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Trends and Research Opportunities of Integration ESD and STEM in Science Education: A Bibliometric Analysis

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ABSTRACT

Rapid changes of the 21st century require education to develop essential skills, sustainability literacy, and complex problem-solving abilities. However, many studies indicate that students' competencies remain low, particularly in environmental awareness, critical thinking, and problem-solving. This condition highlights the need for innovation in science learning that is more relevant to global challenges. Therefore, integrating STEM (Science, Technology, Engineering, and Mathematics) with Education for Sustainable Development (ESD) has become an important approach to improving the quality of learning. This study aims to map research trends and opportunities related to ESD-STEM integration through bibliometric analysis. Data were collected from Scopus-indexed articles published between 2015 and 2025 and analyzed using VOSviewer, including publication performance, co-authorship, keyword occurrence, and thematic mapping analyses. The results show a significant increase in publications, particularly since 2020, focusing on STEM, sustainability, and pedagogical innovation. The dominant subject areas include social sciences, computer science, and engineering, with major contributions from the United States, Indonesia, and Malaysia. These findings confirm that ESD-STEM integration promotes interdisciplinary, contextual, and sustainability-oriented learning, while opening opportunities for future research.

INTRODUCTION

The twenty first century is a period marked by significant changes, often referred to as the modern or digital era, characterized by rapid developments in technology, globalization, social change, and science. In this era, everything has become open and interconnected among communities and nations, commonly referred to as the era of openness or globalization (Wijaya et al., 2016). These changes have also impacted the field of education, which must adapt to the demands of the times. The rapid development of technology and globalization has driven the need for innovation in education to support the advancement of knowledge. Moreover, this era is often referred to as the knowledge age, as nearly all aspects of life depend on knowledge (Wijaya et al., 2016). Therefore, through education, students are expected to develop their knowledge and skills in order to be prepared to face challenges and to explore their potential in this modern era.

New standards need to be designed so that students possess competencies aligned with the demands of the 21st century, namely education based on science and technology (Utami & Emiliannur, 2025). The P21 framework emphasizes the mastery of skills, knowledge, and abilities in the fields of technology, media, information, innovation, as well as life and career skills (Wijaya et al., 2016). 21st-century learning must also encourage students to seek information from various sources, formulate problems, think critically and analytically, and collaborate in problem-solving (Litbang Kemdikbud, 2013). Essential competencies include personalization, collaboration, communication, informal learning, productivity, and content creation (Zubaidah, 2016; Binkley et al., 2012). In addition, the use of technology is necessary to keep pace with the development of the times, with core skills based on the 4Cs: critical thinking, creative and innovative thinking, communication, and collaboration (Redhana, 2019; Rosnaeni, 2021).

In the 21st century, humans face increasingly complex and diverse challenges, making education a primary focus in addressing them. Therefore, the education sector needs to adapt and align with the needs of modern society. Sustainable education becomes key in shaping students who are capable of facing these challenges, making sustainability values important to be implemented in the learning system (Nugraha, 2019). Along with changes in societal dynamics, the educational paradigm must also shift toward lifelong learning processes integrated into daily life (Ansyar, 2015). In addition, sustainable learning focuses on developing skills relevant to future needs, such as creativity, digital literacy, and technological expertise. Thus, sustainable education helps individuals continuously develop skills in accordance with the ever-changing demands of the workforce (Simanjutak, 2019).

In addition to technical skills, students also need to emphasize character development and social responsibility in 21st-century learning. In facing various challenges, students must be equipped with emotional skills, leadership, and strong ethics. 21st-century learning must also instill environmental awareness as an essential part of education. Sustainability values help students understand environmental changes and their future impacts. Amid issues such as climate change and global warming, this type of learning can foster awareness and responsibility toward the environment. Thus, students are expected to manage resources wisely and actively participate in environmental conservation (Jaya et al., 2023).

The integration of innovative learning is an important step in improving the quality of education in the modern era through creative approaches, active methods, and the use of technology. This type of learning can increase student motivation and engagement by employing varied strategies such as discussions, projects, and interactive media (Sanjaya, 2016). Furthermore, innovative learning is expected to accommodate developments in learning theories as well as advances in information and communication technology in the digital era (Raniyah, et al, 2024). This strategy also encourages students to actively participate and develop independence in learning. As a result, the classroom atmosphere becomes more engaging and less monotonous. The integration of innovative learning also allows students to construct their own understanding of concepts through various independent interpretations (Raniyah et al., 2024).

