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# Bibliometric Analysis using R Studio: Sixteen Years of Education for Sustainable Development Studies in Science Learning

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***Abstract****. This study investigates the trends, contributions, and impact of research in the field of Education for Sustainable Development (ESD) in science learning through a bibliometric analysis of Scopus data. The Bibliometrix R package was used as the primary tool for analysis, with visualization supported by Microsoft Excel. The analysis reveals consistent growth in research output, with Indonesia identified as the leading contributor and Universitas Pendidikan Indonesia as the top-performing institution. Based on significant publications in high-impact journals, the most influential author is Ingo Eilks. The study recorded publication peaks in 2022 and 2024, possibly driven by the increasing urgency to address sustainability issues. The findings highlight the importance of international collaboration and continuous adaptation to emerging trends. These insights provide a comprehensive overview of research trends and impacts in ESD and offer straightforward directions for future research development, particularly in the context of global collaboration and responses to evolving sustainability challenges.*

***Keywords*** *Bibliometrics Analysis; R Studio; ESD; Education for Sustainable Development; Science Learning*

## 1. INTRODUCTION

In an ever-changing world, sustainability issues such as climate change, hunger, environmental degradation, and social inequality are increasingly gaining global attention. The urgency of sustainability has become more pronounced, as our decisions and actions will significantly impact the planet and future generations. This awareness arises from recognizing that natural resources are finite, necessitating wise management to ensure their availability for future generations.

This realization underscores the need for collective efforts across various sectors, with education being one of the most effective tools for addressing sustainability challenges. Education is essential for achieving the other 16 Sustainable Development Goals (SDGs) (Giangrande et al., 2019; Widodo et al., 2023). SDG 4, which focuses on quality education, includes education for sustainable development (ESD), as outlined in Target 4.7. This target ensures all learners acquire the knowledge and skills to promote sustainable development (UNESCO, 2017).

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ESD is an educational approach that fosters changes in knowledge, skills, values, and attitudes to build a more just and sustainable society while achieving meaningful social transformation (Eliyawati et al., 2023). Education is key to social transformation, as it helps stakeholders better understand social and environmental issues and enables them to engage creatively and enthusiastically in decision-making. Furthermore, a deep understanding of existing challenges fosters a sense of ownership among stakeholders, leading to long-term solutions. Thus, ESD is a means of transferring knowledge and a critical instrument for achieving lasting social change.

The primary goal of ESD is to empower current and future generations to reflect on their actions and meet their needs through a balanced and integrated approach that considers both local and global perspectives. This approach encompasses the three main dimensions of sustainable development: economic, social, and environmental (Ofei-Manu & Didham, 2012; UNESCO, 2017, 2018). Achieving these goals necessitates a comprehensive transformation of society. ESD applies to all levels of education—formal, non-formal, and informal—and is an integral part of lifelong learning (Mâţă, 2020; UNESCO, 2017).

The scope of ESD extends beyond curriculum content to include teaching methods, learning environments, and learning outcomes (UNESCO, 2014). While holistic approaches to ESD have faced criticism for focusing too heavily on economic and social aspects at the expense of environmental issues (Kopnina, 2014), research has shown that such approaches significantly enhance students' understanding of environmental challenges (Pauw et al., 2015). Moreover, ESD integrates affective components with factual knowledge to enrich students' learning experiences (Olsson et al., 2016; Olsson & Gericke, 2016). UNESCO (2018) has identified eight key competencies necessary for ESD, enabling students to learn and act toward sustainable development: 1) Systems thinking competency, 2) Anticipatory competency, 3) Normative competency, 4) Strategic competency, 5) Collaboration competency, 6) Critical thinking competency, 7) Self-awareness competency, 8) Integrated problem-solving competency.

These competencies can be developed through science learning integrated with ESD. Incorporating ESD into science education offers numerous benefits, enhancing educational experiences and fostering the skills to tackle sustainability challenges. By promoting a holistic understanding of sustainability, ESD equips students with the knowledge and competencies to become proactive change agents. Based on previous

research, integrating ESD into learning not only improves academic performance but also fosters critical thinking (Wang, 2024), analytical reasoning (Bonilla-Jurado et al., 2024), and environmental awareness (Fiel'ardh et al., 2023).

Previous research on ESD in education has been extensive. However, in recent years, very few studies have comprehensively analyzed trends in ESD in science learning. While several articles (e.g., Do et al., 2021; Imaduddin & Eilks, 2024; Kusumaningrum et al., 2023) have mapped ESD using bibliometric methods, these studies have not explicitly linked "Education for Sustainable Development" with "science learning." Hence, this research fills that gap by focusing specifically on trends in ESD in science education through a comprehensive bibliometric analysis.

