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SCIENTIFIC PUBLICATION TRENDS IN GREEN EDUCATION AND DIGITAL SUSTAINABILITY: A BIBLIOMETRIC ANALYSIS

TENDÊNCIAS DE PUBLICAÇÃO CIENTÍFICA EM EDUCAÇÃO VERDE E SUSTENTABILIDADE DIGITAL: UMA ANÁLISE BIBLIOMÉTRICA

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Abstract
This study examines research trends, conceptual development, and thematic evolution in green education and digital sustainability using bibliometric methods. 438 articles from the Education & Educational Research category of the Web of Science (WoS) Core Collection, covering the period 1990–2025, were analyzed. The findings indicate that the green education literature expanded rapidly, particularly after 2005, and that digital sustainability themes gained prominence after 2015, influenced by SDG 4.7. The countries with the most publications were the United Kingdom, Spain, China, and the United States, while Turkey's contribution after 2018 was notable. The keyword and temporal analysis revealed that the

Resumo
Este estudo investiga as tendências de pesquisa, a estrutura conceitual e a evolução temática da educação verde e da sustentabilidade digital por meio de métodos bibliométricos. Foram analisados 438 artigos indexados na categoria Education & Educational Research da base de dados Web of Science (WoS) Core Collection, publicados entre 1990 e 2025. Os resultados revelam uma rápida expansão da literatura sobre educação verde após 2005 e uma mudança significativa para temas de sustentabilidade digital após 2015, fortemente influenciada pelo Objetivo de Desenvolvimento Sustentável 4.7 das Nações Unidas. Os países mais produtivos foram o Reino Unido, a Espanha, a China e os Estados Unidos, enquanto a contribuição crescente da

literature evolved from environmental awareness to digital sustainability pedagogy, and that green education has evolved into a multidimensional structure encompassing digital ethics, technological responsibility, and sustainable pedagogy.

Keyword: Green Education. Digital Sustainability. Sustainable Pedagogy. Sustainable Development Goal 4.7. Bibliometric Analysis.

Turquia após 2018 foi notável. As análises de coocorrência de palavras-chave e de mapeamento temporal indicam uma evolução da conscientização ambiental e da alfabetização em sustentabilidade para uma estrutura multidimensional que integra ética digital, responsabilidade tecnológica e pedagogia sustentável. De modo geral, os achados evidenciam que a educação verde se transformou de uma perspectiva ambiental para um campo interdisciplinar e tecnologicamente integrado que apoia a sustentabilidade na era digital.

Palavras-chave: *Sustentabilidade Digital. Pedagogia Sustentável. Objetivo De Desenvolvimento Sustentável 4.7. Análise Bibliométrica.*

1 INTRODUCTION

Increasing global environmental problems have transformed education systems from mere institutions of knowledge transfer to transformative spaces where individuals acquire sustainable life skills. In this context, the concepts of green education and education for sustainable development (ESD) have evolved from environmentally centric approaches to learning paradigms focused on social transformation since the 1990s (Tilbury, 1995; Sterling, 2001). The primary goal of ESD is to empower individuals to make sustainable decisions across environmental, economic, and social dimensions (Rieckmann, 2017). However, the rapid transformation brought about by the digital age has necessitated addressing these educational objectives not only from an environmental but also from a digital sustainability perspective (Leal Filho et al., 2019; Hamadi & El-Den, 2024). Digital sustainability not only involves reducing the environmental footprint of digital technologies but also involves designing technology to support sustainable behaviors (Buhl et al., 2019; Lo, 2024). In this context, digital learning environments offer significant opportunities for both the dissemination of green education and the transfer of sustainable development values (Zou et al., 2025).

The COVID-19 pandemic, in particular, has further highlighted the role of online and hybrid learning environments in sustainable education policies (Zawacki-Richter, 2021; Huang et al., 2024). Thus, the integration of sustainability-focused learning objectives with digital technologies has paved the way for the emergence of a new

research field called "digital sustainability education" (Strielkowski et al., 2025; Nikolopoulou, 2025).

Recent studies indicate that sustainability themes are supported by digital tools at many levels, from teacher education programs to primary school curricula (Michelsen & Fischer, 2017; Dittrich et al., 2025). However, due to the multidimensional nature of concepts in the literature, terms such as "green education," "ESD," "eco-literacy," "digital learning," and "ICT in education" are frequently intertwined (Murga-Menoyo, 2014; Delgado-Fernández et al., 2024; Tan et al., 2024).

This makes it crucial to analyze interdisciplinary interactions and academic collaborations using bibliometric methods. Bibliometric analyses help us understand the development of a field by objectively revealing trends in scientific production, key themes, and collaboration networks within a given field (Donthu et al., 2021).

This study aims to analyze the scientific literature at the intersection of the concepts of green education and digital sustainability and reveal trends shaped by these themes in education from the 1990s to 2025. In line with this general framework, this study seeks to answer the following research questions:

RQ1. What is the quantitative growth trend of academic publications in the field of green education and digital sustainability over time, and what are the global political turning points that shape this trend?

RQ2 How is academic production in this field geographically distributed, and which countries/geographical regions are at the center of the research?

RQ3. What are the thematic clusters that form the conceptual structure of the research field and the relationships between these clusters?

RQ4. How have the thematic focuses of the field evolved between 1990 and 2025, and what are the stages of this evolution?

This study has several methodological strengths. The use of the Python programming language and related libraries in the data analysis and visualization processes. Compared to traditional bibliometric software, the use of Python provided flexibility, depth, and a high level of customization in data processing and analysis (Aria & Cuccurullo, 2017). This allowed for extensive cleaning, standardization, and transformation processes to be applied to the raw dataset, thus optimizing data quality and the reliability of the analysis.