The standards of 21st-century learning are expected to help students develop skills to face increasingly complex challenges, understand sustainability issues, and improve problem-solving abilities and environmental awareness. However, in reality, the implementation has not been optimal, resulting in low student readiness to face global challenges. This is supported by the study of Hartono et al. (2022), which shows that Indonesian students' abilities in global competence, particularly related to actions for collective well-being and sustainable development, remain low. Cognitive test results indicate that the percentage of correct answers among Indonesian students is below the OECD average and does not exceed 30%. These findings also show that students' understanding of sustainability issues is still limited (Hartono et al., 2022). Overall, these results indicate that Indonesian students' global competence is still low due to a lack of awareness and concern for global issues (Hartono et al., 2022).

In addition to students' low understanding of global sustainability issues, real conditions also show that students' problem-solving abilities remain low. This is consistent with the study by Suryani et al. (2020), which indicates that several indicators of students' problem-solving abilities are still in the low category. In the second, third, and fourth indicators, the percentage of students' abilities remains above 50%, indicating that problem-solving skills are not yet optimal. These results suggest that students still experience difficulties in solving problems systematically. Students' mathematical problem-solving abilities require serious attention, as research results indicate that these abilities are still low. Specifically, the main weakness is seen in the indicator of selecting and applying strategies to solve problems (Suryani et al., 2020).

Environmental awareness is crucial for addressing 21st-century challenges, particularly those related to climate change, global warming, and environmental degradation that affect the sustainability of the planet. This awareness is important to ensure that natural resources are preserved and that future environmental problems can be anticipated. However, in reality, students' environmental awareness is still relatively low. This is supported by a study by Widianingsih et al. (2017) conducted in a public senior high school in Sukoharjo, which found that students' environmental literacy remains low. This low literacy is reflected in three aspects: knowledge, attitudes, and students' concern for the environment. This condition is caused by a lack of student interest in understanding and caring about environmental issues in their surroundings (Widianingsih et al., 2017).

Science education in the 21st century is not only focused on mastering concepts but also on students' ability to face global challenges such as climate change, energy crises, and environmental degradation. The education system must move away from conventional methods and adopt strategies that promote active participation, meaningful engagement, and contextual understanding (Asrizal et al., 2022). Therefore, a learning approach that integrates Education for Sustainable Development (ESD) and STEM (Science, Technology, Engineering, and Mathematics) is needed (UNESCO, 2017). ESD is an educational approach that equips students with the knowledge, skills, values, and attitudes necessary to support sustainable development (UNESCO, 2017). It also emphasizes the integration of sustainability principles, including environmental, economic, social, and cultural dimensions (Rahmadhani et al., 2015). Meanwhile, STEM integrates science, technology, engineering, and mathematics in solving real-world problems (Bybee, 2013). The integration of both approaches enables students to understand scientific concepts while also applying them in the context of sustainability.

The integration of ESD-STEM in science learning emphasizes contextual problems, interdisciplinary approaches, project-based learning, and responsible decision-making. This approach can also enhance critical thinking skills, creativity, and awareness of sustainability issues (Wals & Benavot, 2017). STEM learning is able to train students to solve complex problems (Izzah et al., 2021). In practice, this integration helps students connect scientific concepts with real-life problems in their surrounding environment. In addition, learning becomes more meaningful because students are directly involved in the problem-solving process. This also encourages students to be more active and responsible in the learning process.

ESD and STEM are two highly relevant approaches for addressing 21st-century challenges. STEM combines science, technology, engineering, and mathematics to help students master concepts and problem-solving skills. Meanwhile, ESD emphasizes the importance of awareness of global issues and environmental sustainability. Both complement each other in developing student competencies that are not only academically strong but also environmentally responsible. Through the implementation of this integration, students are expected to be able to face increasingly complex global challenges.

Science education plays an important role as the primary foundation in the STEM approach. Without science education, understanding Science, Technology, Engineering, and Mathematics would be less meaningful. In addition, science education also supports the implementation of ESD principles in learning. Many studies show that science is often used as a context in the integration of ESD and STEM. This indicates that science education holds a strategic position in the development of sustainable learning.