Compared to traditional review methodologies, the bibliometric approach offers unique contributions to advancing the understanding of ESD. By employing knowledge network analyses such as co-citation and co-authorship analyses, bibliometrics reveals relationships among authors, scientific works, and institutions that drive research progress. This approach enables the identification of collaboration patterns and major influences often overlooked in traditional qualitative reviews.

Using tools like Bibliometrix, researchers can conduct comprehensive science mapping analyses, yielding valuable insights into the intellectual and conceptual structure of ESD research (e.g., Aria & Cuccurullo, 2017; Ghorbani, 2024; Siriwong et al., 2024). One significant advantage of bibliometric analysis is its ability to highlight the evolution of research trends over time. For example, bibliometric studies on ESD research from 2019 to 2023 classified ESD studies into five clusters: 1) ESD in the learning context, 2) ESD in educational programs and policies, 3) ESD in teaching and learning practices, 4) ESD linked to sustainable learning competencies or achievements, and 5) ESD in continuous assessment and evaluation. The research questions (RQs) addressed in this study are:

RQ1: What is the main information for developing ESD in science education?

RQ2: Which countries, affiliations, authors, and journals are the top contributors?

RQ3: What are the most impactful and frequently cited papers and journals?

## 2. LITERATURE REVIEW

Education for Sustainable Development (ESD) in science learning is an approach that connects scientific knowledge with sustainability principles. Its goal is to prepare students to address complex environmental, social, and economic challenges. This approach enhances scientific literacy, critical thinking, and problem-solving skills and fosters global responsibility and environmental stewardship. By employing pedagogical strategies and curriculum innovations, ESD can be effectively integrated into various aspects of science education.

One such strategy is project-based learning (PjBL), which allows students to address real-world sustainability issues. For example, implementing sustainability-oriented, low-cost, and eco-friendly projects has improved emotional and cognitive outcomes for pre-service science teachers. Research on creating adsorbents from food waste for wastewater treatment demonstrates how such projects can enhance ESD outcomes and chemistry students' inquiry skills (Anggraeni et al., 2023). Similarly, renewable energy-focused PBL has been shown to develop critical thinking skills among high school students (Rizki & Suprapto, 2024).

Another effective pedagogical model is RADEC (Read, Answer, Discuss, Explain, and Create), which significantly enhances student engagement and motivation in ESD. Designed to promote active learning and critical thinking, the RADEC model improves academic outcomes while fostering a more profound interest in sustainability practices. For instance, studies implementing RADEC-oriented ESD during the COVID-19 pandemic successfully instilled sustainability values in pre-service elementary teachers through biology courses, covering knowledge, attitudes, and values supporting sustainable development (Suratmi et al., 2022). Similarly, RADEC-based ESD education for elementary students has demonstrated increased sustainability awareness across knowledge, attitudes, and behaviors (Lestari et al., 2022).

Integrating Indigenous Knowledge (IK) into ESD enriches science education by aligning local cultural values with sustainable practices. For instance, blending IK with green chemistry principles—such as introducing simple, low-cost, and modern plant extraction methods—has empowered students to evaluate the "greenness" of these methods (Zidny & Eilks, 2022).

## 3. METHODS

This study employed bibliometric analysis as it examines historical developments, structural organization, information dissemination patterns, journal influence, and long-term citation trends (González-Alcaide, 2021; Rico et al., 2021; Zidny et al., 2021; Zupic & Čater, 2015), thereby providing a comprehensive understanding of ESD in science learning. Scopus was chosen as the primary data source due to its reputation as a leading multidisciplinary scientific database, its extensive coverage of high-quality academic journals across various relevant disciplines, its advanced bibliometric features that facilitate data analysis, and its frequent updates that ensure access to the latest research on ESD in science learning. This decision aligns with previous bibliometric studies, such as Prahani et al., 2022, which also utilized Scopus for its advantages in scope and bibliometric features.

The terms "education for sustainable development" and "science learning" served as the primary keywords for the search query. The initial query was entered into the advanced search form in Scopus on December 13, 2024, as follows:

(TITLE-ABS-KEY ("Education for Sustainable Development") AND ("Science Learning"))

The initial search returned 114 documents. PRISMA guidelines (Moher et al., 2009; Page et al., 2021) were applied to refine the results systematically. Figure 1 illustrates the PRISMA flow diagram steps. During the screening phase, Scopus filters were applied to exclude irrelevant documents. Additional filtering was performed to include only journal articles written in English. This filtering ensured that the selected studies were directly relevant to ESD in science learning.

Ultimately, 78 documents were exported and downloaded in CSV format. The dataset contained 78 records with citation details, bibliographic information, abstracts, and keywords. Figure 1 adheres to the PRISMA guidelines as described by Page et al. (2021).