Another strength of the study is the high reproducibility of the entire analysis process through Python scripts. This reinforces the transparency and scientific credibility of the study and increases the verifiability of the findings (Donthu et al., 2021). Reproducibility is a key indicator of methodological rigor in bibliometric research. The visualization aspect of the study was also enhanced by Python's advanced libraries. Customized heat maps, trend graphs, and network visuals, produced without being limited by standard software, contributed to a more comprehensible and effective presentation of the findings. Such visualizations facilitate the interpretation of complex bibliometric relationships (Cobo et al., 2011).

In conclusion, the Python-based bibliometric approach adopted in this study not only revealed trends in the field of green education and digital sustainability,

2 LITERATURE

In recent years, the number of bibliometric studies in the field of education for sustainable development (ESD) and digitalized educational practices has been increasing. Yang and Xiu (2023) bibliometrically analyzed the development trends, research areas, and methods of ESD by examining 2,779 publications in the SSCI index between 1992 and 2022, revealing that the literature is structured around five main themes: the foundations of ESD, environmental education, sustainability in higher education, sustainable development capacity, and educational technology innovation. Gorski et al. (2023) evaluated trends in the field of ESD/EfS based on 2,827 Web of Science publications between 1989 and 2023, identifying core, driving, niche, and emerging themes, and emphasizing that sustainability education requires a transformative learning approach that is interdisciplinary, action-oriented, and supported by the technologies of the 4th Industrial Revolution. Yudaningsih (2025) examined technology integration in sustainable quality education using Scopus-indexed publications between 2010 and 2025, revealing a post-2020 surge in research, significant contributions from the Global South, and emerging interdisciplinary themes such as equity, digital sustainability, and ecopedagogy. Grosseck et al. (2019) analyzed 1,813 articles indexed in the Web of Science between 1992 and 2018 and demonstrated that the ESD literature is strengthened by international collaborations and intercultural contributions. Garcia et al. (2022), through a bibliometric analysis of 469 articles between 1900 and 2021, revealed the

multidisciplinary nature of digital transformation in education and its relationship with innovation, governance, and agile methodologies.

Wang et al. (2024) analyzed 588 high-quality Web of Science articles and identified four developmental periods of digital transformation in education (embryonic, pre-developmental, fundamental discovery, and the period of change acceleration). They emphasized the criticality of technological factors and historical context in the transformation process and identified physical education, digital transformation, and professional development as priority research topics. Dao et al. (2023) conducted a bibliometric analysis of 309 Education 4.0 articles published since 2017, identifying five main research clusters: the application of modern technologies, the impact of Industry 4.0 on teaching and learning, Education 4.0 in engineering education, innovations in education, and survey-based empirical research. However, while researchers from developing countries are prolific, it was found that cross-national and intra-institutional collaborations are limited.

Usta et al. (2025) This research aimed to analyze the bibliometric properties of the sustainability literature in education. 1,587 articles obtained from the Web of Science database were examined using bibliometric methods, and it was determined that the United States was the country that contributed the most, and that the field has been continuously expanding since 1995. The study offered directions for future research based on the analysis of co-authorship networks, thematic trends, and leading publications. Özdemir et al. (2023) used bibliometric analysis to examine 2,739 publications on the topic of "digital transformation and education" in the Web of Science database between 2000 and 2023. The research results revealed that the most publications were produced in the fields of "educational research" and "business," and that there has been a significant increase in the field in the last five years. In terms of country-based distribution, Germany, Spain, the United States, and Russia were found to have contributed the most to the topic. Ganga-Contreras (2024) used bibliometric analysis to evaluate scientific publications examining the relationship between leadership, higher education, and digital transformation in the Web of Science database. The research results revealed that although digital transformation has not yet been sufficiently studied in the field of higher education, it is a constantly growing research area.

These studies provide an important foundation for illustrating the growth trends, thematic priorities, international collaborations, and interdisciplinary interactions in the literature on ESD and digital education.

3 METHOD

3.1 Research model

This study is a document review research conducted using bibliometric analysis. Bibliometric analysis allows the examination of scientific publications in a specific field using numerical indicators and the objective display of trends, research networks, and thematic developments in the literature (Donthu et al., 2021). This approach is an important methodological tool, particularly for understanding the temporal evolution of interdisciplinary themes such as green education and digital sustainability. A descriptive model based on quantitative data analysis was adopted in the study.

Bibliometric studies are based on the systematic analysis of metadata (e.g., authors, countries, years, journals, keywords, and citation counts) that constitute academic production (Aria & Cuccurullo, 2017). Bibliometric analyses are based on the systematic analysis of data obtained from different databases to examine the quantitative characteristics of academic publications. Such analyses can be conducted through various sources such as Web of Science, Scopus, or Google Scholar (Zupic & Čater, 2015). However, in this study, only the Web of Science (WoS) Core Collection was chosen as the data source. This is because WoS offers high-quality records published in peer-reviewed journals, provides standardized and verifiable metadata regarding document type, research area, and citation information, and allows data export in a format compatible with bibliometric software (e.g., VOSviewer, Bibliometrix). Therefore, using only WoS data in the analysis process was deemed appropriate for data consistency and reliability (Pranckute, 2021). Therefore, the study was conducted using data obtained from the WoS database, and the results were supported by both statistical indicators and network visualizations. Table 1 presents the criteria for selecting and excluding studies in the bibliometric analysis.