Research on the integration of STEM and ESD in science education plays an important role in developing contextual and sustainable scientific literacy. Such research can map trends, methodologies, and key focuses in the field while also identifying research gaps that have not been widely explored. Thus, the findings can serve as a basis for developing more effective curricula and learning strategies. The purpose of this study is to analyze publication trends, identify new research opportunities, and provide guidance for the development of science education. The results are expected to support more innovative and sustainability-oriented 21st-century learning.

METHODS

This study applies a bibliometric analysis method, which is a quantitative approach used to describe, evaluate, and monitor scientific publications. This approach allows for more objective and transparent results and helps reduce bias that often arises in qualitative methods (Zupic & Čater, 2015). It is quantitative and structured in nature, enabling an objective analysis of the related literature. Through this method, patterns of collaboration, keyword distribution, and the development of scientific publications within the studied topic can be identified.

The data for this study were obtained from the Scopus database, which was selected as the primary source due to its broad coverage of internationally reputable scientific journals. The search process was conducted by filtering articles published between 2015 and 2025. The data were then limited to specific document types, such as journal articles, conference papers, conference reviews, and review articles. Subsequently, a systematic selection process was carried out to ensure relevance to the research topic and the quality of the analyzed data.

The keywords were carefully determined to ensure that the retrieved literature aligned with the research topic. In the search process, combinations of terms such as STEM and education for sustainable development were used. The search utilized the Boolean operator AND to expand or narrow the scope of results as needed. The keywords were strategically selected to ensure that the collected articles reflected the relationship between STEM and the goals of sustainable education.

This study followed systematic steps to ensure clarity in the analysis process. The procedure was conducted through five stages as proposed by Irawan et al. (2024). The initial stage involved data collection from the Scopus database, followed by article selection based on inclusion criteria. This was followed by data processing, bibliometric analysis, visualization of results, and interpretation of findings. Each stage was designed to produce valid findings consistent with the research focus. This process ensured that only relevant articles meeting scientific standards were analyzed. The research framework is presented in the form of a diagram to facilitate understanding of the workflow through visual representation.

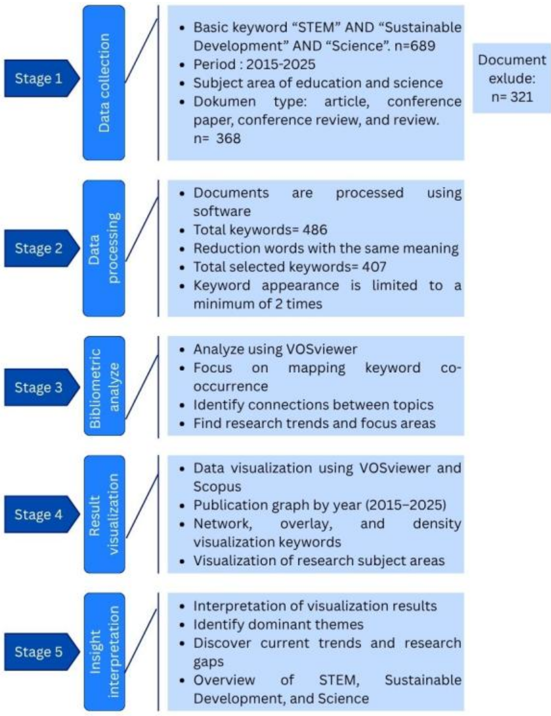

Figure 1. Steps in the Bibliometric Analysis Research

This study utilized several software tools to ensure valid and accurate data visualization. The collected data were processed using Microsoft Excel and Notepad. This stage included the process of keyword simplification, which involved merging keywords with the same meaning but different spellings. Data visualization and interpretation were then carried out using VOSviewer. This software was selected because it can produce interactive displays and clear, easy-to-understand visualizations. The results generated through VOSviewer serve as the basis for interpreting trends and patterns in the analyzed literature data.

The data analysis was conducted starting with processing the data obtained from Scopus. The next stage involved importing the data into VOSviewer for analysis based on keyword occurrences and the relationships between documents. The results were then visualized in several forms, including network visualization, overlay visualization, and density visualization, which were used to explain the visual findings. Visualization results, such as research trend developments and subject areas, were derived from the analysis of data obtained from Scopus.

