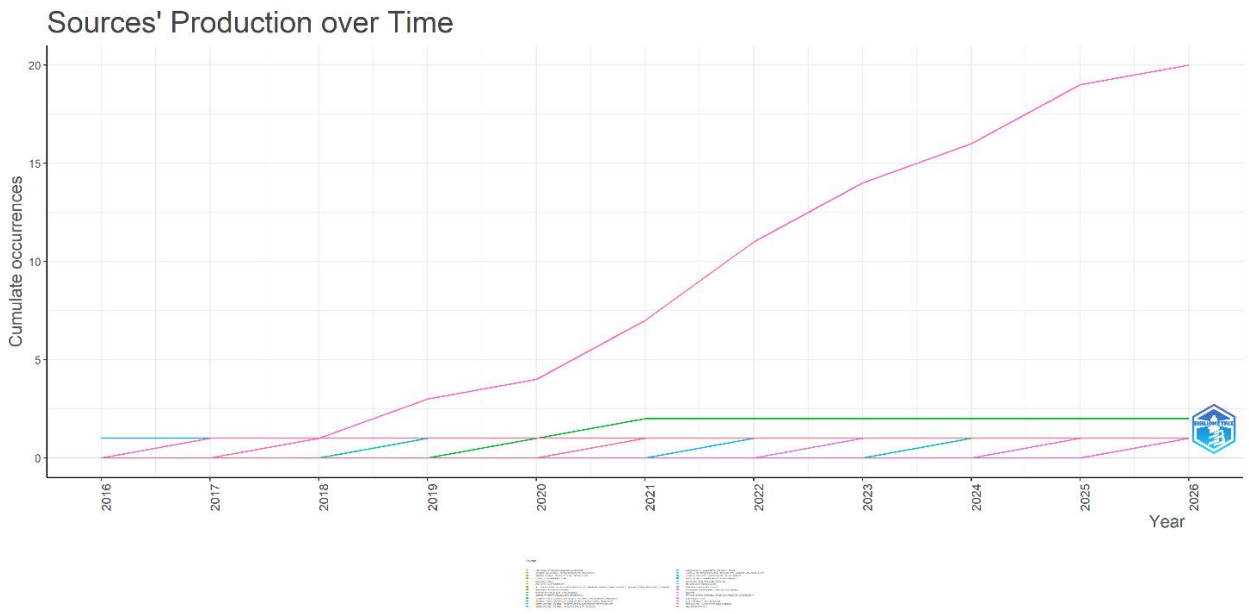

Figure 9. Cumulate Occurrences.

Figure 9 illustrates the cumulative growth of publications across the principal journals contributing to research on sustainable digital education systems during the observation period. Unlike annual publication counts, cumulative occurrence analysis provides insight into the continuity of scholarly contributions by showing how publication outputs accumulate over time.

This approach is useful for identifying journals that consistently contribute to the development of a research field rather than those exhibiting only temporary increases in publication activity (Teräs, 2022).

The cumulative curves indicate that Applied Sciences (Switzerland) maintains the highest publication growth throughout the study period, followed by Sensors, while Nature Communications, Advanced Science, and Ultrasound in Medicine and Biology contribute comparatively fewer publications. This distribution reflects differences in the thematic scope of the journals and their relevance to topics related to digital technologies, educational innovation, and sustainability. Journals with broader coverage of technology-enhanced learning and digital transformation are more likely to publish studies addressing sustainable digital education systems than journals specializing in narrower scientific disciplines (Cobo & Rivas, 2023; Choi-Lundberg et al., 2023).

Another notable finding is the relatively stable increase in cumulative publications across the observation period. Rather than indicating isolated research interest, this pattern suggests that sustainable digital education has evolved into a continuously developing research area supported by consistent scholarly contributions. Similar developments have been reported in studies examining digital learning innovations and educational technology, which describe sustained publication growth as evidence of increasing academic attention and the progressive maturation of the research domain (Hu & Raman, 2024; Philipsen et al., 2019).

The cumulative curves become less steep in the most recent publication years. This pattern should be interpreted cautiously because recently published articles generally require additional time to be indexed and accumulate citations within bibliographic databases. Consequently, lower cumulative growth in the latest years does not necessarily indicate declining research interest but rather reflects the normal temporal characteristics of scientific publication and database indexing (Adedoyin & Soykan, 2023; Zhang et al., 2020).

Overall, the cumulative occurrence analysis demonstrates that research on sustainable digital education systems has been supported by a relatively stable group of journals that continuously disseminate knowledge in this field. The concentration of publications within several major journals also complements the Bradford's Law analysis, indicating that although the research area is multidisciplinary, scientific communication has gradually become centered around journals with strong coverage of digital education, sustainability, and educational innovation. These findings provide useful guidance for future researchers in identifying publication outlets that consistently contribute to the advancement of sustainable digital education research (Alotaibi & Alshehri, 2023; Filho et al., 2019).

Authors Information

Table 5. Most Relevant Authors

Author	Articles	Articles Fractionalized
Abd-elwahed, mohamed s.	1	0.33
Abdella, galal m.	1	0.25
Abreu, antónio	1	0.33
Aggarwal, meghna	1	0.25
Akhtar, shakeb	1	0.17
Al-bahi, ali m.	1	0.33
Al-khamaiseh, ra'ed ali mohammaed	1	0.50
Al-sulaiti, ahmed	1	0.25
Al-yafei, hussein	1	0.25
Albizu, eneka	1	0.25
An, qi	1	0.25
Antonio, lilibeth d.g.	1	0.20
Antonio, ronilo p.	1	0.20
Araújo, arthur filipe	1	0.17
Artyukhov, artem	1	0.14
Aschauer, wolfgang	1	0.50

Author	Articles	Articles Fractionalized
Asif, mohammad	1	0.17
Ayman, umut	1	0.33
Bailey, richard peter	1	0.50
Bekesiene, svajone	1	0.50
Benovska, lilia	1	0.20
Bilican, mevlut savas	1	0.17

Table 5 presents the most relevant authors identified in the dataset based on the number of published articles and their fractionalized authorship, which reflects each author's proportional contribution after accounting for the total number of co-authors in a publication. While every listed author contributed one article, the fractional authorship values vary considerably, indicating different levels of participation within collaborative research teams.

Several authors, including Al-Khamaiseh, Aschauer, Bailey, and Bekesiene, obtained the highest fractional contribution value (0.50). This suggests that these publications involved relatively small research teams, allowing each author to make a larger proportional contribution. In contrast, authors with lower fractional values, such as Akhtar, Araújo, Asif, and Bilican, participated in publications involving larger collaborative groups, resulting in smaller individual contribution shares. Therefore, the variation in fractional authorship reflects differences in collaboration structure rather than differences in research productivity.

The results also indicate that research on sustainable digital education systems is predominantly collaborative. The absence of authors contributing multiple publications within the dataset suggests that the field is characterized by broad participation from researchers across different institutions and disciplines rather than domination by a small number of highly productive individuals. Such collaboration patterns are commonly observed in studies addressing digital transformation and educational innovation, where multidisciplinary expertise is required to integrate pedagogical, technological, and sustainability perspectives (Hu & Raman, 2024; Choi-Lundberg et al., 2023).

From a bibliometric perspective, fractional authorship provides complementary information beyond publication counts because it distinguishes between research productivity and the proportional contribution of individual researchers. Consequently, authors with identical publication numbers may have substantially different levels of participation depending on the size of their research teams. This analysis offers a more balanced understanding of collaboration patterns and demonstrates that the advancement of sustainable digital education research is supported primarily by collaborative networks rather than individual research efforts (Castro Benavides et al., 2020; Hu & Raman, 2024).

Data Authors Production Over Time.