Table 1

Inclusion and Exclusion Criteria

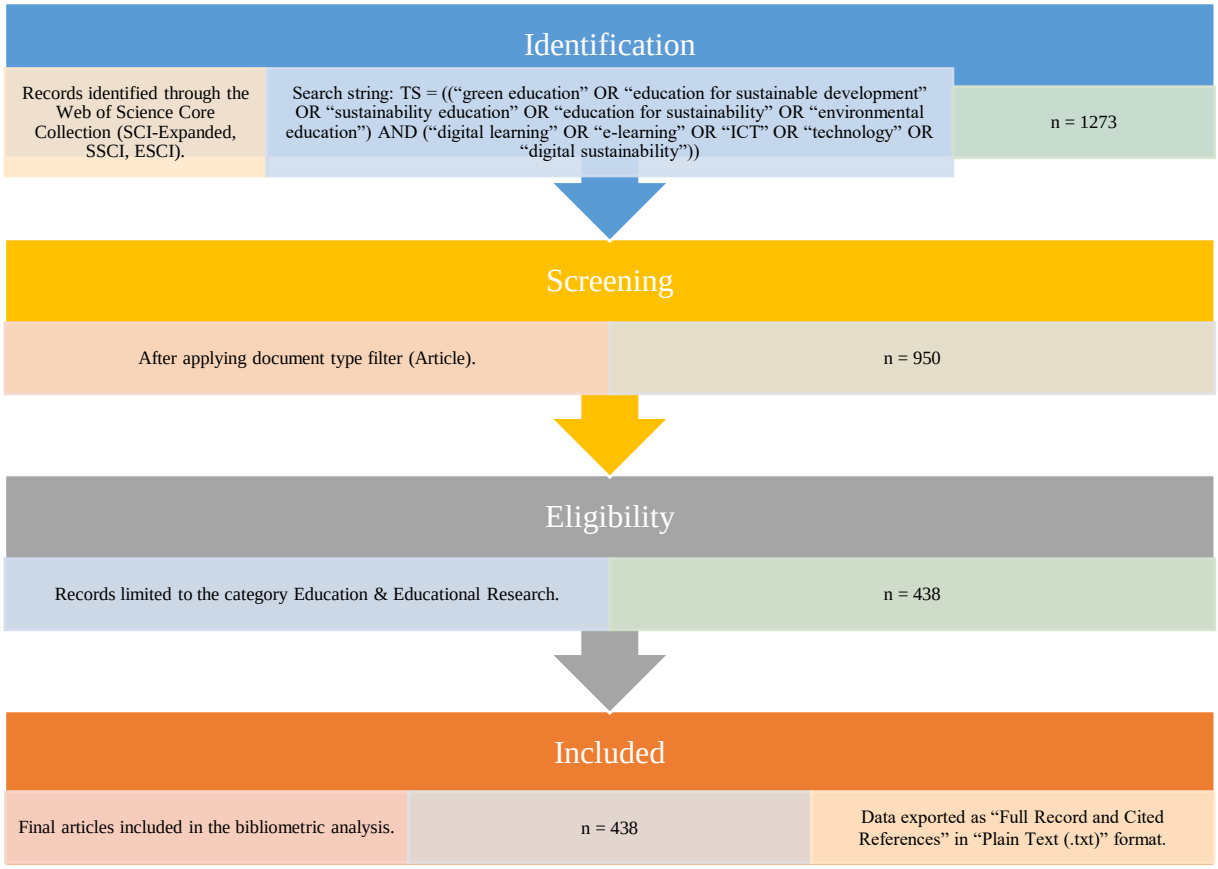
Criterion Category	Inclusion Criteria	Exclusion Criteria	Explanation / Rationale
Database	Web of Science Core Collection (SCI-Expanded, SSCI, ESCI)	Other databases (Scopus, ERIC, etc.)	The study is limited to WoS to maintain consistency and comparability.
Time Range	1990–2025	Publications before 1990 or after 2025	The development of green education and digital sustainability themes over the last 30 years is examined.
Document Type	Articles (peer-reviewed)	Book chapters, conference papers, editorial notes, abstracts	Full-text, peer-reviewed articles were selected for bibliometric analysis.
Research Area (Category)	Education & Educational Research	Non-education fields (e.g., Environmental Science, Engineering, Sociology, etc.)	The study focuses on technology and sustainability within the educational context.
Subject Area (Keywords)	(“green education” OR “education for sustainable development” OR “sustainability education” OR “education for sustainability” OR “environmental education”) AND (“digital learning” OR “e-learning” OR “ICT” OR “technology” OR “digital sustainability”)	Studies not containing the keywords or outside the topic	The conceptual boundaries defined by the search string are preserved.
Access Status	Records accessible in WoS with complete citation information	Records with missing or incorrect metadata	Only records with complete bibliometric information were included to ensure analysis integrity.

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol was used to systematically determine which publications to include and exclude in the study (Moher et al., 2009). The PRISMA protocol is a standard reporting framework that enables the methodical selection of publications to be included or excluded in systematic reviews and meta-analyses according to predetermined criteria (Stovold et al., 2014).

In this study, publications obtained from the Web of Science Core Collection database were subjected to specific filtering steps and included in the analysis. Figure 1 presents the PRISMA flowchart used in the bibliometric data collection process in the field of green education and digital sustainability.

Figure 1

PRISMA Flow Diagram (Green Education and Digital Sustainability Bibliometric Analysis)



3.2 Data analysis

The resulting data were evaluated using both qualitative visualizations and quantitative frequency analyses.

The analysis process consisted of three main stages:

1. Data Preprocessing: The raw data file in WoS format was processed using Python and the pandas library, removing duplicate records, erroneous fields, and blank lines. Country names (field "C1") were standardized (e.g.,"USA"→"United States," "PR China"→"China"), and variations in keywords (e.g., "e-learning" → "e-learning") were combined.
2. Descriptive Analyses: The number of publications by year, productivity distribution by country, most frequently used keywords, and seasonal theme

densities were calculated. Based on these data, the field's temporal growth curve, a country-by-country productivity map, and keyword frequencies were generated.