RESULTS AND DISCUSSION

Results

Trends and Publications Related to ESD and STEM

Bibliometric analysis has become an important approach for mapping publication patterns, research collaboration, and the distribution of emerging topics in this field. Through this approach, it is possible to identify the contributions of countries, institutions, and authors that play a dominant role in advancing studies on STEM and sustainable development. Therefore, the results of this analysis are expected to provide a comprehensive overview of research directions and dynamics as a basis for further study development.

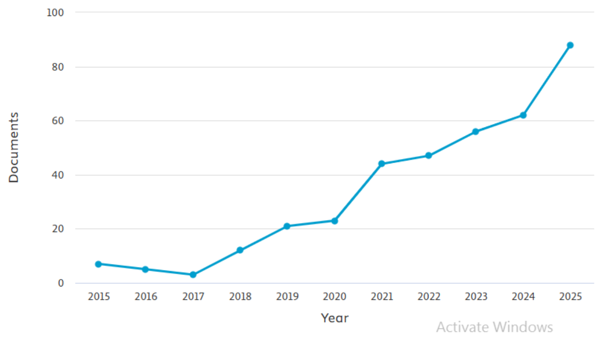

Figure 2. Publication Trends Related to ESD and STEM from 2015 to 2025

The figure above shows publication trends related to ESD and STEM. From the figure, it can be observed that the line graph illustrates the development of the number of documents based on the analyzed keywords from 2015 to 2025, showing an overall increasing trend. In the early period of 2015, the number of documents was relatively low and tended to be stable, even experiencing a slight decline around 2017. However, starting in 2018, there was a significant increase, reaching its highest peak in 2025. This pattern indicates that research on this topic has become increasingly intensive over time.

Results of the Analysis Based on Subject Area

The distribution of subject areas in bibliometric analysis provides an overview of the range of disciplines involved in a particular research topic. Through this analysis, it is possible to identify the most dominant fields of study as well as the relative contributions of each discipline in shaping the research landscape. In addition, this distribution reflects the level of integration and interdisciplinary trends that evolve over time.

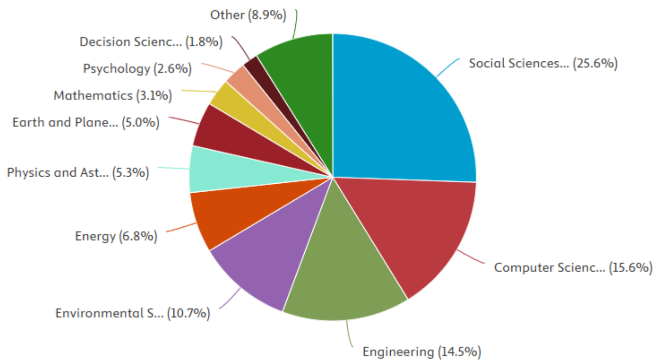

Figure 3. Analysis Based on Subject Area Distributions

Figure 3 shows a pie chart illustrating the distribution of subject areas based on the percentage contribution of documents. It can be seen that Social Sciences dominate with the largest proportion at 25.6%, followed by Computer Science at 15.6% and Engineering at 14.5%. Meanwhile, other fields such as Environmental Science, Energy, Physics, Mathematics, and others contribute smaller yet still significant proportions. This distribution indicates that research or document production is more focused on social and technological issues. It also reflects that research interest and trends are predominantly concentrated in the social and technological fields.

Results of the Analysis Based on Country Distribution

In bibliometric studies, countries provide an overview of the geographical contributions to the development of a research field. Through this approach, it is possible to identify the most productive countries and reveal patterns of international collaboration that reflect the level of interconnectedness among researchers across different regions. Therefore, the distribution of countries serves as an important indicator for understanding the dissemination of knowledge and the potential for future global collaboration.