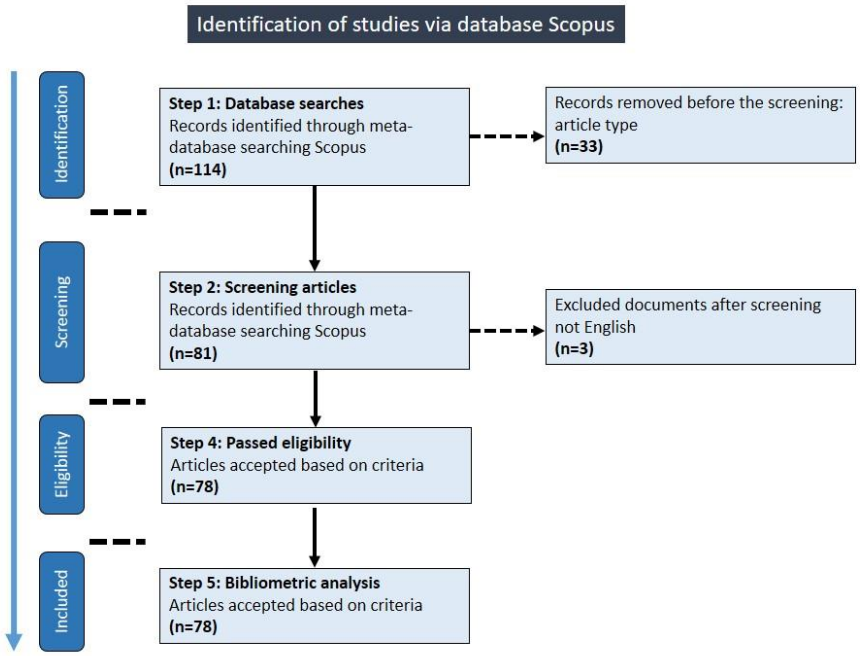


**Figure 1.** Article Selection Process

The bibliometric analysis utilized several software applications to enhance visual appeal. The Biblioshiny program must be executed within the R Studio application. This program is built on the open-source Bibliometrix package developed by Aria and Cuccurullo (2017), and the R application was chosen to conduct and visualize data through bibliometric analysis.

Biblioshiny is a web-based extension of the Bibliometrix package that enables researchers to perform bibliometric analyses interactively via program calls within the R application (Aria & Cuccurullo, 2017). Users can import data in CSV or BibTeX format, run various analyses such as network analysis, thematic analysis, and trend exploration, and quickly generate visualizations and reports.

## 4. RESULTS

### 1.1 Main Information

The leading information is presented in Table 1.

**Table 1.** Main Information

| Description | Results |
|---|---|
| *Main Information About Data* | |
| Timespan | 2008:2024 |
| Sources (Journals, Books, etc) | 49 |
| Documents | 78 |
| Annual Growth Rate % | 17,93 |
| Document Average Age | 3,53 |

| | |
|---|---|
| Average citations per doc | 14,37 |
| References | 4963 |
| *Document Contents* | |
| Keywords Plus (ID) | 151 |
| Author's Keywords (DE) | 284 |
| *Authors* | |
| Authors | 258 |
| Authors of single-authored docs | 3 |
| *Authors Collaboration* | |
| Single-authored docs | 3 |
| Co-Authors per Doc | 3,58 |
| International co-authorships % | 24,36 |
| *Document Types* | |
| article | 78 |

The literature on ESD in science learning has consistently grown over the years, as evidenced by data from the Scopus database. This field has demonstrated significant impact, reflected in the average citations per document, which indicates its importance and influence. Research in this area has grown steadily each year, benefiting from strong author collaboration, as evidenced by the high percentage of co-authorship (Prahani et al., 2024). The high co-authorship percentage also highlights a robust collaboration index within the field. Research on ESD in science learning continues to evolve, characterized by a diverse range of Keywords Plus and interdisciplinary themes among authors.

## 2 Top Countries, Affiliations, Authors, and Journals

### 2.1 Annual Trends in the Number of Publications

Figure 2 illustrates the annual publication trends, highlighting the growth and fluctuations in research output.