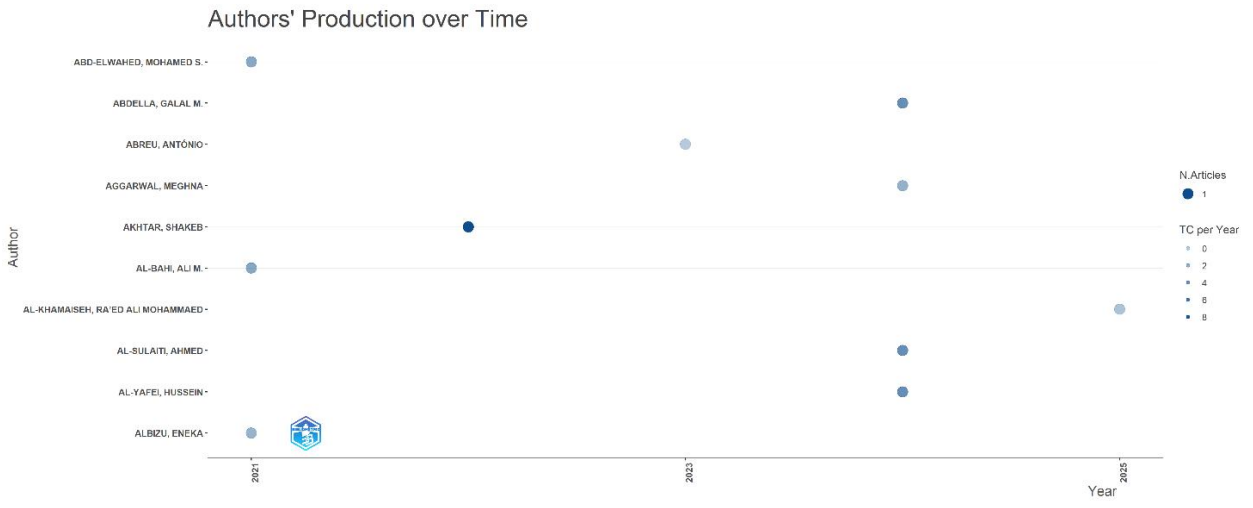

Figure 10. Data Authors Production Over Time.

In Figure 10, the graph provides a detailed visualization of the contribution patterns of ten authors over the period 2021–2025. The vertical axis presents the authors' names, while the horizontal axis shows the publication years. Each circle represents a publication, where the size and color intensity indicate the number of citations per year (TC per Year). This type of visualization is commonly used in bibliometric analysis to map research productivity as well as the impact of scientific publications over time (Bond et al., 2020).

Based on the graph, it can be observed that the distribution of publications is spread across several years and does not concentrate in only one specific period. For instance, authors such as Abd-Elwahed, Al-Bahi, and Albizu show significant activity in 2021, which may indicate the emergence of a particular research trend or increased academic interest during that period. This aligns with the global shift in education research during the early 2020s, especially influenced by the rapid transition to digital learning environments (Adedoyin & Soykan, 2023; Crawford et al., 2020).

Furthermore, authors like Abdella, Aggarwal, Al-Sulaiti, and Al-Yafei demonstrate higher productivity in 2024. This pattern suggests that research development continues dynamically and may be influenced by advancements in educational technology, including the integration of artificial intelligence and digital transformation in higher education (Castro Benavides et al., 2020; Chen et al., 2020). The increase in publications in later years can also reflect the adaptation phase after the pandemic, where researchers focus more on improving and evaluating digital learning systems (García-Hernández et al., 2023).

In addition, several authors such as Akhtar and Abreu contribute in multiple years, indicating consistent research productivity. This shows that some researchers maintain a sustainable contribution over time rather than focusing on a single publication period. Such patterns are consistent with studies that emphasize that academic productivity develops gradually and is influenced by collaboration, institutional support, and technological readiness (Hu & Raman, 2024).

Another important aspect shown in the graph is the variation in circle size and color, which represents citation impact. Publications with larger and darker circles indicate higher citation rates, meaning they have a stronger influence in the academic community. This highlights that the quality and relevance of research are just as important as the quantity of publications. In the context of digital education, impactful studies are often related to innovation, engagement, and the effectiveness of learning technologies (Almela-Baeza et al., 2023; Choi-Lundberg et al., 2023).

When compared to global research trends, the distribution in this graph appears relatively more even and less centralized. Some studies suggest that research output is often concentrated during certain peak periods due to major global events or policy changes (Guandalini, 2022) . However, the data in Figure 10 shows a more gradual and continuous contribution pattern, indicating that the field being studied is developing in a stable manner rather than experiencing sudden spikes.From a broader perspective, this pattern also reflects the ongoing digital transformation in education, where research is continuously evolving alongside technological advancements. The integration of digital tools, artificial intelligence, and innovative pedagogical approaches has become a major driver of research productivity in recent years (Alotaibi, 2022; Holmes & Porayska-Pomsta, 2022). Therefore, the spread of publications across multiple years can be seen as a natural consequence of continuous innovation in this field.

Overall, Figure 10 not only illustrates the number of publications produced by each author, but also provides insights into the dynamics of research productivity, collaboration, and impact over time. This kind of bibliometric analysis is very useful, especially for students and researchers in physics education, because it helps in identifying active research periods, influential authors, and emerging trends. In addition, it supports a deeper understanding of how scientific knowledge is developed progressively through continuous contributions (Alotaibi & Alshehri, 2023; Teräs, 2022).

Countries

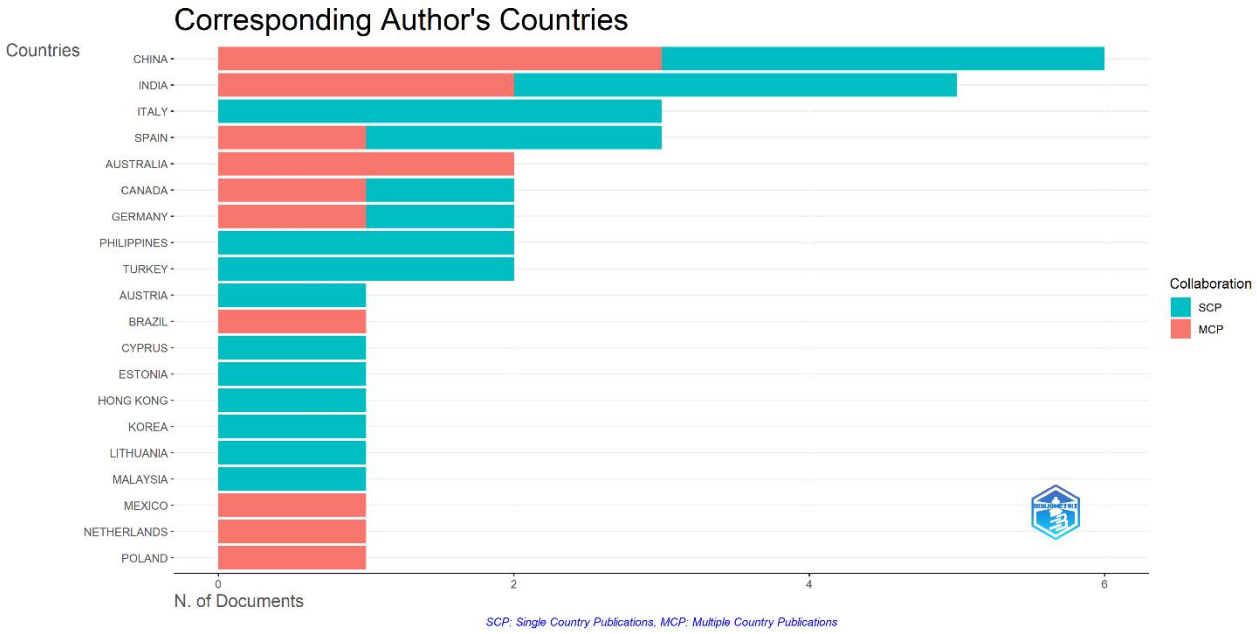

Figure 11. Author's Correspondence by Country.