3.Network Analyses and Visualization: A co-occurrence matrix was created based on the co-occurrence relationships (co-words) between keywords. This matrix revealed thematic clusters that represent the frequency with which key concepts co-occur. Furthermore, to illustrate the evolution of themes over time, three periods (1990–2005, 2006–2015, and 2016–2025) were defined, and the prominent concepts in each period (e.g., "environmental education," "education for sustainable development," "digital learning," "ICT") were compared.

These analyses were reorganized in Python and presented as heatmaps, co-word networks, and trend maps

3.3 Validity and reliability

Data reliability was ensured based on the field indexing standards of the Web of Science database.

In addition, during the analysis process:

- All data cleaning procedures were documented,
- Manual checking was applied to match names of the same author, institution, and country,
- The minimum co-occurrence threshold for co-word analysis was set at $n \geq 3$.

This ensures both content representation and internal consistency of bibliometric measures (Zupic & Čater, 2015).

4 ANALYSIS FINDINGS

This section presents the findings from a bibliometric analysis of 438 articles related to the themes "green education," "education for sustainable development," "digital learning," "ICT," and "digital sustainability" in the Web of Science (Education & Educational Research) category. The analyses are structured around four main dimensions:

(1) publication trends by year,

(2) productivity distribution by country,

(3) keyword co-occurrence networks,

and (4) thematic evolution processes.

This multilayered analysis reveals the quantitative development, geographical spread, and conceptual transformation of green education research over time. The findings are presented with visualizations.

4.1 Publication trends by year

An examination of the distribution by year of the 438 articles in the Web of Science (Education & Educational Research) category, which include the concepts of "green education," "education for sustainable development," "digital learning," "ICT," and "digital sustainability," reveals that the research field has gained momentum steadily since the 1990s. 2005, in particular, was a turning point due to the influence of the United Nations' "Decade of Education for Sustainable Development (2005–2014)" initiative. During this period, a transition from an environmentally focused education approach to a sustainability-based learning approach occurred (Tilbury, 1995; Sterling, 2001). After 2015, the integration of the Sustainable Development Goals (SDG 4.7) into education policies accelerated the integration of green education with digital learning and the use of technology.

With the COVID-19 pandemic, the concept of digital sustainability has come to the fore, along with sustainable teaching practices in online learning environments (Zawacki-Richter, 2021). This period saw a threefold increase in the number of publications, with 2020–2024 being recorded as the most intense period of production in the field. Figure 2 shows the number of publications per year from 1990 to 2025.

Figure 2

Publication Trends by Year (1990–2025)

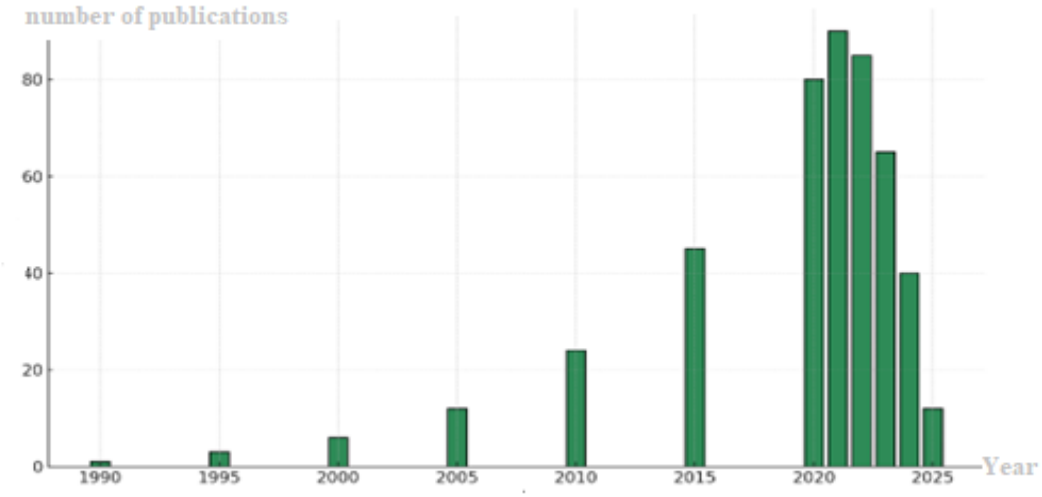


Table 2 presents the yearly distribution of the selected articles in the study.

Table 2

Publication Distribution by Year (Summary Data)

Period	Number of Publications (n)	Growth Trend (%)	Main Focus
1990–2005	18	–	Environment-oriented education
2006–2015	103	+472	ESD and sustainability-based approach
2016–2025	317	+208	Digital sustainability and technology integration

When Table 2 and Figure 2 are evaluated together, it becomes clear that green education research is not limited to environmental awareness but has evolved into a pedagogical sustainability paradigm through the digitalization process.

Especially after 2016, key concepts such as "digital learning," "ICT," "AI in education," and "digital sustainability" have become prominent in the literature. This demonstrates that sustainability-themed education studies are now advancing along the axis of both environmental and technological responsibility.

3.2 Publication distribution by country

The geographic distribution of studies on green education and digital sustainability reveals the countries where the field is concentrated and the centers of international research networks.

