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Evolution of Education for Sustainable Development Across Science and Sustainability Education: Intellectual Structure and Scholarly Influence

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Index Terms:

Education for Sustainable Development, bibliometric analysis, bibliographic coupling, citation analysis, science education, sustainability education

Abstract. Education for Sustainable Development (ESD) has become a central framework for addressing global sustainability challenges through education, yet its intellectual organization and scholarly foundations within science and sustainability education remain fragmented. This study mapped the intellectual structure and scholarly influence of ESD research through a bibliometric analysis of publications indexed in Scopus from 2005 to 2025. Following a systematic screening process, 1,245 English-language journal articles were analyzed using VOSviewer (version 1.6.20). Bibliographic coupling was employed to examine the intellectual structure of the field, while citation analysis of sources identified the journals that have most strongly influenced ESD scholarship. The bibliographic coupling analysis revealed six major intellectual clusters encompassing sustainability competencies and transformative learning, curriculum integration and institutional change, environmental literacy and learner engagement, teacher education and socioscientific issues, systems thinking and climate change education, and Sustainable Development Goals (SDGs)-oriented higher education. Citation analysis identified *Sustainability (Switzerland)*, the *International Journal of Sustainability in Higher Education*, *Journal of Cleaner Production*, and *Environmental Education Research* as the most influential scholarly sources, illustrating the multidisciplinary nature of ESD research. Together, the findings demonstrate that ESD has evolved into an integrated field supported by sustainability science, environmental education, science education, and higher education scholarship. This study provides a comprehensive synthesis of the intellectual organization and scholarly foundations of ESD research and offers valuable directions for future investigations, interdisciplinary collaboration, and evidence-based curriculum development.

Introduction

Education for Sustainable Development (ESD) has become a globally recognized educational framework for equipping individuals with the knowledge, competencies, values, and attitudes necessary to address complex environmental, social, and economic challenges while contributing to the achievement of sustainable development. Since the adoption of the United Nations' *2030 Agenda for Sustainable Development***,** particularly *Sustainable Development Goal 4.7***,** ESD has gained increasing prominence as a transformative approach that promotes critical thinking, systems thinking, collaborative problem-solving, and responsible citizenship across all levels of education (UNESCO, 2020; Leal Filho et al., 2018). Rather than focusing solely on environmental awareness, contemporary ESD emphasizes interdisciplinary learning that integrates sustainability principles into science education, higher education, environmental education, and curriculum development to prepare learners for informed decision-making in an increasingly interconnected world (Barth & Michelsen, 2013; Wiek et al., 2011).

Over the past two decades, scholarly interest in ESD has expanded substantially, resulting in a rapidly growing and highly diverse body of literature. Research has investigated a wide range of themes, including sustainability competencies, transformative learning, environmental literacy, teacher education, systems thinking, climate change education, curriculum innovation, institutional sustainability, and Sustainable Development Goals (SDGs)-oriented educational practices (Cebrián & Junyent, 2015; Ojala, 2023; Schuler et al., 2018). This diversification reflects the inherently multidisciplinary character of ESD, drawing contributions from education, sustainability science, environmental studies, and the social sciences.

Consequently, while the field has matured considerably, its expanding scope has also generated a fragmented knowledge base in which multiple research streams have evolved simultaneously with varying theoretical foundations and disciplinary perspectives (Leal Filho et al., 2015; Wamsler, 2020).

Although numerous empirical investigations, systematic reviews, and bibliometric studies have examined specific dimensions of ESD, existing reviews have primarily focused on publication trends, thematic evolution, sustainability competencies, higher education initiatives, or the implementation of the Sustainable Development Goals (Prieto-Jiménez et al., 2021; Acosta Castellanos & Queiruga-Dios, 2022; Lim et al., 2022). Comparatively fewer studies have examined how influential publications are intellectually connected through shared knowledge bases or identified the scholarly journals that collectively shape the evolution of ESD across science and sustainability education. Consequently, the contemporary intellectual structure of the field and its underlying scholarly foundations remain insufficiently synthesized, limiting a comprehensive understanding of how ESD knowledge has developed over time.

Bibliometric analysis provides a rigorous and transparent approach for examining the evolution of scientific knowledge by quantitatively mapping relationships among scholarly publications, identifying influential research themes, and revealing the structural organization of research fields (Aria & Cuccurullo, 2017; Donthu et al., 2021; Zupic & Čater, 2015). Among science-mapping techniques, *bibliographic coupling* identifies contemporary research fronts by grouping publications that share common reference patterns, thereby revealing the intellectual structure of an active research domain (Kessler, 1963). Complementing this approach, *citation analysis of sources* identifies the journals that have exerted the greatest scholarly influence on knowledge development, illustrating how scientific ideas are disseminated across disciplines and publication venues. Together, these complementary techniques provide a comprehensive understanding of both the intellectual organization and the scholarly foundations of Education for Sustainable Development research.

Research Questions

This study investigates the evolution of Education for Sustainable Development across science and sustainability education through bibliographic coupling and citation analysis of sources using publications indexed in the Scopus database between 2005 and 2025. Specifically, the study aims to
(1) identify the intellectual structure of ESD research through bibliographic coupling analysis and;
(2) determine the most influential scholarly sources that have shaped the development of the field through citation analysis.

By integrating these complementary bibliometric approaches, this study provides a comprehensive synthesis of the contemporary knowledge landscape of ESD, offering valuable insights for researchers, educators, curriculum developers, and policymakers while informing future research directions, interdisciplinary collaboration, and evidence-based sustainability education initiatives.

Methodology

Research Design

This study adopted a bibliometric research design to investigate the intellectual structure and research trends of Education for Sustainable Development (ESD) in science education. Bibliometric analysis is a quantitative and systematic approach that examines scholarly publications and citation patterns to assess the development, structure, and dynamics of a research field (Donthu et al., 2021; Aria & Cuccurullo, 2017). As a well-established review methodology, bibliometric analysis enables researchers to synthesize large bodies of literature, identify influential publications and research themes, and uncover patterns of scientific knowledge production that may not be readily apparent through traditional literature reviews (Zupic & Čater, 2015; Cobo et al., 2011). By employing transparent and reproducible procedures, bibliometric methods provide a comprehensive understanding of the evolution of research domains and their underlying intellectual foundations (Broadus, 1987; Ellegaard & Wallin, 2015).