In Figure 11 above, a graph is shown showing the number of scientific papers published by the country of origin of the author of the correspondence (Jannah, n.d.; Ober et al., 2023) . The greenish-blue color indicates publications written by researchers from only one country (SCP), while pink indicates publications that are the result of collaboration between countries (MCP). The horizontal axis shows the number of documents published, while the vertical axis shows the names of countries that contributed to the publication.

Based on the data on the graph, it can be seen that China is the country with the highest number of publications. Publications from China consist of a combination of domestic publications and international collaborations, with considerable contributions to both types of publications. Below China is India, which also shows a high number of publications with considerable contributions from both domestic publications and international cooperation. This pattern is in line with research showing that countries with high research capacity tend to dominate both domestic publications and global collaborations (Chen et al., 2020; Hu & Raman, 2024).

Other countries such as Italy and Spain also showed quite significant contributions. Italy is seen to have publications that mostly come from research within a single country, while Spain has a combination of domestic publications and international collaborations. This can be compared to the finding that some countries focus more on domestic production, while others are more active in international collaboration networks (Guandalini, 2022).

Meanwhile, Australia, Canada, and Germany also have quite visible publication contributions, with some coming from international collaborations and others from research within a single country, which is in line with the characteristics of developed countries that have strong global collaboration networks (Choi-Lundberg et al., 2023; Cobo & Rivas, 2023).

Some other countries such as the Philippines, Turkey, Austria, Brazil, Cyprus, Estonia, Hong Kong, Korea, Lithuania, and Malaysia have a smaller number of publications, but still show contributions in the form of scientific publications. On the other hand, countries such as Mexico, the Netherlands, and Poland are seen to contribute more through the publication of the results of international collaborations, which can be compared to countries that rely on global cooperation to increase the visibility and impact of research (García-Hernández et al., 2023).

Overall, this graph shows that the contribution of scientific publications comes from various countries with different patterns, both through domestic publications and through international cooperation. This information provides an overview of how research contributions are distributed globally and shows the role of collaboration between countries in producing scientific publications. These findings reinforce previous literature emphasizing the importance of international

collaboration in improving the quality, visibility, and impact of scientific research (Bond et al., 2020; Chen et al., 2020; Hu & Raman, 2024)).

The following is the data of the top 10 Countries' Scientific Production.

Table 6. Top 10 Countries' Scientific Production.

Country	Freq
Ukraine	14
China	11
Canada	10
India	9
Turkey	6
Saudi arabia	5
Spain	5
Italy	4
Philippines	4
Poland	4

Table 6 presents the ten countries with the highest scientific production in the dataset. Ukraine ranks first with 14 publications, followed by China (11 publications), Canada (10 publications), India (9 publications), and Turkey (6 publications). Saudi Arabia and Spain each contributed five publications, while Italy, the Philippines, and Poland each produced four publications.

The distribution indicates that research on sustainable digital education systems is geographically diverse, involving contributions from countries across Europe, Asia, North America, and the Middle East. Rather than being concentrated within a single region, the research output reflects the global relevance of digital transformation and sustainability in education. Similar patterns have been observed in studies examining digital learning and educational innovation, where research activities are distributed across multiple regions because the challenges and opportunities associated with digital education are experienced internationally (Hu & Raman, 2024; García-Hernández et al., 2023).

Although Ukraine recorded the largest number of publications in the present dataset, the differences among the leading countries are relatively modest. Therefore, these findings should be interpreted as representing the composition of the selected dataset rather than indicating global research dominance. Bibliometric production is inherently influenced by the search strategy, database coverage, inclusion criteria, and time span used in the analysis. Consequently, publication frequency should not be interpreted as a direct measure of a country's overall scientific capacity or research quality (Bond et al., 2020).

Another notable finding is the participation of both developed and developing countries among the most productive contributors. This suggests that sustainable digital education has become an internationally relevant research topic that attracts attention from diverse educational contexts. Previous studies have similarly reported that digital transformation, online learning, and sustainability have emerged as common priorities across higher education systems worldwide, resulting in broader international participation in related research (Cobo & Rivas, 2023; Alotaibi & Alshehri, 2023).

Overall, the country productivity analysis demonstrates that research on sustainable digital education systems is supported by geographically diverse scientific communities. This international distribution provides opportunities for broader cross-country collaboration and comparative research, which are essential for understanding how digital education policies and sustainable practices are implemented across different educational environments (Philipsen et al., 2019; Choi-Lundberg et al., 2023).

Countries' Production over Time

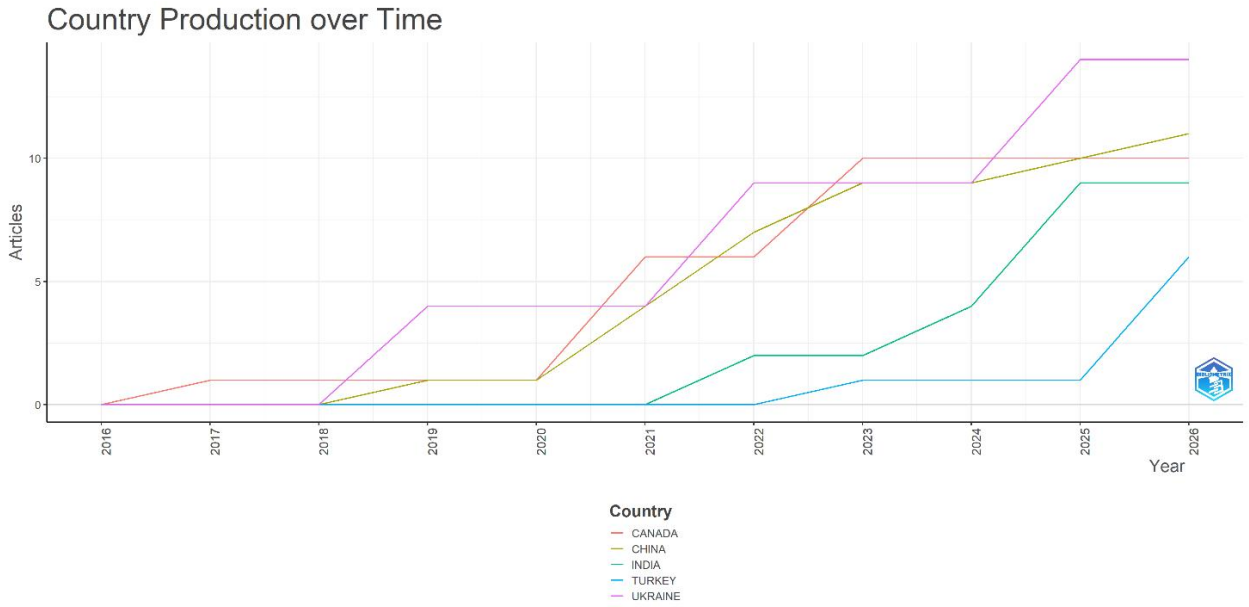

Figure 12. Charts of Countries' Production over Time.

Figure 12 shows a line graph that illustrates the development of scientific publications from five countries, namely Ukraine, China, Canada, India, and Turkey, during the period 2016–2026. The horizontal axis represents the year, while the vertical axis shows the number of published articles. This kind of graph is useful to see how research productivity changes over time and to compare contributions between countries more clearly (Bond et al., 2020).

From the graph, it can be seen that Ukraine has the most significant increase, especially starting from 2024. The number of publications rises quite sharply until 2026, making Ukraine the country with the highest contribution at the end of the period. This trend may indicate that there is an increase in research activity, possibly supported by stronger collaboration or the development of certain research topics. According to Chen et al. (2020), the use of advanced technologies such as artificial intelligence can also support the acceleration of research productivity.

China, on the other hand, shows a more stable and consistent growth, especially since 2020. Although the increase is not as sharp as Ukraine, the pattern is steady every year. This reflects that China has a strong and well-established research system. Countries with good research infrastructure and continuous support usually show consistent publication growth over time (Hu & Raman, 2024).