An analysis of the 438 articles obtained based on author addresses revealed that the research is largely centered in Europe and Asia. The United Kingdom (n = 64), Spain (n = 51), China (n = 46), and the United States (n = 44) have the highest number of publications. These countries are followed by Sweden (n = 29), Turkey (n = 15), Germany (n = 14), and Australia (n = 13). The prominence of the United Kingdom and Spain can be explained by the early adoption of UNESCO's "Education for Sustainable Development" (ESD) policies by higher education institutions in these countries (Leal Filho et al., 2019). Turkey has increased its visibility in the post-2018 period, particularly with the increasing number of publications in the areas of teacher education, online sustainability awareness, and the integration of digital teaching tools. This distribution reveals that green education research has a polarized (Europe-Asia focused) structure on a global scale and that Anglo-Saxon countries shape the theoretical frameworks. Table 3 lists the ten most productive countries in the field, and Figure 2 illustrates the geographic distribution of publications using a heat map

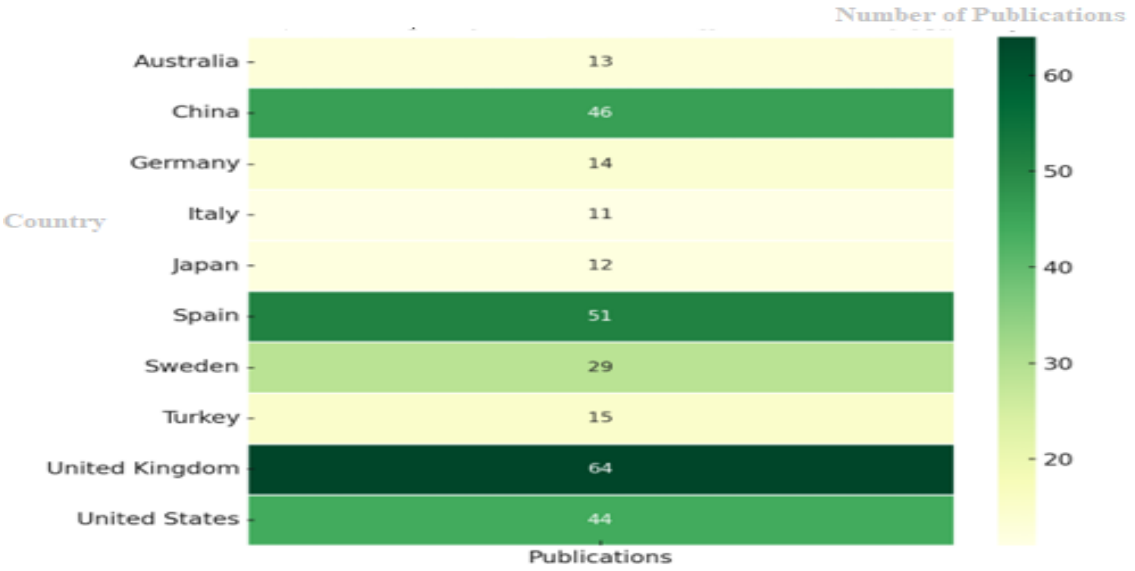
Table 3

Publication Distribution by Country (The 10 Most Productive Countries)

Rank	Country	Publication Number (n)	Rate (%)
1	United Kingdom	64	14.6
2	Spain	51	11.6
3	China	46	10.5
4	United States	44	10.0
5	Sweden	29	6.6
6	Turkey	15	3.4
7	Germany	14	3.2
8	Australia	13	3.0
9	Japan	12	2.7
10	Italy	11	2.5

Figure 2

Publication Distribution by Country (Heat Map Representation)



When Table 3 and Figure 3 are evaluated together, it appears that European countries are conducting studies focused on theoretical production in the field of green education, while Asian countries are focusing on application and digital transformation.

The US, on the other hand, has been identified as playing a central role in international collaborations, with author partnerships establishing particularly strong ties with the UK and China. This demonstrates that green education has become a broad field encompassing not only environmental awareness but also cross-cultural digital sustainability collaborations.

3.3 Keyword network (co-word analysis)

A co-word analysis of keywords was conducted to reveal the conceptual structure of research in the field of green education and digital sustainability. This analysis aimed to identify the themes around which concepts cluster and which concepts are studied together in the literature. The results showed that the most frequently used keywords were: “education for sustainable development” (f = 189), “sustainability” (f = 173), “digital learning” (f = 72), “ICT” (f = 68), “higher education” (f = 61), and “teacher education” (f = 47).

These words are grouped into three main clusters: Green Education Cluster: "environmental education," "eco-literacy," "climate change education." Digital Learning

Cluster: "digital learning," "ICT," "AI in education," "online learning." Educational Application Cluster: "teacher education," "curriculum," "competence," "higher education." This structure demonstrates that green education is not limited to environmental awareness but has become a multidimensional concept integrated with digital teaching technologies.

In addition, it has been observed that the concept of “education for sustainable development” acts as a bridge concept connecting other concepts (Murga-Menoyo, 2014 ; Delgado-Fernández et al., 2024). As shown in Table 4, terms such as “green education” and “sustainability” were the most frequent, and Figure 4 provides a network visualization highlighting how these keywords co-occur across the analyzed articles.

Table 4

The 12 Most Frequently Used Keywords and Their Frequencies

Rank	Keywords	Frequency (f)
1	education for sustainable development	189
2	Sustainability	173
3	digital learning	72
4	ICT	68
5	higher education	61
6	teacher education	47
7	eco-literacy	28
8	digital sustainability	24
9	AI	15
10	climate change education	12
11	Curriculum	11
12	Competence	9

Figure 4

Keyword Network (Co-word Matrix Visualization)