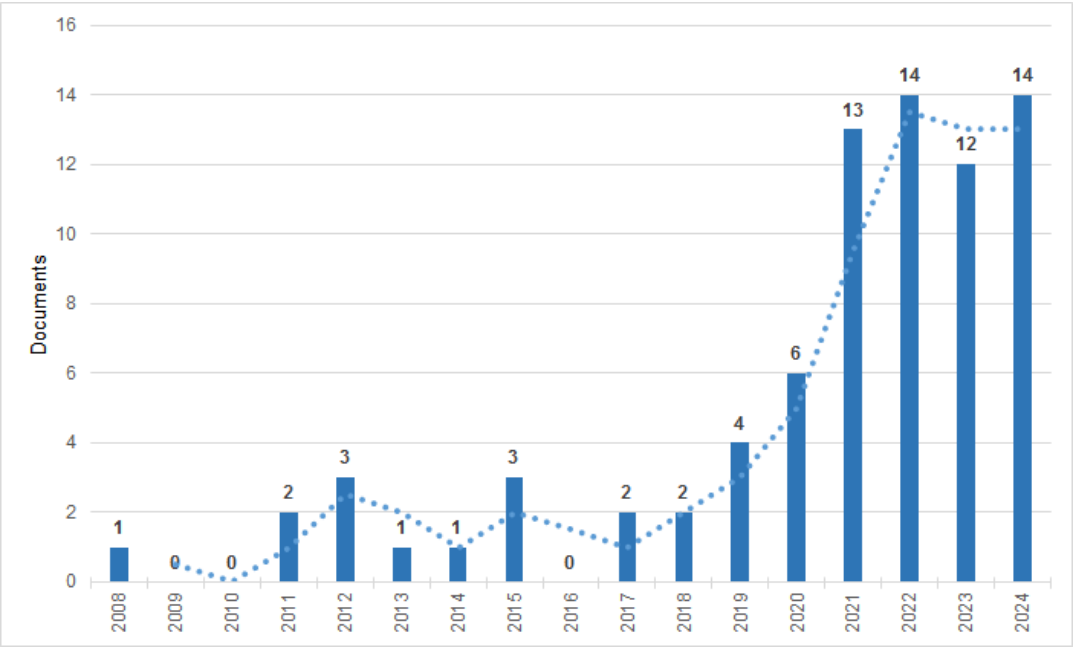


**Figure 2.** Annual Trends in the Number of Publications

From Figure 2, it can be observed that the number of publications between 2008 and 2017 was relatively low and inconsistent. However, there was an increase starting in 2018 (2 documents), reaching 14 documents in 2022, indicating growing interest among researchers in this field. In 2023, the number of publications slightly decreased to 12, followed by a rebound in 2024, with 14 documents published again.

Despite these fluctuations, the overall trend indicates sustained growth in research on ESD in science learning, with periodic increases likely driven by shifts in research focus or external factors influencing publication rates. Research on ESD in science learning is crucial because science plays a strategic role in helping students understand scientific concepts relevant to global issues. Through ESD, students learn how to apply scientific theories to solve sustainability challenges in real-life contexts.

Various studies on ESD in science education have focused on issues such as climate change (e.g., Solihah et al., 2024), food chains and energy (e.g., Wennersten et al., 2023), biodiversity (e.g., Gutiérrez-García et al., 2024; Hartanti et al., 2024; Id Babou et al., 2023), environmental pollution (e.g., Rico et al., 2021; Zidny & Eilks, 2022), volcanology (e.g., Hariyono et al., 2019), and waste management (e.g., Nandiyanto et al., 2023). These studies also promote innovation and creativity, encouraging students to think beyond traditional approaches and develop new ideas relevant to sustainability.

In an era of globalization and rapid socio-economic changes, students must deeply understand sustainability. This knowledge equips them to face significant challenges such as food security, resource scarcity, and environmental disaster risks. Thus, ESD in science learning plays a vital role in preparing a generation that understands science and can provide tangible solutions for a better future.

### 2.2 Top 10 Country Production

The top 10 countries contributing to research in ESD in science learning are illustrated in the following figure.

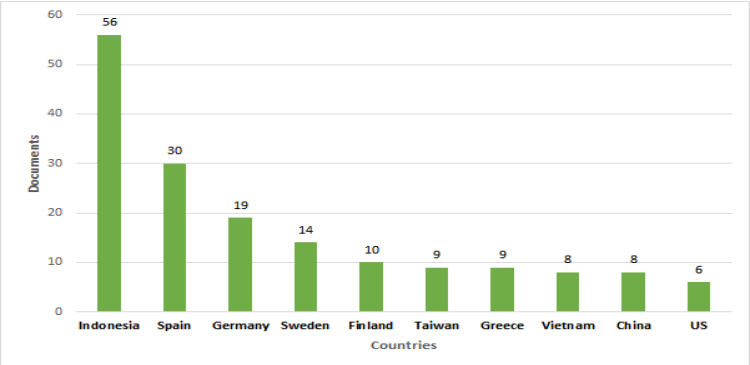


**Figure 3.** Country Production Over Time

Figure 3 illustrates the distribution of research outputs across various countries. The figure reveals that Indonesia leads the field, contributing 56 documents. Following Indonesia, Spain accounts for 30 documents, highlighting its substantial contribution to this area. Other countries, such as Germany (19 documents) and Sweden (14 documents), also play significant roles, though their contributions are considerably smaller compared to Indonesia and Spain. This distribution indicates that while a few countries dominate research production in this field, there is still a diverse range of contributions from other regions. This reflects global interest and collaboration in this area of study.

