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Education for Sustainable Development in Science Classrooms: A Bibliometric Analysis and Literature Review

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a b s t r a c t

Education for sustainable development is an intriguing and evolving topic. There is a potential to integrate sustainable education with science education as both share aligned goals and can mutually support each other. Therefore, this article aims to visualize research trends on sustainable education in science classrooms over five years (2019-2023) to explore new potential research innovations in the related field and identify strategies that can be applied to integrate sustainable values into science education. Data were obtained from one of the most significant publication sources, Scopus, resulting in 134 research articles. The data were processed using two methods, namely bibliometric analysis and systematic literature review, assisted by VOSviewer software and Microsoft Excel 2016. The analysis indicates a consistent upward trend in research on this topic, reaching 45 publications in 2022 and declining to 36 in 2023. Additionally, seven clusters were identified from the visualization map, each containing 2-8 keywords. On the other hand, the analysis in the systematic literature review reports that there are five strategies to incorporate sustainable education into science classrooms.

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1. Introduction

Quality education occupies the fourth position among the seventeen Sustainable Development Goals formulated by the United Nations to shape the ideal global community. Education, besides being a primary goal of sustainability, is also believed to be the key to achieving other sustainable goals, as individuals with sustainable knowledge, awareness, actions, attitudes, and behaviors are more likely to bring about positive changes through decision-making based on sustainability values (UNESCO, 2018; Valenci, 2018; Widodo et al., 2023). Therefore, quality education and education for sustainable development have a close parallel relationship, to integrate quality education into sustainable education and vice versa—to ensure that the knowledge, skills, and values needed by society are passed on to future generations through lifelong learning (Ferguson, 2019; Kioupi & Voulvoulis, 2019; Lestari et al., 2023; Scherak & Rieckmann, 2020; UNESCO, 2018).

Although the concept of sustainability had gained popularity internationally several years before it was publicly introduced, the framework of education for sustainable development was officially introduced in 1992 at the Rio de Janeiro conference held by the United Nations and promoted its goals and agenda in 2002 (Nuwangi et al., 2023; Scherak & Rieckmann, 2020; Valenci, 2018; Warlenius, 2022). Education for sustainable development is seen as a path to fundamentally changing the future, not only by altering human perspectives on various issues but also by encouraging the emergence of solution-oriented actions to address various challenges, with the ambition of empowering the next generation to be problem-solvers and agents of change within their communities (Ferguson, 2019; Scherak & Rieckmann, 2020; Wiek et al., 2011). In achieving this, education for sustainable development fosters the competencies individuals need to thrive in potentially adverse future conditions, known as key sustainability competencies (Tristananda, 2018; UNESCO, 2017; Wiek et al., 2011).

Eight key sustainability competencies need to be cultivated within an individual: systems-thinking competency, anticipatory competency, normative competency, strategic competency, collaboration competency, critical thinking competency, self-awareness competency, and integrating problem-solving competency (UNESCO, 2017, 2018; Wiek et al., 2011). As evidence of the mutual support between education for sustainable development and quality education, these eight key competencies can be categorized into three domains of learning: system-thinking competency, anticipatory competency, normative competency, and critical thinking competency in the cognitive domain; collaboration and self-awareness in the socio-emotional domain; and strategic competency and integrated problem-solving competency in the behavioral domain (UNESCO, 2017; Vilmala et al., 2022).

Arising from human concerns about uncertainty due to environmental changes affecting various sectors of life, and balanced with hopes of improving future life quality, education for sustainable development focuses on three main supporting pillars: environmental, sociocultural, and economic (Nuwangi et al., 2023; Ojala, 2017; UNESCO, 2018). This distinguishes education for sustainable development from environmental education, as it emphasizes holistic integration across scientific fields, achievable through interdisciplinary, multidisciplinary, and transdisciplinary approaches, ensuring that learning extends beyond environmental issues alone (Lorenz et al., 2022; Nuwangi, 2022; Nuwangi et al., 2023; Widodo et al., 2023).