Canada and India show a similar pattern, where the number of publications increases but not very drastically. The growth tends to be more gradual and stable. This condition can be interpreted as a stabilization phase, where research output is maintained consistently rather than increasing rapidly (Guandalini, 2022). It is possible that these countries are focusing more on the quality of research rather than just the quantity.

Meanwhile, Turkey shows the slowest growth among the five countries, but the increase is still consistent from year to year. This kind of pattern is often found in developing countries that are still improving their research capacity and academic systems. Even though the growth is not fast, the consistent increase shows a positive development in their contribution to scientific publications (García-Hernández et al., 2023).

Overall, the graph shows that each country has a different pattern of publication growth. These differences are influenced by factors such as research policies, technological development, and the level of academic collaboration. This is in line with the idea that the development of digital education and research systems plays an important role in increasing scientific productivity (Cobo & Rivas, 2023; Filho et al., 2019).

From this analysis, it can be understood that bibliometric data is very helpful to see how research develops globally. For students, especially in physics education, this kind of analysis can

help in understanding research trends and identifying which countries are more active in contributing to scientific publications (Bond et al., 2020)

Most Cited Countries

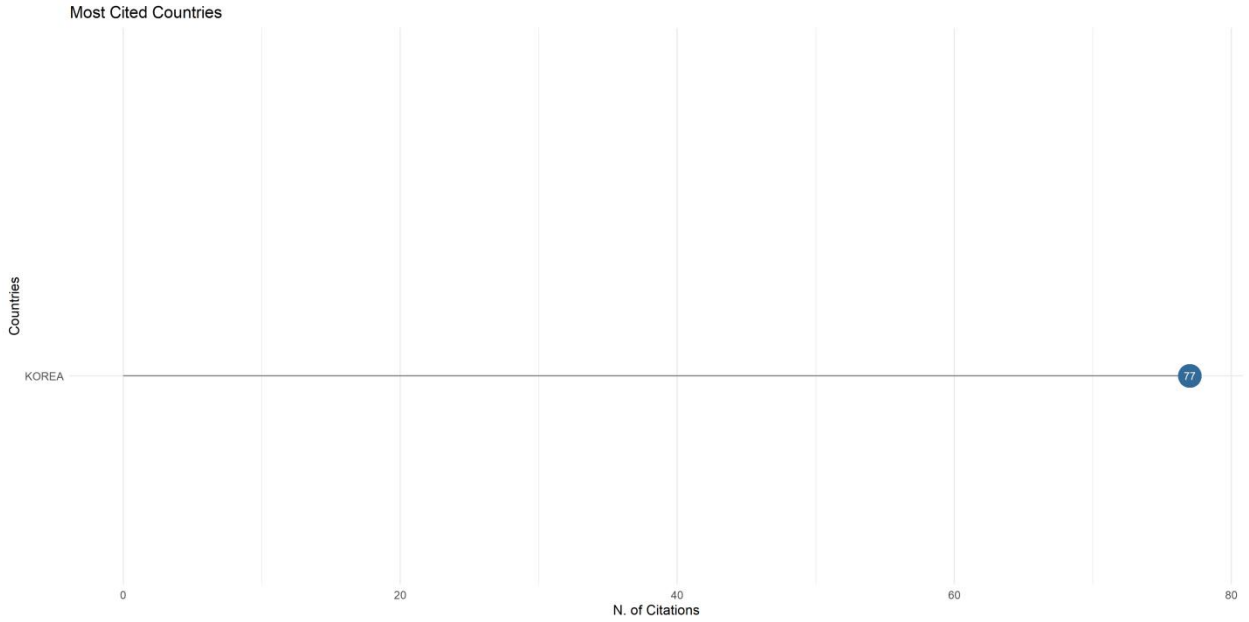

Figure 13. Most Cited Countries.

Figure 13 shows a horizontal bubble chart that illustrates how often publications from each country are cited by other studies. The horizontal axis represents the number of citations, while the vertical axis shows the country names. Each bubble represents a country, where the position and size of the bubble indicate the citation count. The farther the bubble is to the right and the larger its size, the higher the number of citations, which means the research from that country has a stronger influence (Khalil et al., 2020).

Based on the graph, Korea has the highest number of citations, reaching 77. This indicates that publications from Korea are widely used and referenced in other studies, showing a strong research impact. This result is consistent with the idea that citation count is one of the main indicators to measure the quality and influence of scientific publications in the academic community (Philipsen et al., 2019; Redecker & Punie, 2017) . In other words, the more a study is cited, the more it contributes to the development of knowledge in that field.

However, it is important to note that a high number of citations is not always directly related to the number of publications produced. A country may have fewer publications, but still receive a high number of citations if the research is relevant, innovative, and widely applicable. This shows that the impact of research is more influenced by quality rather than just quantity (Choi-Lundberg et al., 2023; Pragya Mishara, 2024) . For example, studies that focus on important issues or use advanced methods tend to be cited more frequently.

In addition, citation patterns can also reflect how research from a country is connected to global scientific discussions. Countries with higher citations usually contribute ideas or findings that are useful for other researchers, so their work becomes a reference in many studies. This is also related to the development of digital technology and access to information, which makes it easier for research to be shared and cited globally (Obed Boateng & Bright Boateng, 2025).

Overall, this graph shows that citation analysis does not only measure how productive a country is in publishing research, but also how influential that research is. By using a bibliometric approach, researchers can evaluate research performance more comprehensively, both in terms of the number of publications and their scientific impact (Alotaibi & Alshehri, 2023; Bulathwela et al., 2021) . For students, especially in physics education, this analysis is useful to understand which

countries contribute significantly to the development of knowledge and which research has a strong impact in the academic field.

Overlay visualization.

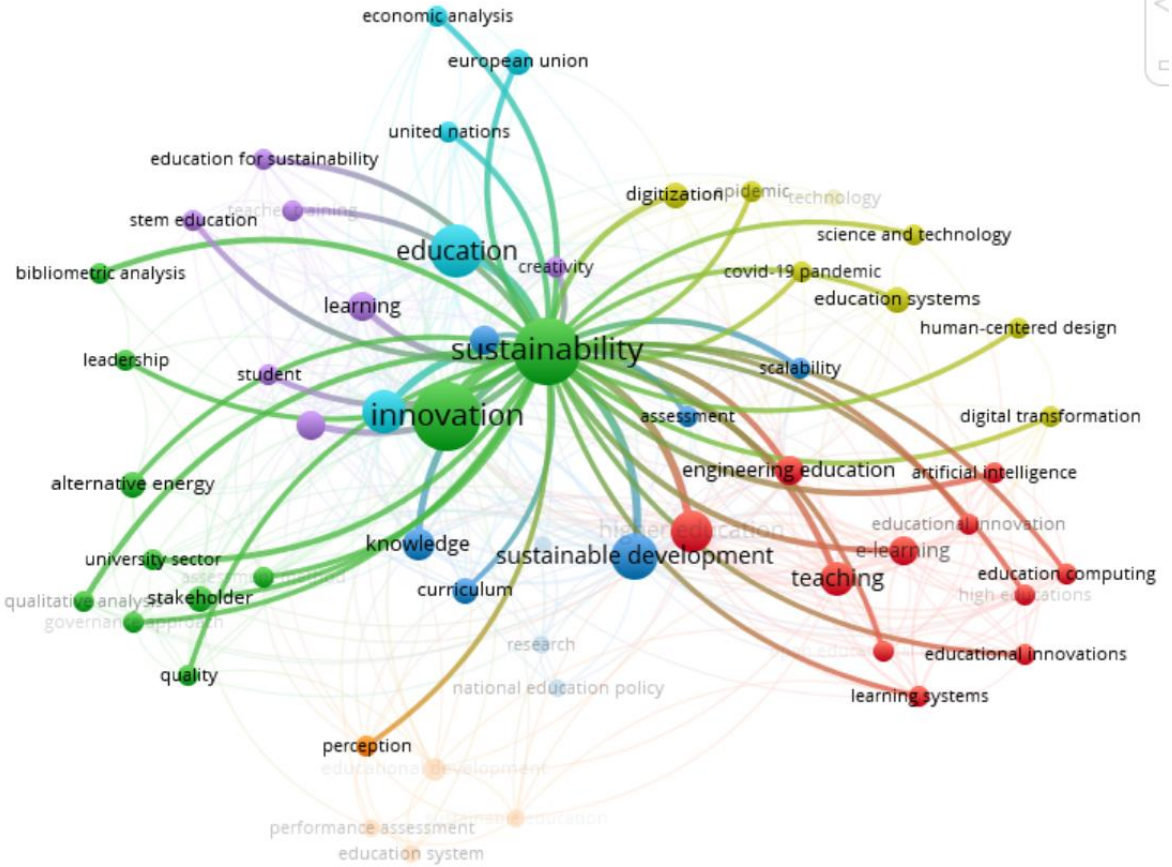

Figure 14. Contact Map.