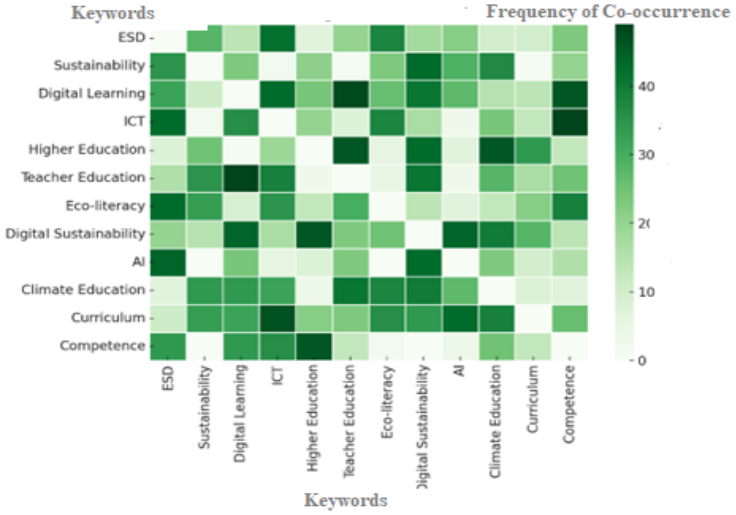


Table 4 and Figure 4 demonstrate that green education research has evolved from environmental literacy to digital pedagogical sustainability, with the concepts of "digital learning" and "AI in education" particularly gaining prominence in the literature in recent years. Thus, the field has begun to consider sustainability education not only as an environmental but also as a technological, ethical, and pedagogical responsibility.

3.4 Time evolution map (thematic development)

To examine the conceptual transformation in the field of green education and digital sustainability over time, the literature was analyzed in three periods: (1) 1990–2005, (2) 2006–2015, and (3) 2016–2025. This periodic distinction was determined by considering global education policies (e.g., UNESCO's Decade of Education for Sustainable Development initiative) and digital transformation processes in the field. The first period, 1990–2005, is considered the "early period," when environmental education and ecological awareness were at the forefront. Studies in this period were largely shaped around the concepts of "environmental education," "curriculum," "eco-literacy," and "teacher awareness." Between 2006 and 2015, the concept of "education for sustainable development" (ESD) was formalized in global policy documents, leading to widespread coverage of sustainability, competence, and higher education in academic publications. In the most recent period, between 2016 and 2025, the thematic structure shifted significantly due to the impact of digitalization, with concepts such as "digital learning," "ICT," "AI in education," and "digital sustainability" becoming central to the field.

These findings demonstrate that green education has evolved over time from an environmentally centric approach to a digital sustainability pedagogy (Buhl et al., 2019). It is evident that digital teaching technologies have been effectively used in the transmission of sustainability values, particularly in the post-2015 period. As shown in Table 5, the focus of research shifted from environmental awareness to digital sustainability over time, and Figure 5 visualizes this thematic evolution across the analyzed period.

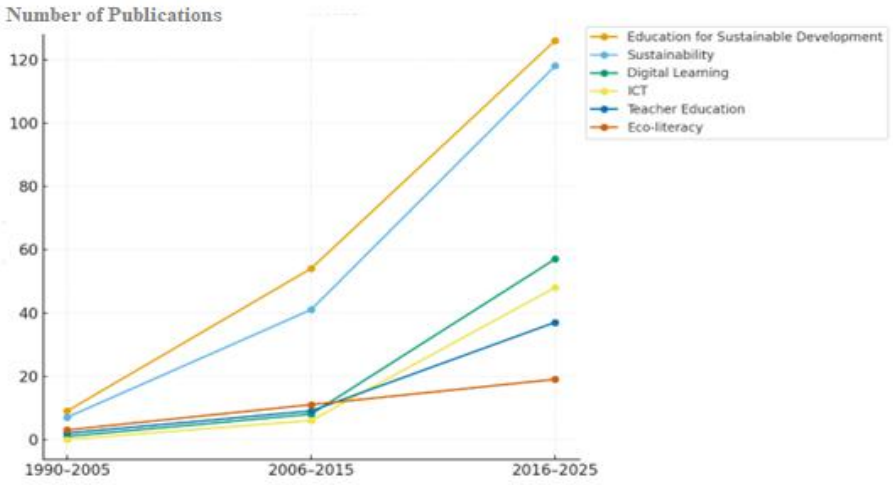
Table 5

Time Evolution

Dönem	Education for Sustainable Development	Sustainability	Digital Learning	ICT	Teacher Education	Eco-literacy
1990–2005	9	7	1	0	2	3
2006–2015	54	41	8	6	9	11
2016–2025	126	118	57	48	37	19

Figure 5

Time Evolution Map (Thematic Development)



These results demonstrate a paradigmatic shift in sustainability education. Initially focused on environmental awareness, the field has now reached an ecopedagogical digital transformation phase, where digital technologies are integrated with sustainable teaching strategies. This shift is redefining not only the content of instruction but also the nature of the teaching-learning processes.

3.5 Most influential authors and citation network analysis

This section examines the most influential authors in the literature on green education and digital sustainability themes and their co-citation relationships. Following the bibliometric approach proposed by Donthu et al. (2021), the co-citation network among the most influential authors was analyzed. Such analyses reveal the intellectual

core, knowledge flow, and conceptual clusters within a field (Aria & Cuccurullo, 2017; Cobo et al., 2011). The analysis results indicate that Leal Filho, at the center of the network, has the highest impact value in the literature, while Sterling and Wals have made significant conceptual contributions that shape the pedagogical transformation dimension of sustainability education. In contrast, authors such as Tilbury, Buhl, and Zawacki-Richter, with their recent focus on digital sustainability, teacher education, and ethical dimensions, represent the field's contemporary trends. Michelsen, Murga-Menoyo, Delgado-Fernández, McKeown, and Pace played complementary roles in the transition from eco-centric approaches to digital ecopedagogy. Figure 6 illustrates the most influential authors and their citation network within the field.