To address the objectives of the study, science mapping techniques were employed to examine relationships among publications and scholarly sources within the ESD and science education literature. Specifically, bibliographic coupling analysis was used to identify the intellectual structure of the field by clustering publications that shared common references, thereby revealing major research streams and scholarly communities (Kessler, 1963). In addition, citation analysis of sources was conducted to identify the journals that have most strongly influenced the development and dissemination of ESD scholarship. These analyses were performed using VOSviewer version 1.6.20, a widely used software

application for constructing, visualizing, and interpreting bibliometric networks (van Eck & Waltman, 2010; van Eck & Waltman, 2017).

Data Source and Retrieval Procedure

Bibliographic data was retrieved from the Scopus database on 20 June 2026 using a structured Boolean search strategy designed to capture publications related to Education for Sustainable Development (ESD) and science education. Scopus was selected due to its extensive coverage of high-quality peer-reviewed literature across education, sustainability, and interdisciplinary research fields. The initial search yielded 2,677 documents, which were subsequently refined by applying the following inclusion criteria: publication years 2005–2025, document type Article, language English, and source type Journal. These filtering procedures reduced the dataset to 1,246 records. A data-cleaning process was then conducted to identify duplicate entries based on document titles, authors, publication years, DOI numbers, and Scopus EIDs. One duplicate record was identified and removed, resulting in a final dataset of 1,245 unique publications, which served as the basis for the bibliographic coupling and citation analysis of sources undertaken in this study.

Screening and Data Cleaning Procedures

Prior to analysis, the dataset underwent a data-cleaning procedure involving both automated and manual screening. Records were examined for duplicate titles, duplicate document identifiers (EIDs), versioned publications, and other indexing anomalies. Manual verification was conducted by comparing publication titles, authors, publication years, source information, DOI numbers, and document identifiers. The screening process identified one duplicate record indexed in Scopus. Following established bibliometric data-cleaning procedures, the duplicate record was removed from the dataset. No additional duplicate records requiring removal were identified. Consequently, the final dataset consisted of 1,245 articles, which served as the basis for the bibliographic coupling and citation analysis of sources conducted using VOSviewer version 1.6.20.

Screening Stage	Number of Records
Initial Scopus search (20 June 2026)	2,677
Records after applying inclusion criteria (2005–2025, English, Article, Journal)	1,246
Duplicate screening and data cleaning	1,245
Final dataset for bibliometric analysis	1,245

Table No. 1. Dataset Filtering Process

To ensure transparency and reproducibility of the data collection process, the study employed a systematic screening procedure in the Scopus database. The retrieved records were filtered according to predefined inclusion criteria, including publication year, language, document type, and source type. Figure 1 presents the dataset retrieval and screening process, illustrating the number of records retained at each stage until the final dataset used for bibliometric analysis was obtained.

As shown in Figure 1, the initial Scopus search conducted on 20 June 2026 retrieved 2,677 records. After applying the inclusion criteria of publication years 2005–2025, English language, document type Article, and source type Journal, 1,246 records remained. The dataset subsequently underwent automated and manual data-cleaning procedures, including duplicate screening and verification of indexing inconsistencies. One duplicate record was identified and removed, resulting in a final corpus of 1,245 documents. This final dataset served as the basis for the bibliographic coupling and citation analysis of sources conducted using VOSviewer.

A structured search strategy was developed to identify publications related to Education for Sustainable Development (ESD) in science education. The search incorporated keywords representing the concepts of Education for Sustainable Development, sustainability education, science education, and STEM education. Boolean operators (AND and OR) were used to combine the search terms and maximize retrieval accuracy.

To ensure transparency and reproducibility, the complete search strategy used in the Scopus database is reported in this study. Reporting the exact search query is essential in bibliometric research because database contents are continuously updated and search results may vary over time. Consequently, future researchers attempting to replicate the study may obtain different results if alternative search strings are used or if the search is conducted on a different date. Following established bibliometric research practices (Donthu et al., 2021; Zupic & Čater, 2015), the complete search string is presented in Table 2 to facilitate verification and replication of the data retrieval process.

No.	Research String	Justification
1	("education for sustainable development" OR ESD OR "sustainability education" OR "education for sustainability")	This group of search terms was included to capture the core concept of Education for Sustainable Development (ESD). The terms encompass both the widely recognized acronym (ESD) and alternative expressions frequently used in the literature to describe educational initiatives that promote sustainability knowledge, values, competencies, and practices. Including synonymous terms increases the comprehensiveness of the search and minimizes the risk of excluding relevant publications indexed under different terminology.
2	(science OR STEM OR "science education")	This group of search terms was included to capture the science education context of ESD research. The terms encompass general science-related studies, science education, and STEM (Science, Technology, Engineering, and Mathematics) education, reflecting the interdisciplinary nature of sustainability education. Including these terms ensures the retrieval of publications that examine the integration of sustainability concepts within science teaching, learning, curriculum development, and STEM-based educational practices.

Table No. 2. Search String in Scopus Database

The search was conducted in the Scopus database on 20 June 2026. The initial search yielded 2,677 records. To ensure the relevance and quality of the dataset, the results were refined by applying the following inclusion criteria: publication years 2005–2025, document type Article, language English, and source type Journal. After applying these criteria, 1,246 publications were retained for further screening.

Prior to analysis, the dataset underwent automated and manual data-cleaning procedures to identify duplicate records and indexing anomalies. Records were examined using document identifiers (EIDs), publication titles, authors, publication years, DOI numbers, and source information. The screening process identified one duplicate publication indexed in Scopus. Following established bibliometric data-cleaning procedures, the duplicate record was removed from the dataset. No additional duplicate records requiring removal were identified. Consequently, the final dataset consisted of 1,245 publications, which served as the basis for the bibliographic coupling and citation analysis of sources conducted using VOSviewer version 1.6.20.