### 2.3 Most Productive Affiliations

Data on the most productive affiliations is presented in the following figure.

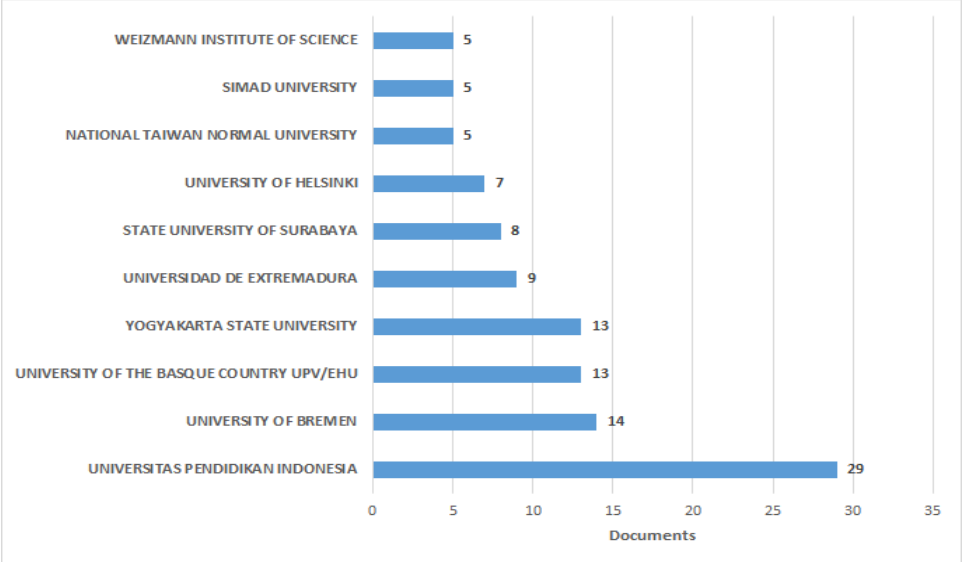


**Figure 4.** Publications by Affiliations

Figure 4 depicts the distribution of articles across various academic institutions, highlighting that Universitas Pendidikan Indonesia is the leading contributor with 29 articles, underscoring its prominent role and strong research focus in this field. Following closely, the University of Bremen has produced 14 articles, showcasing its significant contribution and well-established research presence. Other institutions, such as the University of the Basque Country, also demonstrate considerable research activity, reflecting the active engagement and expertise of their researchers in this area. Additionally, Yogyakarta State University contributes 13 articles, indicating a strong but somewhat less dominant presence compared to the top contributors. Universidad de Extremadura, with 9 articles, also emerges as an important contributor, although its output is more modest compared to the leading institutions.

### 2.4 Most Productive Authors

Data on the most productive authors is presented in the following table.

**Table 2.** Authors with the Most Publication Volume

| Ranked by NP | Author | Affiliation | NP | TC |
|---|---|---|---|---|
| 1 | Eilks I. | Universität Bremen Germany | 6 | 77 |
| 2 | Zidny, R. | Universität Bremen, Germany and Universitas Sultan Ageng Tirtayasa, Indonesia | 3 | 43 |
| 3 | Bogner, FX. | University of Bayreuth, Germany | 2 | 22 |
| 4 | Chang, CY. | Nanyang Technological University, Singapore | 2 | 54 |
| 5 | Fujii, H. | Okayama University, Japan | 2 | 17 |
| 6 | Hariyono, E. | State University of Surabaya, Indonesia | 2 | 0 |
| 7 | Kaniawati, I. | Universitas Pendidikan Indonesia, Indonesia | 2 | 14 |
| 8 | Kuswanto H. | Yogyakarta State University, Indonesia | 2 | 4 |
| 9 | Madlazim | State University of Surabaya, Indonesia | 2 | 0 |
| 10 | Malandrakis G. | Aristotle University of Thessaloniki, Greece | 2 | 32 |

Notes: **NP** = number of publication; **TC** = total citations
Source: Table created by authors

The rankings in Table 2 are based on publication volume and total citations. According to the rankings, the most productive researcher is Eilks, with six documents underscoring his prominent role in the field of ESD in science learning. Another active researcher, Zidny, has published three papers, indicating a significant contribution but slightly less dominant than the top-ranked author.