Moreover, science education aims to produce scientists, engineers, technologists, and other professionals who require a strong science background in the future. It emphasizes to students that science is one of the fundamental disciplines needed in society (Taber, 2017). Therefore, science education needs to be meaningful and directed toward sustainability to prepare generations aware of critical global issues, equipping them with skills to solve problems both personally and within their environment, through designing, developing, and communicating solutions (Vilmala et al., 2022). Science education materials typically have contexts closely related to the seventeen sustainable development goals. Integrating education for sustainable development into science education is a great way to promote both simultaneously.

Unfortunately, teachers still fail to understand the potential of integrating these two fields or are hesitant to start due to confusion about initial steps, resulting in the limited widespread adoption of education for sustainable development in educational institutions or within science education in classrooms (Vilmala et al., 2022; Widodo et al., 2023). Two main obstacles faced by teachers can explain this. One, teachers are unfamiliar with education for sustainable development approaches. It leads them to prefer familiar approaches, which may not be suitable for the taught content. Two, teachers are confused about understanding education for sustainable development content, even the overall concept of SDGs, leading them to focus solely on the environmental aspect and neglect the economic and socio-cultural aspects. From the students' perspective, the greatest barrier lies in the lack of motivation to take concrete sustainability actions after learning and the occurrence of biases toward learning (Ssosssé et al., 2021). Therefore, future research is suggested to focus on the effectiveness of teaching methods used to implement education for sustainable development in classrooms (Riess et al., 2022; Ssosssé et al., 2021).

To bridge the gap between goals and learning outcomes identified during efforts to integrate sustainable values into science subjects, as previously outlined, and to enrich the reference sources for both academics and field practitioners, this research is conducted by mapping trends in scientific studies on education for sustainable development integrated into science education over the past five years (2019—2023). Based on this urgency, the main objectives of this research are: 1) to describe the current conditions and patterns of previous research; and 2) to elaborate on information about several strategies believed to be effective in combining education for sustainable development and science education taught in classrooms. Hope the results of this research will inspire, especially for educators who contribute actively during learning activities.

2. Method

This research was conducted using the literature mapping analysis method, bibliometric analysis, and a systematic literature review, through secondary data sources obtained from the research archive provider website Scopus (https://www.scopus.com). Bibliometric analysis is a process of analyzing publications using mathematical or statistical approaches to identify distributions, patterns, and research developments in a specific field of study, which can also describe its impact, wherein its operation involves seeking relationships among various unique keywords (Indriyanti et al., 2023; Kurdi & Kurdi, 2021; Yani & Soebagyo, 2023). Bibliometric analysis visualizes the interconnection of research concepts, where gaps found among these keywords can be used to innovate future studies (Astuti et al., 2023). Meanwhile, a literature review is the basis for expanding knowledge efforts to formulate new ideas based on existing findings, considering implications, limitations, suggestions, directions for future research, and scientific advancements (Perwitasari et al., 2023).

Bibliometric analysis in this research followed five stages developed by Tranfield in 2003, namely keyword determination, keyword search, refinement of initial search results, compilation of statistical data, and data analysis (Indriyanti et al., 2023; Lestari et al., 2023). The keywords used to limit the search for publication documents were "education for sustainable development" or "ESD"; "science education"; "classroom"; and "student." After applying filters such as 1) research articles only; 2) excluding literature or bibliometric study articles; 3) open access; 4) written in English; and 5) published from 2019 to 2023, the search yielded 133 documents. This data was then downloaded in .csv format. The processing of search results data was assisted by Microsoft Excel 2016 and VOSviewer software. The visual mapping produced by VOSviewer was downloaded for analysis. Furthermore, the collection of article data in Microsoft Excel used in VOSviewer was systematically filtered based on title, abstract, and overall context to obtain relevant research on the application of sustainable education in science education classrooms before synthesis. Meanwhile, a systematic literature review comprises five stages, as shown in Figure 1.