Data Analysis

Bibliographic Coupling Analysis

Bibliographic coupling analysis was conducted to examine the intellectual structure of Education for Sustainable Development (ESD) research in science and sustainability education. The analysis was performed using VOSviewer version 1.6.20, which identifies relationships among documents based on the references they share. To focus on the most influential publications, a minimum citation threshold of 71 citations per document was applied. Of the 1,245 publications included in the dataset, 101 met the threshold criterion. Because some documents were not connected within the network, only the largest connected component consisting of 60 documents was retained for visualization and cluster analysis. The resulting network was used to identify six major thematic clusters and the intellectual foundations of the field.

The resulting bibliographic coupling network was analyzed to identify major intellectual clusters, thematic research streams, and relationships among influential studies. Total link strength (TLS) was used to assess the degree of intellectual connectedness among publications.

Citation Analysis

A citation analysis of sources was performed using VOSviewer version 1.6.20 to identify the influential journals shaping Education for Sustainable Development research. The analysis employed *full counting*, with a *minimum threshold of two documents per source and eleven citations per source*. Of the *488 sources* in the dataset, *92 met the inclusion criteria* and were included in the citation network visualization.

Results and Discussion

The search in the Scopus database was conducted on 20 June 2026 and retrieved 2,677 records before filtering. After applying the predefined inclusion criteria and removing one duplicate record, the final dataset consisted of 1,245 publications. For the bibliographic coupling analysis, a minimum citation threshold of 71 citations per document was applied using VOSviewer. Of the 1,245 documents, 101 met the threshold criterion. Because some documents were not

connected within the network, only the largest connected component consisting of 60 documents was retained for visualization and cluster analysis. The resulting network was grouped into six clusters, indicating that the literature is organized into several distinct yet interconnected thematic strands.

The citation analysis of sources identified 488 scholarly sources in the dataset. Applying a minimum threshold of two documents per source and eleven citations per source resulted in 92 sources meeting the inclusion criteria for the citation network visualization. Together, the bibliographic coupling analysis and citation analysis of sources reveal the intellectual structure and scholarly foundations of Education for Sustainable Development research in science and sustainability education.

Publication Trends

To provide an overview of the temporal development of research on Education for Sustainable Development (ESD) in science education, the annual distribution of publications was examined. Analyzing publication output over time helps reveal the growth trajectory, research activity, and evolving scholarly interest within the field. Figure 1 presents the number of publications indexed in Scopus from 2005 to 2025 that met the study's inclusion criteria.

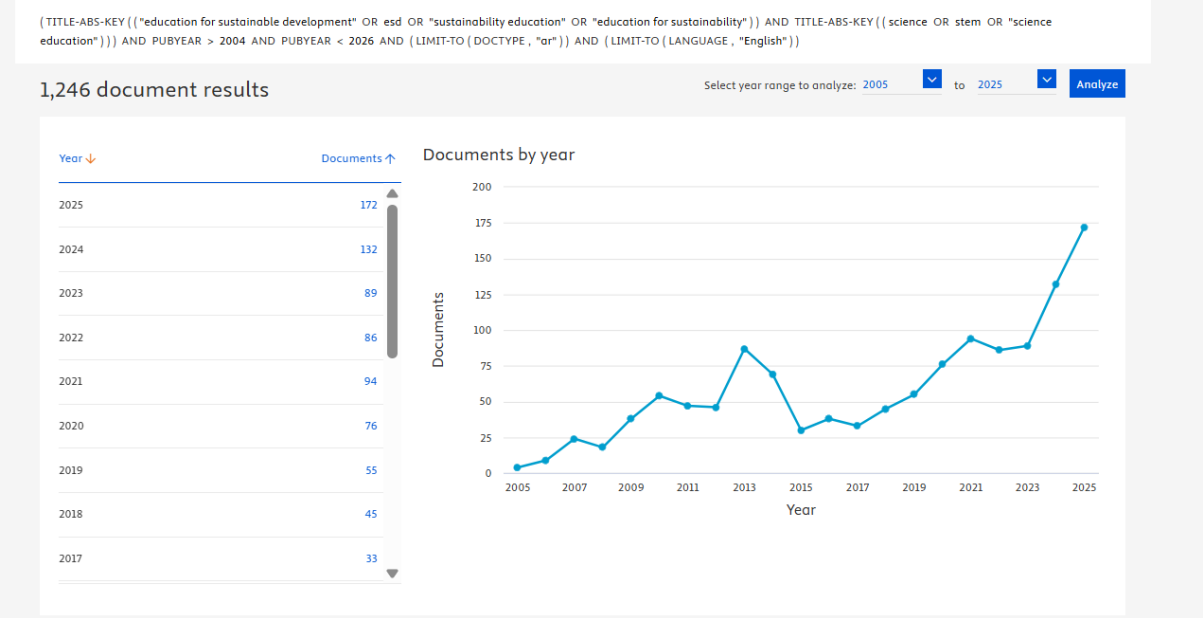

Figure 1. Annual publication output on Education for Sustainable Development in science education indexed in Scopus (2005–2025).

As shown in Figure 1, research on Education for Sustainable Development in science education exhibited a substantial overall increase between 2005 and 2025. Publication output remained relatively low during the early years of the study period, with fewer than 25 publications annually between 2005 and 2008. A gradual increase was observed from 2009 onward, followed by a notable rise in 2013, when the number of publications reached nearly 90 documents. Although publication output fluctuated during the mid-2010s, the overall trend remained positive. Beginning in 2018, the field experienced sustained growth, with annual publications increasing steadily and exceeding 90 documents by 2021. The most significant expansion occurred during the final years of the period, culminating in a peak of approximately 172 publications in 2025. This pattern suggests a growing scholarly interest in integrating sustainability principles within science and STEM education, likely influenced by increasing global attention to sustainability challenges, the United Nations Sustainable Development Goals (SDGs), and the expanding role of education in promoting sustainable development. The sustained upward trajectory indicates that ESD in science education has evolved into an active and rapidly growing area of research with continuing relevance to educational policy, curriculum development, and teaching practice.