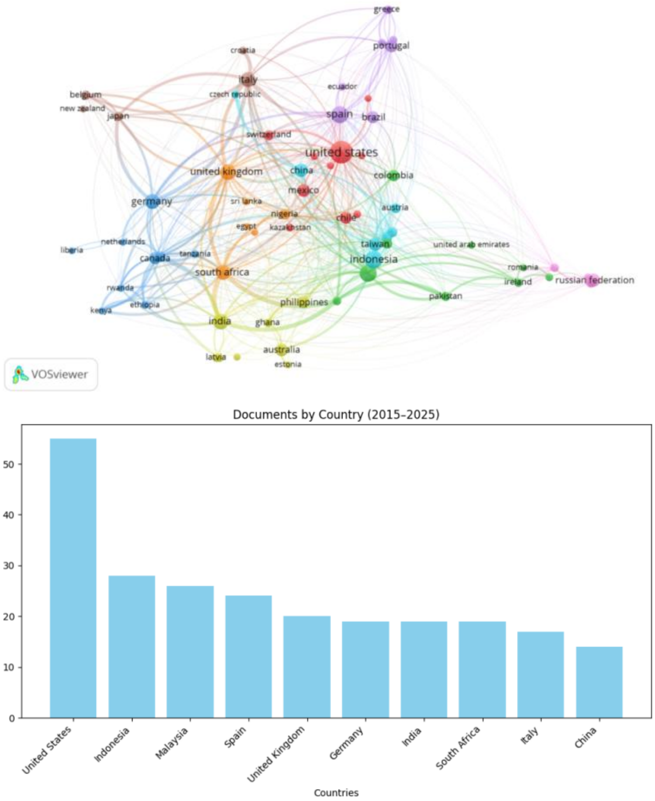

Figure 4. Analysis Based on Country Distribution

From the data obtained from Scopus and the visualization generated using VOSviewer, it can be observed that research trends have developed significantly across various countries. The figure shows that research on STEM and sustainable development is most extensively conducted in the United States, Indonesia, and Malaysia. Indonesia is among the countries with a high level of research activity in this area. This also indicates that this topic is frequently addressed by researchers in Indonesia.

Results of Network Visualization Analysis

Network visualization–based analysis in bibliometric studies provides a visual representation of the relationships and interconnections among research elements, such as authors, keywords, and institutions. Through this approach, patterns of collaboration, topic clusters, and the intellectual structure of a field can be identified more clearly and systematically, and it also enables researchers to understand the strength of relationships and the central position of specific topics within research trends.

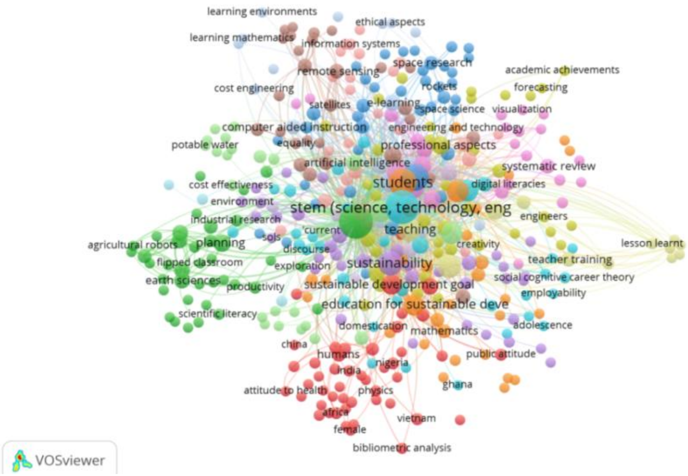

Figure 5. Analysis Based on Network Visualization

In the presented visualization, each node represents a keyword, and the links between keywords indicate co-occurrence relationships. The colors shown in the figure represent clusters that group related topics. This network map illustrates the identification of dominant research themes and emerging directions within the field. Based on the bibliometric analysis in Figure 5, the most frequently occurring keyword is "STEM," indicating that this topic serves as the main focus of the research. In addition, the presence of other keywords such as "sustainability," "sustainable development goals," and "education for sustainable development" shows a strong interconnection among these concepts. Other keywords such as "digital literacies," "teaching," "student," "e-learning," "creativity," and "artificial intelligence" further add complexity to the thematic network in this research mapping.

Results of Overlay Visualization Analysis

Overlay visualization–based analysis of subject area distribution in bibliometric studies provides a dynamic overview of the temporal development of various scientific disciplines. This approach enables the identification of fields that developed earlier as well as those that have more recently emerged, based on color intensity and publication time. Therefore, overlay visualization analysis is important for understanding the evolution of topics and the direction of research development in a more comprehensive manner.