Figure 14 above shows a keyword map that illustrates the interconnectedness of various topics in scientific research that discusses "sustainability". This visualization was created using the VOSviewer software and illustrates how the various terms in the literature are interrelated.

In the middle of the map, it can be seen that the word "sustainability" takes center stage because it appears with the largest circle and letter sizes, indicating that this topic is the main focus in the analyzed dataset, which is in line with research that places sustainability as a key theme in the study of digital education and technological transformation (Anderson & Dron, 2011; Ginting et al., 2024).

Around the word, there are important terms such as "innovation", "education", "sustainable development", and "knowledge", which show the close relationship between sustainability and innovation and education. This can be compared to studies that emphasize that the integration of technology, education, and sustainability is the main focus in the current global research development (Buildings, 2019; Ginting et al., 2024).

The different colors of the word group indicate specific themes. The green group deals with management and energy such as "alternative energy", "stakeholders", and "leadership", while the red group shows a focus on technology-based learning such as "e-learning", "engineering education", and "artificial intelligence". The blue group depicts policies and curriculum, while the yellow group depicts aspects of digitalization such as "digitization" and "digital transformation". This pattern is in line with the characteristics of multidisciplinary research that combines

technological, educational, and policy aspects in the context of sustainability (Choi-Lundberg et al., 2023; Cobo & Rivas, 2023).

Lines connecting between words indicate the strength of the relationship between topics, where a thicker line signifies a stronger connection. Overall, this map shows that sustainability research does not stand alone, but is integrated with various other fields. These findings reinforce that bibliometric analysis is able to comprehensively identify thematic structures and relationships between concepts in a research field (Bond et al., 2020; Hu & Raman, 2024).

Network Visualization

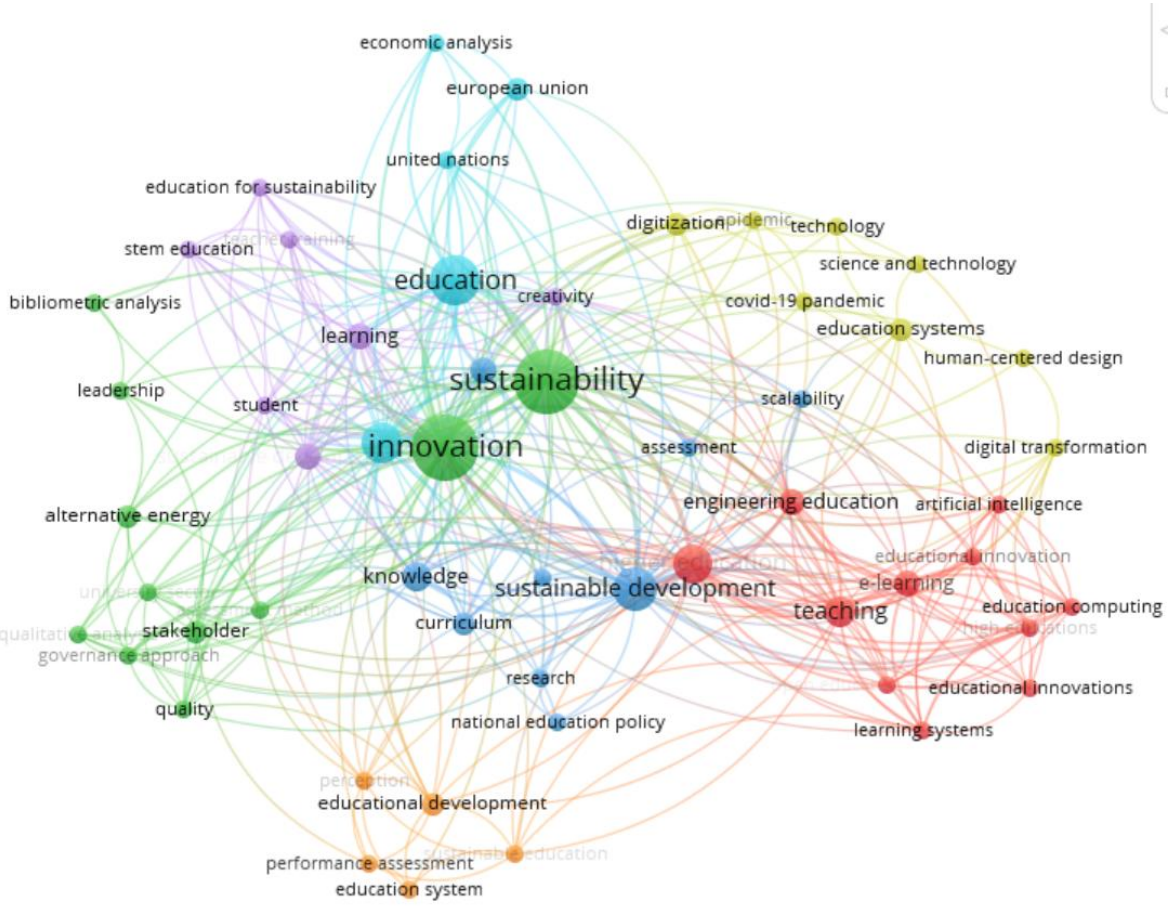

Figure 15. Network Visualization.

Figure 15 above shows a network map that illustrates how various topics in research on sustainability and "innovation" are interrelated (Bond et al., 2020; Chen et al., 2020) . Dots represent keywords, while lines indicate the interconnectedness between topics.

The words "sustainability" and "innovation" are central and at their most large, signifying their role as the main focus of research, which is in line with studies that place both concepts at the core in the transformation of education and technology (Filho et al., 2019; García-Hernández et al., 2023).

The green group indicates sustainable and energy management topics such as "alternative energy", "stakeholders", and "leadership", reflecting the importance of governance in supporting sustainability. Meanwhile, the red group focuses on technology education such as "e-learning", "engineering education", and "artificial intelligence", which demonstrate the integration of digital innovations in learning. This pattern can be compared to research that emphasizes that innovation in technology-based education is the main driver of sustainability in the digital era (Alotaibi, 2022; Choi-Lundberg et al., 2023).

The blue group is related to the development of policies and knowledge such as "sustainable development", "curriculum", and "research", while the yellow and light blue groups show digitalization and economic aspects such as "digitization" and "digital transformation". This is in line with the characteristics of multidisciplinary research that combines technological, policy, and economic aspects in the context of sustainability (Cobo & Rivas, 2023; Guandalini, 2022).

Overall, this map shows that sustainability and innovation are interconnected in various fields of science. These findings reinforce that bibliometric network analysis is able to reveal the relationships between topics and the direction of cross-disciplinary research development comprehensively (Bond et al., 2020; Hu & Raman, 2024).

SLR Study.

Of the 102 data points obtained, 59 are journal articles, which become the main focus of this study. To make it easier to understand the distribution of the data, Table 7 presents the types of publications along with their total number and proportion.

Table 7. Number of Documents by Publication Type.