Bibliographic Coupling Analysis: Intellectual Structure

The bibliographic coupling analysis revealed the intellectual structure of research on Education for Sustainable Development (ESD) in science education. Applying a minimum citation threshold of 71 citations resulted in 101 eligible documents from the total dataset of 1,245 publications. Because some documents were not connected to the main network, only the largest connected set consisting of 60 documents was retained for visualization and analysis in VOSviewer. The resulting network formed several interconnected thematic clusters, indicating that the literature is organized into distinct yet related research streams. These clusters reflect major areas of scholarly inquiry, including sustainability competencies and transformative learning, environmental and scientific literacy, curriculum and teacher education for sustainability, STEM-integrated sustainability education, policy and implementation perspectives, and the conceptual foundations of Education for Sustainable Development.

Table 3 presents the top 10 documents in the bibliographic coupling analysis ranked according to total link strength (TLS). Higher TLS values indicate stronger intellectual connections among publications through shared references, reflecting their centrality within the knowledge network. The table also reports cluster assignments and citation counts to illustrate both the thematic positioning and scholarly influence of the most interconnected studies in the field.

Rank	Publication (APA 7th Edition)	Cluster	TLS	Citations
1	Barth, M., & Michelsen, G. (2013). Learning for change: An educational contribution to sustainability science. *Sustainability Science, 8*(1), 103–119. https://doi.org/10.1007/s11625-012-0181-5	1	86	243
2	Wilhelm, S., Förster, R., & Zimmermann, A. B. (2019). Implementing competence orientation: Towards constructively aligned education for sustainable development in university-level teaching and learning. *Sustainability, 11*(7), Article 1891. https://doi.org/10.3390/su11071891	1	80	113
3	Cebrián, G., & Junyent, M. (2015). Competencies in education for sustainable development: Exploring the student teachers' views. *Sustainability, 7*(3), 2768–2786. https://doi.org/10.3390/su7032768	2	64	369
4	Sonetti, G., Brown, M., & Naboni, E. (2019). About the triggering of UN Sustainable Development Goals and regenerative sustainability in higher education. *Sustainability, 11*(1), Article 254. https://doi.org/10.3390/su11010254	1	60	141
5	Disterheft, A., Caeiro, S. S., Leal Filho, W., & Azeiteiro, U. M. (2016). The INDICARE-model: Measuring and caring about participation in higher education's sustainability assessment. *Ecological Indicators, 63*, 172–186. https://doi.org/10.1016/j.ecolind.2015.11.057	2	55	73
6	Borg, C., Gericke, N., Höglund, H.-O., & Bergman, E. (2012). The barriers encountered by teachers implementing education for sustainable development: Discipline-bound differences and teaching traditions. *Research in Science & Technological Education, 30*(2), 185–207. https://doi.org/10.1080/02635143.2012.699891	4	55	198
7	Birdman, J., Wiek, A., & Lang, D. J. (2022). Developing key competencies in sustainability through project-based learning in graduate sustainability programs. *International Journal of Sustainability in Higher Education, 23*(5), 1139–1157. https://doi.org/10.1108/IJSHE-12-2020-0506	1	50	77
8	Brundiers, K., & Wiek, A. (2013). Do we teach what we preach? An international comparison of problem- and project-based learning courses in sustainability. *Sustainability, 5*(4), 1725–1746. https://doi.org/10.3390/su5041725	1	50	253
9	Weiss, M., Barth, M., & von Wehrden, H. (2021). The patterns of curriculum change processes that embed sustainability in higher education institutions. *Sustainability Science, 16*(5), 1579–1593. https://doi.org/10.1007/s11625-021-00984-1	2	45	98
10	Sund, P., & Gericke, N. (2020). Teaching contributions from secondary school subject areas to education for sustainable development: A comparative study of science, social science and language teachers. *Environmental Education Research, 26*(6), 772–794. https://doi.org/10.1080/13504622.2020.1754341	3	44	94

Note. TLS = Total Link Strength. Higher TLS values indicate stronger intellectual connections between documents based on shared references in the bibliographic coupling network.

Table No. 3. Top 10 Bibliographically Coupled Documents on Education for Sustainable Development in Science Education

Table 3 presents the ten most influential documents identified through the bibliographic coupling analysis of Education for Sustainable Development (ESD) in science education. These publications exhibited the highest Total Link Strength (TLS), indicating strong intellectual connections with other studies in the network through shared references. Barth and Michelsen (2013) ranked first with a TLS of 86, suggesting that their work on learning for change and sustainability science occupies a central position within the intellectual structure of the field. Wilhelm et al. (2019) and Cebrián and Junyent (2015) also recorded high TLS values of 80 and 64, respectively, highlighting the importance of competency-based approaches and the development of sustainability competencies among learners and future educators.

The highly coupled documents further reveal the prominence of sustainability competencies, transformative learning, and curriculum innovation as key themes within the field. Studies by Brundiers and Wiek (2013), Birdman et al. (2022), and Sonetti et al. (2019) emphasize the role of project-based learning, problem-based learning, and institutional sustainability initiatives in developing sustainability-related knowledge and skills. Similarly, Disterheft et al. (2016) and Weiss et al. (2021) highlight the significance of sustainability assessment, participation, and curriculum transformation within higher education institutions, reflecting the growing interest in embedding sustainability across educational systems and organizational practices.

Another prominent theme emerging from the highly coupled publications concerns the implementation of Education for Sustainable Development in formal educational settings. Borg et al. (2012) examined barriers encountered by teachers when integrating ESD into classroom practice, while Sund and Gericke (2020) and Berglund et al. (2014) explored the contributions of different subject areas and the development of sustainability consciousness among students. Collectively, the most strongly coupled documents indicate that research on ESD in science education is shaped by interconnected themes related to sustainability competencies, pedagogical innovation, curriculum transformation, institutional change, teacher implementation, and student learning outcomes. The strong coupling relationships among these studies suggest that they represent the principal intellectual streams underpinning contemporary scholarship on Education for Sustainable Development in science education.