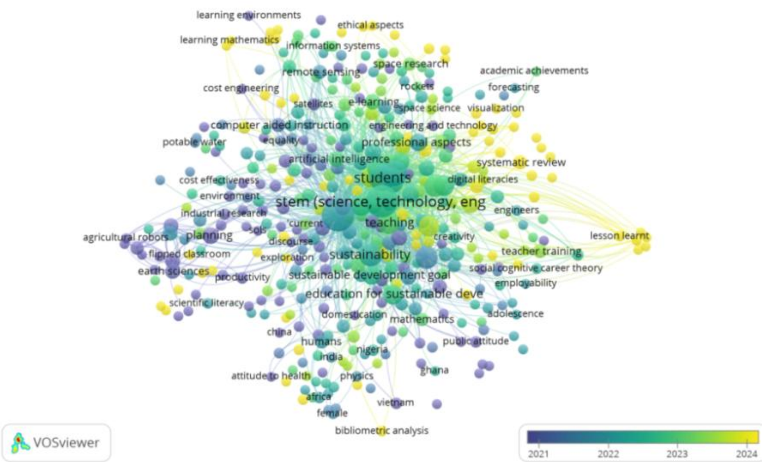

Figure 6. Analysis Based on Overlay Visualization

The overlay visualization generated using VOSviewer illustrates the temporal development of research related to STEM and sustainability from 2021 to 2024. The node colors represent the year of publication, where a gradient from blue to yellow indicates more recent studies. It can be observed that "STEM" remains the central node within the network and has strong connections with "sustainability" and "education for sustainable development". This indicates that the integration of STEM and sustainability continues to evolve and remains a key focus in recent research. In addition, the emergence of terms such as "digital literacies," "systematic review" and "teacher training," displayed in lighter colors, suggests new trends that have gained increasing attention in recent years.

Results of Density Visualization Analysis

Density visualization–based analysis in bibliometric studies provides an overview of the density and intensity of occurrence of research elements, such as keywords or specific topics. Through this approach, areas with high concentration can be identified as the main focus in research development. This visualization also helps distinguish between well-studied topics and those that still offer opportunities for further exploration.

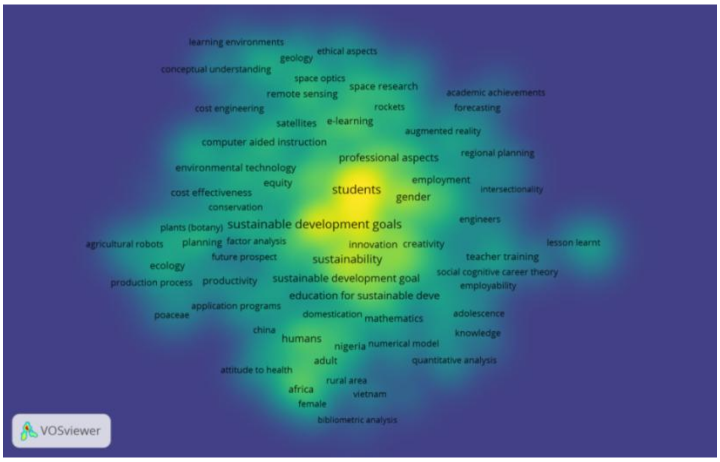

Figure 7. Analysis Based on Density Visualization

The density visualization generated using VOSviewer illustrates the level of density and co-occurrence of keywords in research on STEM and sustainability. Areas highlighted in bright yellow indicate the most frequently occurring and strongly connected topics, namely "students," "sustainable development goals," and "sustainability." This suggests that the main focus of the research lies in the role of students within STEM-based education integrated with sustainable development goals. In addition, the presence of terms such as "innovation," "creativity," and "education for sustainable development" around the central dense area indicates that the STEM approach is being used to foster innovation in addressing sustainability issues. Areas with medium to low density (green to blue colors) represent supporting topics such as "environmental technology," "engineering," "teacher training," and "employability," which still contribute to the broader STEM and sustainability research ecosystem.