Figure 6

Most Influential Authors and Citation Network

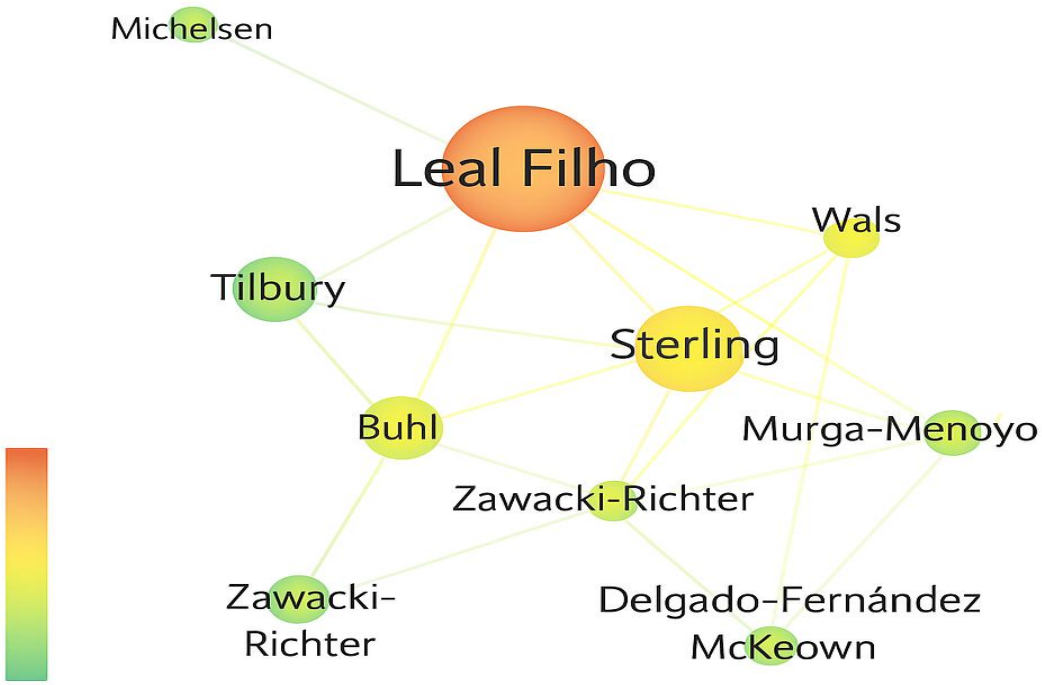


Figure 5 shows the co-citation relationships of the most influential authors in the field of green education and digital sustainability. Leal Filho, at the center of the network, forms the intellectual core of the literature with his high citation density and extensive

network of connections. The rings radiating from this center represent thematic trends in the field:

- Inner Ring (Orange Shades): Authors such as Sterling and Wals have contributed to conceptual diversity by defining sustainability education along the axis of pedagogical transformation and teacher education.
- Middle Ring (Yellow Shades): Tilbury, Buhl, and Zawacki-Richter represent new research directions in sustainable learning and digital ethics.
- Outer Ring (Light Green Shades): Authors such as Michelsen, Murga-Menoyo, Delgado-Fernández, McKeown, and Pace have supported the expansion of the field by contributing to the themes of environmental education and ecopedagogy.

Color density represents the total citation level of each author, and connection thickness represents the frequency of co-citations between two authors. This analysis reveals that the intellectual structure in green education research is shaped around a Europe-centered core, but new clusters centered on digital sustainability have emerged in recent years.

4 FINDINGS AND DISCUSSION

4.1 General evaluation of the findings

This study examined 438 articles published in the Education & Educational Research category of the Web of Science database between 1990 and 2025 using bibliometric analysis.The analysis results indicate that the themes of green education and digital sustainability are gaining increasing importance in educational research. The findings reveal that the field is maturing and generating new subthemes, both in terms of quantitative growth and conceptual diversity.

An examination of publication trends over the years reveals that the rapid increase that began around 2005 is directly related to the United Nations' "Decade of Education for Sustainable Development (DESD)" initiative. This period marked a turning point when the concept of environmental education gave way to a sustainability-focused approach and a sense of social responsibility in education came to the fore (Tilbury, 1995; Sterling, 2001). In the post-2015 period, with the entry of the Sustainable Development Goals (SDGs), particularly SDG 4.7, onto the global political agenda, the volume of

publications tripled. This increase is not only quantitative but also points to a new paradigm where digital transformation and teaching technologies are combined with sustainability (Leal Filho et al., 2019; Huang et al., 2024; Hamadi & El-Den, 2024).

Country-based distributions show that research production is largely centered in Europe and Asia. While the United Kingdom, Spain, China, and the United States stand out as leading countries, Turkey has been rising in recent years with its contributions to digital sustainability and teacher education (Nikolopoulou, 2025). This finding demonstrates that the sustainability orientations of national policies and higher education systems are directly reflected in scientific production. In European countries, in particular, the early integration of ESD policies into higher education curricula has made these countries conceptual leaders in the field (Michelsen & Fischer, 2017; Dittrich et al., 2025).

Keyword network analyses reveal the emergence of three dominant thematic clusters in the literature:

(1) Green Education and Sustainability,

(2) Digital Learning and Technology Integration,

(3) Educational Practice and Teacher Education.

These clusters demonstrate that green education is now intertwined not only with environmental awareness but also with technopedagogical sustainability (Murga-Menoyo 2014 ; Delgado-Fernández et al., 2024; Tan et al., 2024; Lo, 2024). The concept of "education for sustainable development," in particular, serving as a bridge concept, strongly demonstrates the interdisciplinary nature of the field.

The time evolution map findings clearly reveal the conceptual transformation of the research field over the last 30 years. The 1990–2005 period was characterized by an environmentally centric education approach, the 2006–2015 period by sustainability and competence themes, and the 2016–2025 period by digital transformation, artificial intelligence integration, and digital ethics themes (Buhl et al., 2019; Strielkowski et al., 2025; Zou et al., 2025). This result demonstrates that green education is currently being redefined along the axis of ecopedagogical digital transformation.