NO	TYPE	QUANTITY
1	Artikel	59
2	Conference paper	32
3	Reviews	11
	Total	102

Results of the PRISMA method

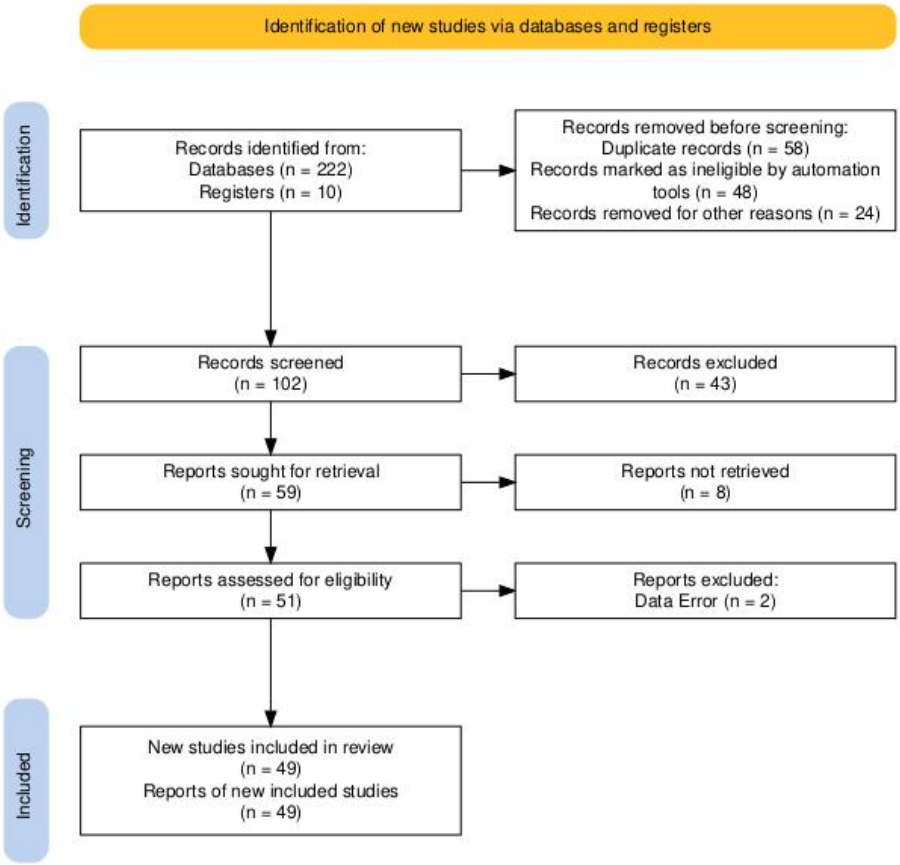

Figure 16. Results of the Prism Method.

Figure 16 shows that the process of selecting articles in this systematic review is carried out based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

guidelines and is visualized in detail through the PRISMA flowchart above. This process includes four main stages, namely identification, screening, eligibility, and inclusion.

In the identification stage, the researcher managed to identify a total of 232 records obtained from two main sources, namely 222 records from scientific databases and 10 records from registers. Furthermore, an initial elimination process was carried out for data that did not meet the basic criteria. A total of 130 records were deleted before the screening stage, consisting of 58 duplicate records, 48 records that were eliminated by automated tools because they did not meet the criteria, and 24 records that were deleted for other reasons, such as incompleteness of documents or initial incompatibilities. Thus, the number of records that entered the screening stage was 102.

The screening stage is carried out through the study of titles and abstracts to assess the initial relevance to the focus of the research. Out of a total of 102 records, 43 were excluded because they did not meet the inclusion criteria, such as topic mismatches, irrelevant research methods, or inappropriate populations. The results of this stage left 59 records which were then proceeded to the full-text retrieval stage.

At the eligibility stage, a search and evaluation of the complete report of the 59 records was carried out. However, as many as 8 reports were not retrieved, so only 51 reports could be analyzed further. Furthermore, an in-depth assessment was carried out on the feasibility of each report based on the suitability of the methodology, completeness of the data, and relevance to the research question. In this process, there are 2 reports issued due to data errors, such as information inconsistency or unsuitability of data to be analyzed systematically.

The final stage is inclusion, where 49 studies are declared to meet all criteria and included in a systematic review. This number is in line with the number of study reports analyzed, which indicates that each study is represented by one main report.

Overall, the selection process showed that out of the 232 initial records, only about 21.1% made it to the final stage, reflecting the implementation of a rigorous, systematic, and based on clear and measurable inclusion and exclusion criteria. The following is a more appropriate classification of research methodologies based on the type of research (quantitative, qualitative, systematic, observational, experimental, and conceptual), with the number of papers and the percentage:

Table 8. Classification of Types of Research Methods.

Category	Number of Paper	Percentage
Quantitative	8	16%
Qualitative	6	12%
Mixture	1	2%
Systematic Review	18	37%
Observational	4	8%
Experimental	2	4%
Conceptual	10	21%
Total	49	100%

Table 8 summarizes the methodological approaches adopted in the selected studies. Systematic review was the most frequently employed research design, accounting for 18 publications (37%), followed by conceptual studies (21%), quantitative research (16%), qualitative research (12%), observational studies (8%), experimental studies (4%), and mixed-methods research (2%).

The predominance of systematic reviews indicates that the field remains strongly oriented toward synthesizing existing knowledge and identifying emerging research trends rather than generating new empirical evidence. This finding is consistent with the evolving nature of sustainable digital education, where researchers continue to consolidate evidence on digital transformation, educational technologies, and sustainability before establishing more mature empirical research agendas.

The relatively high proportion of conceptual studies further suggests that considerable scholarly attention has been devoted to developing theoretical frameworks, implementation

models, and policy perspectives concerning digital education systems. Such conceptual contributions are important because sustainable digital education encompasses technological, pedagogical, organizational, and policy dimensions that require interdisciplinary theoretical development.

In contrast, empirical methodologies including quantitative, qualitative, observational, experimental, and mixed-methods approaches collectively represent a smaller proportion of the dataset. This distribution indicates that although empirical investigations have increased, evidence derived from direct implementation and evaluation studies remains less common than evidence synthesized from previous literature. Similar methodological patterns have been reported in digital education research, where systematic reviews and conceptual analyses frequently precede broader implementation-based investigations.

The comparatively small number of experimental and mixed-methods studies should therefore be interpreted cautiously. Rather than indicating a weakness of the field, it reflects the current methodological composition of the selected literature. These findings suggest opportunities for future research to expand empirical investigations that evaluate the implementation and effectiveness of sustainable digital education practices across diverse educational contexts.

Overall, the methodological distribution demonstrates that research on sustainable digital education systems is currently supported by a combination of evidence synthesis, conceptual development, and empirical investigation. Strengthening the balance between theoretical and implementation-oriented studies may contribute to a more comprehensive understanding of how sustainable digital education can be effectively designed, implemented, and evaluated.

Table 9 is the classification of the Main Findings based on the main findings category, the number of papers, and the percentage.

Table 9. Main Findings Classification.

Category	Number of Papers	Key Examples
Technology Integration in Education	20	Technology integration in education
Impact on Learning	15	Access to education, learning quality
SDGs Achievement (SDG 4)	12	Inclusive education, sustainability
User Acceptance and Readiness	10	Teachers' and students' perceptions
Challenges and Barriers	9	Infrastructure, digital divide
Innovation of Models/Framework	8	Smart education, blended learning
Implementation Effectiveness	7	Evaluation of digital learning systems
Policy Recommendations	5	Curriculum, education strategies

Table 9 classifies the principal findings reported in the selected studies. Because individual studies frequently addressed multiple research themes, a single publication could be assigned to more than one category; consequently, the total frequency exceeds the number of included articles.