The figure below presents the Bibliographic Coupling Analysis

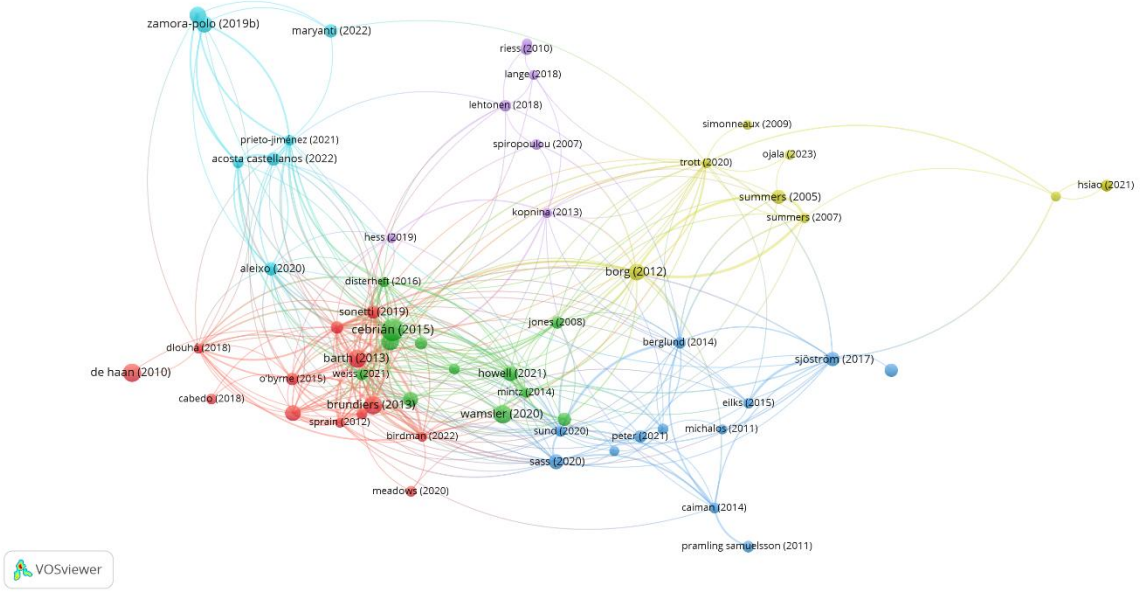

Figure 2.Bibliographic coupling network of documents on Education for Sustainable Development in science education.

The map was generated using VOSviewer with a minimum citation threshold of 71 citations. Of the 1,245 publications in the dataset, 101 met the threshold criterion. Because some documents were not connected to the main network, only the largest connected set consisting of 60 documents was retained for visualization and cluster analysis. The resulting network reveals the intellectual structure of the field by grouping documents according to shared references and thematic relationships.

Cluster 1: Sustainability Competencies, Transformative Learning, and Curriculum Innovation.

This cluster represents a major intellectual stream in Education for Sustainable Development (ESD) research, focusing on the development of sustainability competencies through transformative and learner-centered educational approaches. The publications within this cluster emphasize the importance of equipping learners with the knowledge, skills, values, and dispositions necessary to address complex sustainability challenges. Studies by Barth and Michelsen (2013), De Haan (2010), and Wilhelm et al. (2019) highlight competency-based frameworks and curriculum alignment as essential foundations for effective ESD implementation. Complementing these perspectives, Brundiers and Wiek (2013), Sprain and Timpson (2012), and Birdman et al. (2022) demonstrate the value of project-based, problem-based, and interdisciplinary learning experiences in fostering sustainability-related competencies. Other studies in the cluster underscore the role of curriculum transformation, institutional commitment, and transdisciplinary approaches in integrating sustainability across higher education programs. Collectively, the strong bibliographic connections among these publications indicate that competency development, innovative pedagogy, and curriculum reform constitute a central foundation of contemporary ESD research and practice.

Cluster 2: Transformative Learning, Curriculum Integration, and Institutional Change for Sustainability

Cluster 2 centers on the integration of sustainability principles into higher education through curriculum transformation, innovative pedagogical approaches, and institutional change. The studies within this cluster emphasize the development of sustainability competencies among students while highlighting the critical role of universities in fostering transformative learning experiences. Research by Cebrián and Junyent (2015), Wamsler (2020), and Howell (2021) underscores the importance of competency-based education, active learning, reflective practice, and transformative pedagogies in promoting sustainability-oriented mindsets and behaviors. Complementing these perspectives, Weiss et al. (2021), Ralph and Stubbs (2014), Ferrer-Balas et al. (2010), and Leal Filho et al. (2015) examine how sustainability can be embedded across institutional structures, policies, and curricula, emphasizing the need for systemic change within higher education institutions. Other studies in the cluster highlight the contribution of innovative teaching approaches, including flipped learning, creativity, and participatory engagement, to enhance sustainability learning outcomes. Collectively, the strong intellectual connections among these publications indicate that effective Education for Sustainable Development requires not only curriculum reform and pedagogical innovation but also institution-wide commitment to sustainability as a guiding principle for teaching, learning, and organizational transformation.

Cluster 3: Environmental Literacy, Sustainability Consciousness, and Learner Engagement in Science Education

Cluster 3 focuses on the development of environmental literacy, sustainability consciousness, and learner engagement across diverse educational contexts. The studies in this cluster emphasize how learners develop knowledge, attitudes, values, competencies, and behaviors related to sustainability through science and environmental education. Research by Berglund et al. (2014), Sass et al. (2020), and Michalos et al. (2011) highlights the cultivation of sustainability consciousness and action competence as essential outcomes of Education for Sustainable Development. Other studies examine learner engagement across different educational levels, ranging from early childhood education (Pramling Samuelsson, 2011; Caiman & Lundegård, 2014) to secondary and higher education (Uitto et al., 2011; Peter et al., 2021). Contributions from Eilks (2015), Sjöström et al. (2017), and Sund and Gericke (2020) further demonstrate the close relationship between science education and sustainability by emphasizing critical thinking, environmental awareness, and socially responsible decision-making. Collectively, these publications indicate that fostering environmentally literate and sustainability-conscious learners is a central objective of ESD, positioning science education as a key avenue for promoting informed action and long-term commitment to sustainable development.