Discussion

Figure 2 shows an increase in the number of documents, reflecting the growth of research interest and the development of knowledge (Aria & Cuccurullo, 2017). The sharp rise during 2020–2025 can be interpreted as the impact of increasing publication demands in the digital era. Advances in information technology and easier access to publication platforms have also significantly contributed to the growth in document numbers. This trend indicates not only an increase in quantity but also greater collaboration and productivity, particularly in academic and professional sectors. This is in line with the view that digital transformation accelerates the global production and distribution of knowledge (Sachs, 2015).

The analysis presented in Figure 3 shows that document production is focused on global and technological issues. This pattern reflects research priorities influenced by societal needs and technological developments (Waltman et al., 2010). The presence of fields with small proportions such as psychology, decision sciences, and earth sciences indicates the diversity of research topics. The dominance of social sciences, computer science, and engineering suggests increasing attention to societal issues alongside rapid digital transformation. This is in line with the importance of integrating technology and social aspects in addressing modern global challenges (Castells, 2010).

From Figure 4 shows the dominance of the United States in publications, reflecting strong research capacity and support for the integration of ESD and STEM, which aligns with findings that developed countries tend to lead innovation in sustainability- and technology-based education (Bybee, 2013). The high contributions of Indonesia and Malaysia indicate growing attention from developing countries to sustainable education in achieving the SDGs (UNESCO, 2017). This distribution suggests that the integration of ESD and STEM is a global trend emerging across various regions. The distribution of publications across countries also reflects collaboration networks and research focus within a field (Aria & Cuccurullo, 2017). Therefore, differences in publication output reflect not only research capacity but also educational policy priorities and investment in sustainability-based education.

Figure 5 shows the keyword “STEM” positioned at the center and directly connected to “sustainability” and “education for sustainable development”. This indicates that STEM research has been integrated with sustainable development efforts. STEM education plays a strategic role in supporting the achievement of sustainable development goals by enhancing science and technology literacy (UNESCO, 2020). Its connection with subtopics such as “scientific literacy”, “environment”, and “sustainable development goals” reflects a holistic approach to global issues. Thus, STEM not only improves academic skills but also prepares learners to face sustainability challenges (Bybee, 2010).

Figure 6 shows the development of STEM integration with sustainable development principles to address global challenges (UNESCO, 2017). This visualization emphasizes that sustainability has become a core element in various modern educational approaches. The connection between “sustainability”, “students”, and “teaching” indicates that STEM learning is directed toward environmental awareness and contextual problem-solving. The emergence of terms such as “employability”, “creativity”, and “engineering and technology” highlights an orientation toward workforce readiness and sustainability. This is consistent with the importance of linking learning to real-world problems and 21st-century competencies (Bybee, 2013; National Research Council, 2012). Thus, the overlay map shows a research trend toward stronger integration between STEM and sustainability, with an emphasis on educational innovation and the development of 21st-century competencies.

Based on the analysis in Figure 7, the dominance of keywords related to “sustainability” and “sustainable development goals” indicates that current educational research is increasingly directed toward supporting the global development agenda (UNESCO, 2017). The high density of the keyword “students” also emphasizes that learners are at the center of STEM-based and sustainability-oriented learning processes (Bybee, 2013). Meanwhile, the presence of keywords such as “innovation” and “augmented reality” reflects the integration of technology in enhancing the quality of learning (Zollman, 2012). The lower density observed in several topics suggests that these areas still offer opportunities for further development. This pattern also indicates an imbalance in research focus, where certain topics are more dominant than others. Therefore, a more balanced exploration is needed to ensure that the development of STEM and sustainability-based education can progress in a comprehensive manner (Sanders, 2009).

CONCLUSION

Bibliometric analysis shows that research on the integration of ESD and STEM in science education experienced significant growth from 2015 to 2025, with the sharpest increase occurring between 2020 and 2025, indicating rising research interest and productivity. STEM emerges as the main focus closely associated with sustainability and education for sustainable development, supported by concepts such as digital literacies, creativity, and problem solving. The distribution of subject areas shows the dominance of social sciences, computer science, and engineering, reflecting a balance between social issues and technological advancement. Geographical analysis reveals the greatest contributions from the United States, Indonesia, and Malaysia, while also highlighting the potential for international collaboration. Network and density visualizations emphasize the roles of students, sustainable development goals, and pedagogical innovation as central focuses. These findings confirm that the integration of ESD and STEM promotes innovative, contextual, interdisciplinary, and sustainability-oriented science learning.

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