Several other researchers, including Bogner, Chang, Fujii, Hariyono, Kaniawati, Kuswanto, Madlazim, and Malandrakis, each contributed two papers. This distribution highlights a range of contributors with varying levels of research output, reflecting broad academic interest and participation from researchers worldwide. In terms of citations, as shown in Table 2, the most highly cited authors are Eilks (77 citations), Chang (54 citations), and Zidny (43 citations). Combining both indicators (publication volume and total citations), Eilks and Zidny emerge as top-ranked contributors across both categories. However, despite having the fewest publications (2 documents), Chang has the highest citation-per-document ratio. This ratio indicates that Chang's research is highly influential and frequently referenced within the field.

## 2.5 Top 10 Most Published Journals

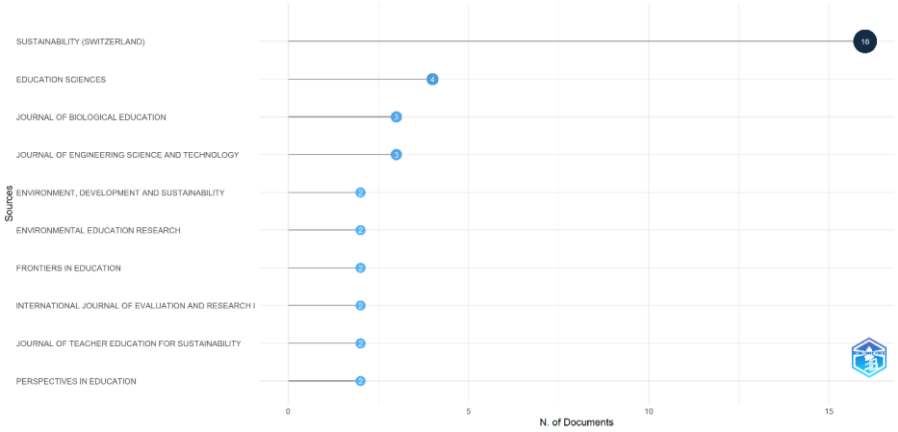


**Figure 5**. Top 10 Journals in the ESD in the Science Education Field

Figure 5 highlights the journals with the highest number of articles published in the domain of ESD in science education. The journal "Sustainability" leads with 16 documents, followed by "Education Sciences" with four documents, and "Journal of Biological Education" and "Journal of Engineering Science and Technology" with three documents each. These journals demonstrate higher output than others, indicating their more substantial focus on ESD in science learning.

Additionally, several other journals, such as "Environment, Development, and Sustainability," "Science and Technology," "Environmental Education Research," "Frontiers in Education," "International Journal of Evaluation and Research," "Journal of Teacher Education for Sustainability," and "Perspectives in Education," each published two documents. These journals also contribute to the domain but with slightly lower publication volumes.

The right journal is crucial for successful research publication (Nicholas et al., 2022). Selecting an appropriate journal increases the likelihood of acceptance and ensures that the research reaches the relevant audience, maximizing its impact in the field (Tracy, 2019). Factors such as the journal's scope, quality, reputation, indexing, and impact factor should be carefully considered when making this choice (Waltman, 2016). By selecting the right journal, researchers can enhance the visibility of their work and contribute more effectively to scientific advancements, particularly in ESD in science education, thereby maximizing the impact of their research within the academic community.

# 3 Most Impactful and Frequently Cited Papers and Journals

## 3.1 Top 10 Most Cited Papers

The data on the top 10 most cited papers is presented in the following table:

**Table 3.** Top 10 Most Cited Papers

| Rank | Author | Paper | Journal | Total Citations | TC per Year | Normalized TC |
|---|---|---|---|---|---|---|
| 1 | Pauw JB. (2015) | The Effectiveness of Education for Sustainable Development | Sustainability | 263 | 26,30 | 2,61 |
| 2 | Uitto A. (2011) | Secondary school students' interests, attitudes and values concerning school science related to environmental issues in Finland | Environmental Education Research | 81 | 5,79 | 1,98 |
| 3 | Mandler D. (2012) | High-school chemistry teaching through environmentally oriented curricula | Chemistry Education Research and Practice | 60 | 4,62 | 2,95 |
| 4 | To Khuyen NT. (2020) | Measuring Teachers' Perceptions to Sustain STEM Education Development | Sustainability | 39 | 7,80 | 1,76 |
| 5 | Fredriksson U. (2020) | A Comparative Study of Curriculums for Education for Sustainable Development (ESD) in Sweden and Japan | Sustainability | 39 | 7,80 | 1,76 |
| 6 | Kilinc A. (2013) | Turkish Student Science Teachers' Conceptions of Sustainable Development: A phenomenography | International Journal of Science Education | 38 | 3,17 | 1,00 |
| 7 | Boeve De Pauw J. (2019) | Effective field trips in nature: the interplay between novelty and learning | Journal of Biological Education | 35 | 5,83 | 1,92 |
| 8 | Malandrakis G. (2019) | An education for sustainable development self-efficacy scale for primary pre-service teachers: construction and validation | The Journal of Environmental Education | 31 | 5,17 | 1,70 |
| 9 | Garner N. (2015) | The Potential of Non-Formal Laboratory Environments for Innovating the Chemistry Curriculum and Promoting Secondary | Sustainability | 28 | 2,80 | 0,28 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | School Level Students Education for Sustainability | | | | |
| 10 | Rico A. (2021) | Integrating Mathematics and Science Teaching in the Context of Education for Sustainable Development: Design and Pilot Implementation of a Teaching-Learning Sequence about Air Quality with Pre-Service Primary Teachers | Sustainability | 25 | 6,25 | 1,87 |