Cluster 4: Teacher Education, Socioscientific Issues, and Transformative Sustainability Pedagogies

Cluster 4 highlights the role of teacher education, learner engagement, and transformative pedagogical approaches in advancing Education for Sustainable Development within science education. The studies in this cluster emphasize the preparation of teachers to address sustainability issues through interdisciplinary, emotionally responsive, and socially relevant instructional practices. Research by Summers et al. (2005, 2007), Borg et al. (2012), and Ojala (2023) focuses on teachers' conceptions of sustainable development, challenges in ESD implementation, and the importance of emotional awareness in climate change education. Complementing these perspectives, Simonneaux and Simonneaux (2009) and Bencze et al. (2012) advocate for the integration of socioscientific issues and student activism to promote critical thinking and informed decision-making regarding sustainability challenges. Other studies explore innovative learning approaches,

including garden-based education, arts-science integration, and STEAM education, which aim to enhance student motivation, participation, and sustainability-oriented action. Collectively, the publications within this cluster demonstrate that effective ESD requires pedagogies that connect scientific understanding with ethical reflection, emotional engagement, and active participation in addressing real-world sustainability concerns.

Cluster 5: Systems Thinking, Climate Change Education, and Transformative Sustainability Perspectives

Cluster 5 emphasizes the theoretical and pedagogical foundations needed to address sustainability challenges through systems thinking, climate change education, and transformative learning. The studies in this cluster highlight the importance of helping learners and teachers understand the interconnected nature of environmental, social, and economic systems. Research by Riess and Mischo (2010) and Schuler et al. (2018) positions systems thinking as a core competency for Education for Sustainable Development, enabling learners to analyze complex sustainability issues and recognize relationships among multiple factors. Similarly, Lehtonen et al. (2018) and Hess and Maki (2019) focus on climate change education, advocating pedagogical approaches that address climate issues as complex and "wicked" problems requiring interdisciplinary understanding and curriculum reform. Lange (2018) contributes a transformative learning perspective by emphasizing relational ways of knowing, while Kopnina (2013) and Spiropoulou et al. (2007) explore sustainability values, attitudes, and environmental literacy among learners and teachers. Collectively, these publications indicate that effective ESD extends beyond knowledge acquisition by fostering systems thinking, critical reflection, and transformative perspectives that support informed action toward sustainable futures.

Cluster 6: Sustainable Development Goals, Higher Education, and Emerging Research Directions

Cluster 6 focuses on the integration of the Sustainable Development Goals (SDGs) within higher education and the growing body of scholarship examining their implementation, assessment, and impact. The studies in this cluster reflect increasing academic attention to aligning educational practices with the United Nations 2030 Agenda for Sustainable Development. Research by Zamora-Polo and Sánchez-Martín (2019), Aleixo et al. (2020), and Acosta Castellanos and Queiruga-Dios (2022) examines how higher education institutions incorporate sustainability and SDG-related principles into curricula, programs, and institutional strategies. Complementing these efforts, Prieto-Jiménez et al. (2021), Maryanti et al. (2022), and Lim et al. (2022) provide bibliometric and systematic reviews that map the evolution of SDG-related educational research, highlighting emerging themes and knowledge gaps. The cluster also emphasizes students' awareness and understanding of the SDGs, reflecting the growing recognition of higher education's role in preparing future generations to address global sustainability challenges. Collectively, these publications indicate that SDG-oriented education has become an increasingly important research frontier, linking sustainability policy, educational practice, and institutional transformation within the broader ESD landscape.

Overall Intellectual Structure

Together, the six clusters reveal that Education for Sustainable Development (ESD) research in science education is organized around (1) sustainability competencies, transformative learning, and curriculum innovation; (2) curriculum integration, institutional transformation, and pedagogical innovation; (3) environmental literacy, sustainability consciousness, and learner engagement; (4) teacher education, socioscientific issues, and transformative sustainability pedagogies; (5) systems thinking, climate change education, and transformative sustainability perspectives; and (6) Sustainable Development Goals (SDGs), higher education, and emerging research directions. These clusters collectively demonstrate that ESD in science education is a multidisciplinary and evolving field that integrates educational theory, sustainability competencies, environmental literacy, teacher preparation, systems thinking, and sustainability-oriented institutional change. The interconnected nature of the clusters highlights the field's emphasis on developing learners' knowledge, values, and action competencies while addressing complex sustainability challenges through innovative pedagogies, curriculum reform, and alignment with global sustainability agendas. Together, these research streams form the intellectual foundation of contemporary ESD scholarship and illustrate the growing role of science education in advancing sustainable development

Table 4 presents the six clusters identified through the bibliographic coupling analysis of Education for Sustainable Development (ESD) in science education. The clusters represent the major intellectual themes within the field, highlighting shared research interests and common reference patterns among influential publications. Together, these clusters reveal the multidisciplinary nature of ESD research, encompassing sustainability competencies, transformative learning, curriculum innovation, environmental literacy, teacher education, systems thinking, climate change education, and

Sustainable Development Goals (SDGs)-oriented educational practices. The clustering structure illustrates how different yet interconnected research streams collectively contribute to the development of knowledge and practice in ESD within science education.