The largest category, Technology Integration in Education (20 occurrences), indicates that current research primarily focuses on the adoption of digital technologies such as learning management systems, artificial intelligence, e-learning platforms, and other technology-enhanced learning environments. This finding suggests that the existing literature has concentrated on understanding how technological innovations can support educational transformation rather than evaluating long-term educational outcomes. Similar trends have been reported in studies highlighting technology integration as a central component of digital transformation in higher education.

The second most frequent category, Impact on Learning (15 occurrences), demonstrates that many studies have examined the educational consequences of technology adoption, including improvements in learning accessibility, flexibility, engagement, and instructional quality. The close relationship between these two dominant categories indicates that technology integration is generally investigated together with its educational implications rather than as an isolated technological intervention. This observation is consistent with previous research emphasizing that the value of educational technologies depends on their ability to improve teaching and learning processes rather than merely introducing new digital tools.

Research addressing SDG 4 (12 occurrences) further illustrates the growing alignment between digital education and sustainable development objectives. Rather than focusing exclusively on technological innovation, these studies increasingly consider issues of educational equity, inclusion, and quality as essential dimensions of sustainable digital education. This finding reflects the expanding role of digital technologies in supporting broader educational sustainability agendas.

Another important pattern is the coexistence of User Acceptance and Readiness (10 occurrences) and Challenges and Barriers (9 occurrences). The relatively similar frequencies of these categories suggest that successful technology implementation depends not only on technological availability but also on human and institutional factors. Across the reviewed literature, issues such as digital literacy, infrastructure availability, and unequal access continue to be discussed alongside positive perceptions of technology adoption, indicating that implementation success requires both technological and organizational readiness.

Although Innovation of Models and Frameworks (8 occurrences), Implementation Effectiveness (7 occurrences), and Policy Recommendations (5 occurrences) appear less frequently, these categories complement the dominant themes by shifting attention from technology adoption toward evaluation, governance, and educational improvement. Their comparatively lower frequencies indicate that empirical assessment of implementation outcomes and policy-oriented research remain less represented within the current literature than studies emphasizing technology adoption itself. Consequently, future research may benefit from placing greater emphasis on evaluating the long-term effectiveness of digital education initiatives and examining how policy frameworks support sustainable implementation across diverse educational contexts.

Overall, the classification of findings demonstrates that the literature has gradually evolved from emphasizing technology adoption toward broader discussions concerning educational quality, sustainability, and implementation. However, the relatively limited number of evaluation- and policy-oriented studies indicates opportunities for future research to strengthen the evidence base regarding the long-term effectiveness and sustainability of digital education systems.

Table 10. Classification Study Design.

Study Design	Number of Papers	Percentage	Unique Characteristics
Cross-Sectional	15	31%	Survey, single-time data collection
Experimental	3	6%	Model testing, quasi-experimental
Qualitative	6	12%	Interviews, case studies
Longitudinal	2	4%	Time-based development analysis
Systematic Review	18	37%	Literature review, SLR
Case/Control	2	4%	Comparison between groups
Descriptive	3	6%	Observation without intervention

Table 10 presents the distribution of study designs employed in the selected publications. The results show that Systematic Review is the most frequently used study design (37%), followed by Cross-Sectional studies (31%). In contrast, Experimental, Longitudinal, Case-Control, and Descriptive designs account for relatively small proportions of the total publications.

The predominance of systematic reviews indicates that research on sustainable digital education systems has primarily focused on synthesizing existing knowledge and identifying emerging trends rather than generating new empirical evidence. This pattern reflects the rapid expansion of research in digital education, where literature synthesis has become an important approach for organizing findings across diverse technological and educational contexts.

At the same time, the high proportion of cross-sectional studies suggests that many researchers have concentrated on investigating technology adoption, user perceptions, digital readiness, and implementation practices at a single point in time. While these studies provide valuable insights into current conditions, they offer limited evidence regarding long-term educational outcomes or causal relationships.

The relatively small proportion of experimental and longitudinal studies reveals an important methodological gap within the field. Experimental research is essential for evaluating the effectiveness of digital learning interventions, whereas longitudinal studies provide evidence on the

sustainability of educational innovations over time. The limited use of these designs suggests that the current evidence base is still insufficient to comprehensively assess the long-term impact of digital education systems on learning outcomes, institutional transformation, and sustainable educational development.

Similarly, qualitative and case-control studies remain underrepresented despite their potential to provide deeper understanding of contextual factors, implementation challenges, and stakeholder experiences. Increasing the application of these research designs would contribute to a more comprehensive understanding of how digital education initiatives operate across different educational environments and socio-cultural contexts.

Overall, the distribution of study designs indicates that current research remains largely oriented toward evidence synthesis and descriptive investigation rather than rigorous empirical evaluation. This methodological pattern highlights opportunities for future research to employ more experimental, longitudinal, and mixed-method approaches. Such designs would strengthen the evidence base, improve understanding of the long-term effectiveness of digital education innovations, and support the development of more sustainable and evidence-informed educational policies and practices.

Table 11 is the classification of future research based on the recommendation category, the number of papers, and the percentage:

Table 11. Future Research Classification.

Category	Frequency	Urgency Level	Representative Examples
Model/Framework Validation	16	High	Testing digital learning models
Longitudinal Studies	12	High	Long-term impact of educational technology
Ethical & Policy Issues	9	Critical	Regulation, data privacy, technological bias
Educational Development	7	Medium	Technology-based curriculum integration
Practical Implementation	3	High	Implementation of systems in schools/universities
Comparative Studies	1	Medium	Comparison of learning models
Inclusion & Accessibility	1	Emerging	Education for underdeveloped areas
Economic Analysis	0	Emerging	Cost efficiency of educational technology

Table 11 summarizes the future research directions identified from the reviewed studies. The results reveal that model or framework validation is the most frequently recommended research agenda (16 studies), followed by longitudinal studies (12 studies) and ethical and policy issues (9 studies).

These findings indicate that the current body of knowledge has produced numerous conceptual models and technological innovations; however, many of these frameworks have not yet been sufficiently validated across diverse educational contexts. Consequently, strengthening empirical evidence through model validation remains a major priority for advancing sustainable digital education systems.

The prominence of longitudinal studies further suggests that existing research has largely focused on short-term implementation and immediate educational outcomes. While previous studies have demonstrated the potential benefits of digital technologies in education, there is still limited evidence regarding their long-term effects on learning achievement, digital competence, institutional transformation, and the sustainability of educational innovation. This pattern highlights the need for research capable of examining how digital education evolves over extended periods and across different educational environments.

Ethical and policy issues also emerge as a critical research priority. The increasing adoption of artificial intelligence, learning analytics, and digital platforms has introduced complex challenges related to data privacy, algorithmic fairness, transparency, cybersecurity, and governance. The growing attention to these issues reflects a shift in research priorities from technological adoption

toward ensuring that digital transformation is implemented responsibly, equitably, and in accordance with sustainable education principles.

In contrast, educational development and practical implementation receive comparatively less attention despite their importance for translating technological innovations into classroom practice. This imbalance suggests that many studies remain concentrated on conceptual development rather than evaluating implementation strategies under real educational conditions. Strengthening implementation-oriented research would therefore help bridge the gap between theoretical innovation and educational practice.

Several topics remain substantially underexplored. Comparative studies appear in only one publication, indicating that little attention has been given to comparing digital education models across countries, educational systems, or institutional contexts. Similarly, inclusion and accessibility receive very limited attention despite being fundamental components of equitable and sustainable education. Even more notable is the complete absence of economic analysis, suggesting that issues such as cost-effectiveness, financial sustainability, and return on investment of digital education initiatives have not yet become major research priorities. Considering that financial feasibility strongly influences the scalability and long-term sustainability of educational innovations, this represents a significant research gap.

Overall, the identified future research directions demonstrate that the field is transitioning from conceptual exploration toward evidence-based implementation and sustainable governance. Future studies should therefore move beyond proposing new technological models by emphasizing rigorous empirical validation, long-term evaluation, implementation in diverse educational settings, inclusive educational practices, ethical governance, and economic sustainability. Addressing these priorities will contribute to a more comprehensive understanding of sustainable digital education systems and provide stronger evidence for policymakers, educational institutions, and researchers in designing future technology-enhanced learning environments.