Table 3 presents the top ten results for the analysis period, detailing the most frequently cited authors and their co-authors, the titles of their works, the journals in which these papers were published, publication years, citation counts, and the relative percentage of citations compared to the top ten most cited articles. The ranking includes articles related to ESD in science learning. These articles vary in terms of total citations, annual citations, and normalized citations, reflecting the impact and influence of each study in its field.

The work by Pauw et al. (2015) on the effectiveness of integrated ESD learning has the highest overall impact, with 263 total citations and a normalized TC of 2.61. This data indicates that their research has had a consistent influence, highlighting the importance of raising student awareness of sustainability to maintain environmental preservation while fostering human well-being.

Interestingly, the list emphasizes the significance of ESD in various aspects of education, ranging from environmental-based curricula and hands-on learning methods to enhancing teacher competencies. The focus is on how ESD can inspire students to think critically, understand sustainability issues, and take meaningful actions for a better future. The variation in normalized citation counts suggests that while some studies have had a broad and lasting impact on the field, others may be more specialized or have influenced a narrower research scope.

For instance, the study by Mandler et al. (2012) on reforming the chemistry curriculum to align with real-world issues demonstrated its ability to enhance students' environmental awareness and motivation to learn chemistry. This research has shown a high annual citation rate, reflecting its relevance in academic discussions. On the other hand, more specific research, such as the study by Garner et al. (2015) on chemistry

learning for high school students through visits to non-formal learning environments, has a lower normalized citation count, indicating a stable but less prominent influence over time. This analysis highlights the dynamic nature of educational research and the varying levels of impact that different methodologies and research focuses can have within the academic community.

### 3.2 Most Impactful Journals

Data regarding the most impactful journals is presented in the following table:

**Table 4.** Top 10 Most Impactful Journals

| No | Source | H-index | G-index | M-index | TC |
|---|---|---|---|---|---|
| 1 | Sustainability (Switzerland) | 12[a] | 16[a] | 1,2[a] | 540[a] |
| 2 | Journal of Biological Education | 3 | 3 | 0,5 | 49 |
| 3 | Education Sciences | 2 | 4 | 0,5 | 41 |
| 4 | Environmental Education Research | 2 | 2 | 0,143 | 87 |
| 5 | Journal of Teacher Education for Sustainability | 2 | 2 | 0,118 | 19 |
| 6 | African Journal of Research in Mathematics, Science and Technology Education | 1 | 1 | 0,071 | 1 |
| 7 | Chemistry Education Research and Practice | 1 | 1 | 0,077 | 60 |
| 8 | Cogent Education | 1 | 1 | 0,25 | 21 |
| 9 | Education Research International | 1 | 1 | 0,333 | 10 |
| 10 | Environment, Development and Sustainability | 1 | 2 | 0,333 | 14 |

[a] Top; **TC** = Total citations

Table 4 compares academic journals in science and technology education based on the H-index, G-index, M-index, and total citations (TC). The journal "Sustainability" stands out with the highest total citations (540), far surpassing the other journals. This fact reflects its vast influence and strong recognition within the academic community. It also ranks highest in H-index (12), G-index (16), and M-index (1.2), indicating that "Sustainability" is one of the most influential and widely recognized journals in the academic community. This data demonstrates that its articles are high quality, scientifically relevant, and frequently cited in other research, making it a primary source in sustainability studies.

Meanwhile, the "Journal of Biological Education" follows "Sustainability" in the rankings. The "Journal of Biological Education" has a total citation count of 49, with an H-index of 3, a G-index of 3, and an M-index of 0.5. This data indicates that the "Journal of Biological Education" has a more specific or limited influence within a particular academic community. Various metrics across these journals highlight their different

strengths: some journals have a broad and consistent impact (with high H and G indices). In contrast, others may have a few significant papers contributing substantially to their total citation count (with high TC).