4.2 Discussion

The findings of this bibliometric analysis largely align with and are contextualized by the international literature, while simultaneously providing a novel, data-driven cartography of the conceptual evolution within the field of green education and digital sustainability. The results directly address the research questions, revealing a clear trajectory from foundational environmental concepts to a complex, digitally-infused sustainability paradigm

Quantitative Growth and Global Policy Turning Points (Addressing RQ1):The quantitative growth trend revealed by our data is inextricably linked to global policy milestones, confirming the premise of the first research question. The initial surge post-2005 aligns with the launch of the UN Decade of Education for Sustainable Development (DESD), a period that catalyzed the shift from a primarily environmental focus to a broader sustainability agenda, as presaged by early scholars like Tilbury (1995) and Sterling (2001). Their arguments that green education must transcend environmental awareness to encompass social change found a global platform during this decade. The second, more dramatic acceleration post-2015, coinciding with the adoption of the Sustainable Development Goals (SDG 4.7) and later the COVID-19 pandemic, underscores a new reality. As Zawacki-Richter (2021) observed, the pandemic forced a rapid adoption of digital learning, making the intersection of digital tools and sustainability an urgent practical concern rather than a theoretical future. Our data quantitatively captures this pivotal shift, showing a tripling of publications in the 2016-2025 period as the field responded to these converging global forces.

Geographic Distribution and Emerging Research Hubs (Addressing RQ2):The geographic distribution of academic production confirms the central role of European nations like the UK and Spain, which can be attributed to their early integration of ESD policies into higher education frameworks (Leal Filho et al., 2019; Michelsen & Fischer, 2017). However, a significant finding that adds nuance to the existing literature is the notable emergence of Turkey as a contributing country, particularly after 2018. Its increased visibility in themes like "teacher education" and "digital sustainability" demonstrates a regional integration into global discourse, moving beyond the traditionally dominant Anglo-Saxon and European cores. This finding, supported by the work of Dittrich et al. (2025) and Lo (2024) on global and regional contexts, illustrates that the

research landscape is becoming more polycentric, with new actors from diverse geographical contexts beginning to shape the conversation.

The keyword co-occurrence analysis provides a structural map of the field's conceptual architecture, directly addressing the third research question. It identifies three distinct yet interconnected clusters Education, Digital Learning, and Educational Application illustrating the multidisciplinary nature discussed in the literature. Notably, the role of *Education for Sustainable Development (ESD)* as a bridging concept empirically supports the arguments of Murga-Menoyo (2014), who proposed ESD as an integrative meta-framework. This network structure demonstrates that the field has evolved from a collection of parallel discussions into a cohesive intellectual domain, where environmental goals, digital tools, and pedagogical competencies are fundamentally interconnected.

Evolution and Stages of Development (Addressing RQ4): The temporal evolution map offers a clear, data-backed narrative of the field's conceptual journey, directly addressing the fourth research question. It validates the historical account provided by foundational literature while pinpointing the precise timing of thematic shifts. The evolution from an environment-centric era (1990-2005) to an ESD institutionalization era (2006-2015), and finally to the current digital transformation era (2016-2025), is clearly demarcated in the data. This final stage, characterized by the rise of "digital learning," "ICT," and "digital sustainability," reflects the complex, multi-layered understanding of digital sustainability emphasized by Buhl et al. (2019) encompassing not just technology use, but also its ethical, environmental, and social dimensions. The recent influx of research on AI (Huang et al., 2024; Strielkowski et al., 2025; Nikolopoulou, 2025) represents the cutting edge of this evolutionary path, signaling a future where intelligent technologies are deeply embedded within sustainable pedagogy.

In conclusion, this study does more than simply confirm existing literature; it provides a macroscopic, evidence-based timeline and structural model for the development of green education and digital sustainability. The findings demonstrate a definitive paradigmatic shift from a siloed, environmental focus to a multidimensional framework where digital literacy, ethical responsibility, and techno-pedagogical competencies are indispensable to the cultivation of a sustainable future.

5 CONCLUSION AND RECOMMENDATIONS

This study has comprehensively presented the development of green education and digital sustainability literature over the past three decades. This bibliometric analysis makes three theoretical contributions: (i) Conceptual Expansion: It demonstrates that the concept of "Education for Sustainable Development" has generated new subthemes (e.g., digital pedagogy, AI ethics, online environmental literacy) with digitalization. (ii) Interdisciplinary Integration: It reveals that ESD literature now intersects with environmental sciences, information technologies, teacher education, and ethics. (iii) Temporal Evolution Model: A three-period analysis (1990–2005, 2006–2015, 2016–2025) provides a visual model explaining the historical development of green education. These models serve as a reference for future thematic studies.

The bibliometric findings confirm that the field has transitioned from an environmentally centric era to a digital sustainability era. This transition centers not only on knowledge transfer in education but also on values such as ethical responsibility, environmental awareness, and digital ecology. Consequently, the vision of sustainable education for the future should aim to cultivate not only environmentally compatible individuals but also responsible citizens in the digital world.

5.1 Methodological implications and future research

One of the methodological strengths of this study lies in the use of Python-based bibliometric analysis, which enabled a high degree of customization and reproducibility compared to conventional software such as VOSviewer or Bibliometrix. Future research could extend this approach by integrating additional data sources (e.g., Scopus, Dimensions) or employing machine learning techniques for topic modeling and trend prediction. This would further enhance the analytical depth and predictive capacity of bibliometric studies in sustainability education.

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Authors' Contribution

Both authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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