Cluster	Cluster Label	Number of Articles	Representative Publications
1	Sustainability Competencies, Transformative Learning, and Curriculum Innovation	13	Barth and Michelsen (2013); Wilhelm et al. (2019); Brundiers and Wiek (2013)
2	Transformative Learning, Curriculum Integration, and Institutional Change for Sustainability	12	Cebrián and Junyent (2015); Wamsler (2020); Weiss et al. (2021)
3	Environmental Literacy, Sustainability Consciousness, and Learner Engagement in Science Education	12	Berglund et al. (2014); Sass et al. (2020); Eilks (2015)
4	Teacher Education, Socioscientific Issues, and Transformative Sustainability Pedagogies	9	Borg et al. (2012); Summers et al. (2005); Ojala (2023)
5	Systems Thinking, Climate Change Education, and Transformative Sustainability Perspectives	7	Schuler et al. (2018); Lehtonen et al. (2018); Riess and Mischo (2010)
6	Sustainable Development Goals, Higher Education, and Emerging Research Directions	7	Zamora-Polo and Sánchez-Martín (2019); Prieto-Jiménez et al. (2021); Acosta Castellanos and Queiruga-Dios (2022)

Table No. 4. Coupling Clusters on Education for Sustainable Development in Science Education

Note. Cluster sizes are based on the bibliographic coupling network generated in VOSviewer. Representative publications are selected from the most influential and highly connected documents within each cluster.

Citation Analysis of Scholarly Sources

To identify the journals that have exerted the greatest scholarly influence within the field, a citation analysis of sources was conducted using VOSviewer. *Table 5* summarizes the ten most influential journals based on citation counts and Total Link Strength (TLS), providing insights into both their citation impact and their interconnectedness within the citation network.

Rank	Source	Citations	Total Link Strength (TLS)
1	Sustainability (Switzerland)	4,604	18
2	International Journal of Sustainability in Higher Education	2,065	9
3	Journal of Cleaner Production	1,594	3
4	Environmental Education Research	1,470	8
5	Sustainability Science	1,032	1
6	International Journal of Science Education	432	2
7	Research in Science Education	381	4
8	Science and Education	353	5
9	International Review of Education	332	13
10	Cultural Studies of Science Education	300	5

Table 5. Top 10 Most Influential Scholarly Sources Based on Citation Analysis

Table 5 presents the ten most influential scholarly sources identified through the citation analysis. *Sustainability (Switzerland)* emerged as the most influential journal in the field, receiving *4,604 citations* and exhibiting the highest *Total Link Strength (TLS = 18)*. This finding indicates not only its substantial citation impact but also its central position within the citation network, reflecting extensive citation relationships with other leading journals. As a multidisciplinary journal focusing on sustainability research, its prominence demonstrates its pivotal role in disseminating studies on Education for Sustainable Development (ESD) across science, environmental, and higher education contexts.

The *International Journal of Sustainability in Higher Education* ranked second, accumulating *2,065 citations* with a *TLS of 9*. Its strong citation performance highlights the significant contribution of higher education research to the advancement of

ESD, particularly in areas related to curriculum development, institutional sustainability, and pedagogical innovation. Likewise, *Journal of Cleaner Production* (1,594 citations) and *Environmental Education Research* (1,470 citations) were among the most influential publication venues. While *Journal of Cleaner Production* reflects the integration of sustainability science with environmental and industrial perspectives, *Environmental Education Research* underscores the longstanding contribution of environmental education scholarship to the conceptual and pedagogical development of ESD.

Other influential journals included *Sustainability Science*, *International Journal of Science Education*, *Research in Science Education*, *Science and Education*, *International Review of Education*, and *Cultural Studies of Science Education*. Collectively, these journals represent diverse disciplinary perspectives encompassing sustainability science, science education, curriculum studies, educational philosophy, and higher education. Their presence among the leading sources demonstrates that ESD research has evolved as an inherently interdisciplinary field, drawing upon multiple academic traditions to address sustainability challenges through education.

Although citation counts indicate scholarly influence, Total Link Strength (TLS) provides additional insight into the interconnectedness of journals within the citation network. For example, *International Review of Education* recorded a relatively modest *332 citations* but exhibited a comparatively high *TLS of 13*, suggesting that it serves as an important connecting journal linking different areas of ESD scholarship. Conversely, *Journal of Cleaner Production* accumulated a high number of citations (*1,594*) but a lower *TLS of 3*, indicating substantial scholarly impact while maintaining fewer direct citation relationships with other journals in the network. These differences illustrate that citation influence and network connectivity capture complementary dimensions of scholarly significance.

Overall, the citation analysis reveals that the intellectual development of Education for Sustainable Development has been shaped by a relatively small group of highly influential journals that collectively integrate sustainability science, environmental education, science education, and higher education research. The dominance of these publication venues highlights the multidisciplinary character of ESD scholarship and underscores their critical role in disseminating foundational knowledge, fostering interdisciplinary dialogue, and advancing research that supports the implementation of sustainable development through education.

Figure 4 illustrates the citation network of scholarly sources in Education for Sustainable Development (ESD) research across science and sustainability education. The visualization was generated using VOSviewer (version 1.6.20) through citation analysis of sources, applying a minimum threshold of *two documents per source* and *eleven citations per source*. Of the *488 sources* identified in the dataset, *92 met the inclusion criteria* and were included in the network. Node size represents the citation influence of each journal, links indicate citation relationships among journals, and colors denote clusters of sources sharing similar citation patterns. The network provides a visual representation of the principal publication venues that have shaped the scholarly development of ESD research.