## 4 DISCUSSION

The section highlights specific aspects identified in the corpus of articles collected by the software and analyzed by the researchers. The discussion is significant as it reveals the focus of publications, identifies areas that need improvement for future research and suggests ways to advance the findings of the bibliometric analysis. Bhamra et al. (2011) emphasized that information from the researched field is crucial for future direction and scope to adapt to current conditions. Trends in ESD in science learning have shown a relative increase, although fluctuations were observed from 2008 to 2024, and this growth is expected to continue. This finding aligns with research in renewable energy (Kusumaningrum et al., 2023), water (Imaduddin & Eilks, 2024), and climate change (Solihah et al., 2024).

According to Figure 2, most of the documents were published between 2022 and 2024. In 2022, 14 papers were published, followed by a slight decrease to 12 papers in 2023, but the number increased again to 14 papers in 2024. Further investigation revealed several contributing factors to the high number of documents in this period, including the post-COVID-19 pandemic, the urgent sustainability issues that need addressing, and technological changes, all linked to ESD in science learning.

In addition to influencing the number of publications, this also impacts countries and affiliations. The country with the highest number of publications in ESD within science education is Indonesia (56 documents), while the leading institution is Universitas Pendidikan Indonesia (29 documents). Prominent researchers from Indonesia in ESD in science learning include Robby Zidny (3 papers), Eko Hariyono (2 papers), Ida Kaniawati (2 papers), Heru Kuswanto (2 papers), and Madlazim (2 papers). Their research is typically published in reputable journals indexed in Scopus, particularly in Q-1 journals (e.g., Zidny et al., 2021).

Research in the field of ESD in science learning has rapidly expanded and spread to various countries, including Finland, Taiwan, and many other countries. This expansion indicates that ESD in science learning, which may have initially been concentrated in a few countries or academic communities, is now gaining global attention.

As more countries become involved in the research, each region can contribute uniquely based on its educational, cultural, and policy contexts through cooperative collaboration.

International collaboration among countries, institutional affiliations, and researchers is crucial in advancing knowledge in this field, as they form a global network that supports each other and produces high-quality research (e.g., Fiel'ardh et al., 2023; Zidny & Eilks, 2022). The growth of international collaboration results in more influential publications and encourages the application of findings in classrooms worldwide, leading to broader and more significant impacts on education and learning.

The top 10 journals publishing the most on ESD in science education are presented in Figure 5. One of the top journals publishing works on ESD in science learning is "Sustainability," indexed in Scopus (Q-1) and WoS. However, articles published in journals with the highest publication volume are the most cited. This fact is evidenced by the work of Pauw et al. (2015), which has the highest citation count (263 citations). Following this, "Sustainability" is the most impressive journal in ESD in science learning, with an H-index of 12. According to Costas & Bordons (2007) and Roldan-Valadez et al. (2019), the H-index is among the most influential journal indicators of global publications. Therefore, it is essential to consider the H-index and journal indexing when submitting and publishing papers.

## 5 CONCLUSION

In this study, we conducted a bibliometric analysis to investigate scientific production in ESD in science learning based on PRISMA principles. We aimed to identify how production relates to the research topics of ESD in science learning. The articles analyzed were published in peer-reviewed journals and sourced from the Scopus database. Research on ESD in science learning has seen significant growth and influence over the last two decades, as evidenced by the increasing number of publications and citations in the field. Ongoing interest is reflected in the active collaboration among researchers, both domestically and internationally. Indonesia is the most productive country in terms of publications (n = 56) during the period 2008–2024. Universitas Pendidikan Indonesia is the leading affiliation, contributing the highest number of publications (n = 29). Meanwhile, Eilks, I. (n = 6) is the most contributing author. Additionally, the analysis of leading authors and journals reveals a concentrated yet

dynamic research community that continues to advance the field of ESD in science learning.

Future research could address these limitations by including broader databases and incorporating qualitative studies such as Systematic Literature Reviews (SLR) and quantitative studies such as meta-analyses on integrated ESD learning in other fields of study. In line with the synthesis conducted by UNESCO (2017) on the eight key competencies of ESD, future studies could explore and develop how ESD learning can enhance these key competencies in students. Furthermore, more detailed investigations into the dynamics of international collaboration, especially in underrepresented regions and institutions, are needed. Expanding thematic analysis to include new concepts and interdisciplinary approaches will also be crucial to capture the full scope of the evolving field of ESD. Finally, longitudinal studies examining the long-term impact of publications and significant methodologies could provide deeper insights into the factors driving ESD.

## 6 LIMITATION

Although this study demonstrates growth and strong collaboration in ESD, some limitations could be improved. The analysis is based solely on data extracted from the Scopus database, which may only represent a small fraction of relevant publications from publishers not listed there. Additionally, the focus on quantitative metrics such as citations and publication count may overlook the qualitative impact of the research.

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