Table 12 is the classification of the Summary of the discussion based on the discussion category, the number of papers, and the percentage.

Table 12. Classification Summary of the Discussion.

Category	Number of Papers	Percentage	Key Examples
Integration of Educational Technology	14	29%	E-learning, digital curriculum
Impact on Learning	9	18%	Learning quality, access to education
SDGs Achievement (SDG 4)	7	14%	Inclusive education, sustainability
System Implementation Evaluation	6	12%	Effectiveness of digital platforms
Innovation of Models/Framework	5	10%	Smart education, blended learning
User Perception & Readiness	4	8%	Teacher/student surveys
Challenges & Barriers	3	6%	Infrastructure, digital divide
Policy Recommendations	1	3%	Educational strategies

Table 12 provides an overall synthesis of the major research themes identified across the reviewed studies. The findings demonstrate that integration of educational technology constitutes the dominant research focus, accounting for 14 studies (29%).

This dominance indicates that current research has primarily concentrated on how digital technologies, including e-learning platforms, digital curricula, and online learning environments, can be incorporated into educational systems. The emphasis on technology integration suggests that the field is still largely concerned with facilitating digital transformation rather than evaluating its long-term educational and societal impacts.

The second most prominent theme is the impact on learning (18%), reflecting growing attention to how digital technologies influence learning quality, accessibility, engagement, and

educational outcomes. However, the lower proportion compared with technology integration suggests that many studies prioritize the adoption of technology over comprehensive evaluation of its educational effectiveness. This imbalance indicates that evidence regarding the actual benefits of digital learning innovations remains less developed than research on technological implementation itself.

Research addressing the contribution of digital education to Sustainable Development Goal 4 (SDG 4) represents 14% of the reviewed studies. Although sustainability has become an increasingly important research agenda, the relatively moderate proportion indicates that sustainable education is often discussed as a complementary objective rather than serving as the central focus of digital education research. This finding suggests that stronger integration between technological innovation and sustainability objectives remains necessary to fully support inclusive and equitable quality education.

The categories of system implementation evaluation (12%) and innovation of models and frameworks (10%) further indicate that researchers have begun moving beyond conceptual discussions toward developing and assessing practical educational solutions. Nevertheless, these themes remain less prominent than technology integration, implying that many proposed models have not yet undergone extensive empirical evaluation across different educational contexts.

Studies examining user perception and readiness account for only 8% of the publications, while challenges and barriers represent 6%. Despite their relatively small proportions, these themes highlight critical factors influencing the successful adoption of digital education, including digital literacy, infrastructure availability, institutional readiness, and unequal access to technology. The limited attention given to these issues suggests that implementation challenges are still underexplored despite their direct influence on the success of technology-enhanced learning initiatives.

The least represented category is policy recommendations (3%). This finding reveals that relatively few studies translate research findings into practical policy guidance for governments, educational institutions, or decision-makers. Considering that sustainable digital transformation requires supportive regulations, institutional governance, funding mechanisms, and long-term strategic planning, this limited emphasis represents an important gap in the existing literature.

Overall, the distribution of research themes indicates that the field has progressed substantially in understanding technology integration but remains less developed in evaluating implementation effectiveness, addressing institutional and societal challenges, and generating evidence-based policy recommendations. Future research should therefore adopt a more balanced approach by integrating technological innovation with empirical evaluation, sustainability objectives, implementation strategies, and policy development. Such an approach would strengthen both the scientific foundation and the practical contribution of research on sustainable digital education systems.

Implication

The results of this study show that the integration of digital technology in education has a significant role in supporting sustainable education systems. The findings indicate that digital learning innovations such as e-learning, artificial intelligence, and blended learning can improve accessibility and flexibility in the learning process. This is especially important in supporting the achievement of SDG 4, which focuses on inclusive and quality education. In addition, this study highlights that although technology integration is already widely implemented, there are still challenges related to infrastructure, digital divide, and user readiness. Therefore, the implication of this research is the need for better support systems, including infrastructure development, teacher training, and policy strengthening to ensure effective and sustainable implementation of digital education.

Limitation

This study has several limitations. First, the data sources are limited to Scopus and Google Scholar, so there is a possibility that some relevant studies from other databases were not included. Second, the number of final articles analyzed is relatively limited, which may affect the generalization of the findings. In addition, most of the studies included in this research are

dominated by systematic reviews and conceptual studies, while experimental and longitudinal studies are still limited. This makes it difficult to fully evaluate the real impact of digital education implementation in the long term.

CONCLUSION

This study provides a comprehensive overview of the development of sustainability research in digital education systems by integrating bibliometric analysis with a PRISMA-guided systematic literature review. Unlike previous reviews that primarily focused either on publication mapping or evidence synthesis, this study combines both approaches to reveal the intellectual structure, thematic evolution, methodological characteristics, and future research directions of the field.

The findings indicate that research on sustainable digital education has evolved into an interdisciplinary domain characterized by increasing publication output, strong international collaboration, and the dominance of technology integration as the principal research theme. Bibliometric mapping further demonstrates that scientific production is concentrated within a relatively small number of core journals, while thematic analysis reveals a gradual shift from technology adoption toward broader issues involving sustainability, educational effectiveness, ethical governance, and policy implementation.

These findings suggest that the field is transitioning from conceptual exploration to more comprehensive discussions concerning the sustainable implementation of digital education systems. This study makes two major scientific contributions. First, it provides a comprehensive bibliometric mapping of the research landscape, including publication trends, collaboration patterns, influential journals, thematic evolution, and emerging research priorities. Second, by integrating bibliometric analysis with systematic literature review, this study offers a more holistic understanding of the field than either method could provide independently. The findings may serve as a valuable reference for researchers in identifying research gaps and emerging topics, while also assisting educators, higher education institutions, and policymakers in developing evidence-based strategies for sustainable digital education.

This study is subject to several limitations. The analysis was primarily based on publications indexed in the Scopus database, supplemented by a limited number of additional sources, and therefore may not represent the entire body of global literature. Furthermore, the bibliometric results are influenced by the selected search strategy, inclusion criteria, and publication time span.

Future research should expand database coverage, conduct comparative international studies, and strengthen empirical evidence through experimental, longitudinal, and mixed-method research designs. Greater attention should also be directed toward policy evaluation, ethical governance, educational inclusion, accessibility, and the economic sustainability of digital education initiatives.

Addressing these areas will contribute to developing digital education systems that are not only technologically innovative but also inclusive, evidence-based, and sustainable in the long term.

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AUTHOR CONTRIBUTION STATEMENT

AU contributed to the conceptualization of the study, data collection, bibliometric and PRISMA analyses, manuscript writing, visualization, and preparation of figures and tables. YE

contributed to the analysis and interpretation of the research findings. Both authors reviewed and approved the final version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest. The authors have no financial, personal, academic, or professional relationships that could be perceived as influencing the work reported in this article. Furthermore, no external funding agencies had any role in the study design, data collection, data analysis, interpretation of results, manuscript preparation, or the decision to publish the findings.

INFORMED CONSENT STATEMENT

Not applicable. This study is based on bibliometric analysis and a systematic literature review of previously published scholarly articles and does not involve human participants, animals, or the collection of primary data requiring informed consent.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

During the preparation of this manuscript, the authors used several artificial intelligence (AI) based tools, namely ChatGPT (OpenAI), Elicit AI, and Scite AI, to assist in literature searching, language refinement, grammatical correction, and manuscript organization. The use of Elicit AI and Scite AI was focused on supporting the identification and analysis of relevant scholarly references, while ChatGPT was used to assist in drafting and improving the academic writing quality. After using these tools, the authors carefully reviewed, edited, and validated all content. The authors take full responsibility for the accuracy, integrity, and originality of the final manuscript.

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