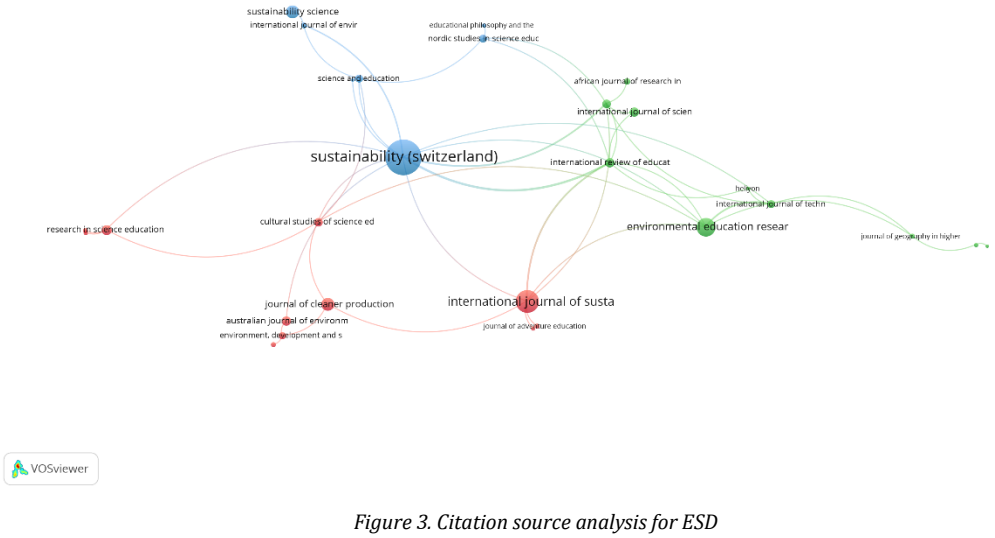

Figure 3. Citation source analysis for ESD

Cluster 1. Sustainability and Transformative Education

Cluster 1 represents the educational foundations of Education for Sustainable Development (ESD), integrating sustainability, higher education, science education, and transformative learning. The cluster is anchored by the *International Journal of Sustainability in Higher Education* and the *Journal of Cleaner Production*, highlighting the importance of institutional sustainability and interdisciplinary approaches to sustainable development. Journals such as *Research in Science Education*, *Chemistry Education Research and Practice*, and *International Journal of Science and Mathematics Education* emphasize the role of science education in developing sustainability competencies, while the *Australian Journal of Environmental Education* and the *Journal of Transformative Education* underscore the value of environmental and transformative pedagogies. Collectively, the cluster reflects the integration of sustainability principles into educational research and practice across multiple learning contexts.

Cluster 2. Science and Environmental Education

Cluster 2 highlights the integration of environmental education, science education, and educational development in advancing Education for Sustainable Development (ESD). The cluster is anchored by *Environmental Education Research*, the most influential journal within the group, emphasizing the central role of environmental literacy and sustainability learning. It also includes prominent science education journals such as *International Journal of Science Education*, *Eurasia Journal of Mathematics, Science and Technology Education*, and the *African Journal of Research in Mathematics, Science and Technology Education*, reflecting the contribution of STEM disciplines to ESD. The presence of journals focusing on early childhood, technology and design, geography, and higher education demonstrates that sustainability education is implemented across diverse educational levels and learning contexts, underscoring the broad and interdisciplinary scope of ESD.

Cluster 3: Sustainability and Science Education

Cluster 3 emphasizes the integration of sustainability science with science education and educational theory in advancing Education for Sustainable Development (ESD). The cluster is dominated by *Sustainability (Switzerland)*, the most influential journal in the entire network, together with *Sustainability Science*, highlighting the central role of sustainability-focused scholarship in shaping the field. Supporting journals, including *Science and Education*, *Educational Philosophy and Theory*, *Nordic Studies in Science Education*, and the *International Journal of Environmental and Science Education*, underscore the importance of science education, educational philosophy, and interdisciplinary approaches in promoting sustainability competencies. Collectively, this cluster reflects the theoretical and pedagogical foundations that support the integration of sustainability into science education and broader educational research.

Overall, the citation analysis reveals that Education for Sustainable Development (ESD) research is supported by three interconnected groups of scholarly sources that collectively define its intellectual foundation. *Cluster 1* emphasizes sustainability and transformative education, highlighting the integration of sustainability principles into higher education, science education, and experiential learning. *Cluster 2* focuses on environmental and science education across diverse educational settings, demonstrating the role of STEM, environmental literacy, and educational development in fostering sustainability competencies. *Cluster 3* centers on sustainability science and educational theory, reflecting the influence of multidisciplinary sustainability research and the theoretical foundations underpinning science and sustainability education. Together, these clusters demonstrate that ESD has evolved as a multidisciplinary field that draws upon sustainability science, environmental education, science education, and higher education scholarship. The strong citation relationships among these journals underscore the collaborative exchange of knowledge across disciplines, reinforcing the role of education as a key mechanism for advancing sustainable development.

This synthesis complements your bibliographic coupling analysis by showing that while influential publications shape the *intellectual structure* of the field, a relatively small group of highly cited journals provides the *scholarly foundation* through which ESD knowledge is generated, disseminated, and advanced.

Cluster	Cluster Label	Number of Journals	Representative Journals
1	Sustainability and Transformative Education	11	*International Journal of Sustainability in Higher Education*, *Journal of Cleaner Production*, *Research in Science Education*, *Australian Journal of Environmental Education*
2	Science and Environmental Education	10	*Environmental Education Research*, *International Journal of Science Education*, *International Review of Education*, *International Journal of Technology and Design Education*

3	Sustainability Science and Science Education	7	*Sustainability (Switzerland)*, *Sustainability Science*, *Science and Education*, *Educational Philosophy and Theory*

Table No. 6. Citation Analysis Clusters of Scholarly Sources in Education for Sustainable Development Research

Conclusion and Recommendations

This bibliometric study provides a comprehensive understanding of the evolution of Education for Sustainable Development (ESD) across science and sustainability education by revealing its intellectual structure and scholarly influence. The findings demonstrate that ESD has developed into a mature, multidisciplinary field characterized by interconnected research themes centered on sustainability competencies, transformative learning, environmental literacy, systems thinking, and Sustainable Development Goals (SDGs)-oriented education. These findings underscore the importance of adopting interdisciplinary and competency-based educational approaches that enable learners to address complex sustainability challenges. Furthermore, the identification of influential scholarly sources offers researchers valuable guidance in selecting key literature, fostering research collaboration, and identifying appropriate publication venues. By mapping the field's intellectual foundations and scholarly landscape, this study provides a useful reference for researchers, educators, curriculum developers, and policymakers seeking to strengthen sustainability-oriented education and advance future research that supports the achievement of global sustainable development goals.

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Competing Interests Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Data Availability Statement

The bibliographic dataset analyzed during this study was retrieved from the Scopus database. The data are publicly available through Scopus, subject to its subscription and licensing policies. No additional datasets were generated by the author.

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Appendices

No appendices are attached to this study.