Figure 1. Systematic Literature Review Research Stages
(Day et al., 2018)

The first stage, which is the formulation of research questions, includes two research questions: 1) What are effective strategies for integrating education for sustainable development into science education, particularly in the classroom?; and 2) What are the advantages of these effective strategies? Subsequently, in the next stage, which is the determination of literature sources, only one literature source was used, namely Scopus, with the input of keywords and a filtering system as described in the bibliometric method section. Out of the 133 articles obtained, article selection and evaluation were conducted through three stages: elimination based on title and abstract (resulting in 57 articles), elimination based on general topic relevance of the articles (resulting in 40 articles), and elimination based on article substance suitability (resulting in 10 articles). The three stages of selection and evaluation left 10 articles considered suitable according to all research criteria, which were then analyzed individually to extract the core elements of the articles needed for the synthesis stage. The synthesis stage proceeded concurrently with the results compilation stage, thus building new comprehensive information from the organized pieces of information grouped based on conceptual similarities.

3. Result and Discussion

Research Trend

Based on the bibliometric analysis, ten articles with the highest citations or frequently cited in other research were identified. These ten articles can be seen in Table 1. Articles with the highest citations are predominantly from 2020, and most are from the Sustainability journal (published by MDPI). The article with the highest citation, "Toward sustainable learning during school suspension: Socioeconomic, occupational aspirations, and learning behavior of Vietnamese students during COVID-19," was written by Tran et al. (2020). This article discusses the attitudes of Vietnamese students across compulsory education levels while studying at home during the pandemic. It identifies differences in learning behaviors based on socio-economic status, type of school (public and private), and students' interest for careers in STEM and non-STEM fields.

Table 1. 10 Articles with the highest citations

Author(s)	Title	Journal	Citations
Tran et al. (2020)	Toward sustainable learning during school suspension: Socioeconomic, occupational aspirations, and learning behavior of Vietnamese students during COVID-19	Sustainability, 12(10)	64
González-Zamar et al. (2020)	Managing ICT for sustainable education: Research analysis in the context of higher education	Sustainability, 12(19)	46
Bucea-Manea-Ţoniş et al. (2020)	Sustainability in higher education: The relationship between work-life balance and XR e-learning facilities	Sustainability, 12(14)	43
Howell (2021)	Engaging students in education for sustainable development: The benefits of active learning, reflective practices and flipped classroom pedagogies	Journal of Cleaner Production, 325	38
Sund & Gericke (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)	32
Hsiao & Su (2021)	A study on the impact of STEAM education for sustainable development courses and its effects on student motivation and learning	Sustainability, 13(7)	31
Pocol et al. (2022)	Knowledge Co-creation and Sustainable Education in the Labor Market-Driven University–Business	Frontiers in Environmental	31

Author(s)	Title	Journal	Citations
	Environment	Science, 10	
Filter et al. (2020)	Virtual Reality Nature Experiences Involving Wolves on YouTube: Presence, Emotions, and Attitudes in Immersive and Nonimmersive Settings	Sustainability, 12(9)	30
Pardo-Garcia & Barac (2020)	Promoting employability in higher education: A case study on boosting entrepreneurship skills	Sustainability, 12(10)	27
Manasia et al. (2020)	Pre-service teacher preparedness for fostering education for sustainable development: An empirical analysis of central dimensions of teaching readiness	Sustainability, 12(1)	26

Meanwhile, from Figure 2, we can observe the trend in publication rates of articles regarding education for sustainable development in science classrooms, with a graph showing a consistent increase before declining towards the end. Research on this topic shows a high trend in 2022, with the number of publications reaching 45 articles in a single year. In contrast, 2019 had the fewest articles, with only seven. The average publication rate discussing education for sustainable development in science classroom learning over 5 years is 26.6 articles.

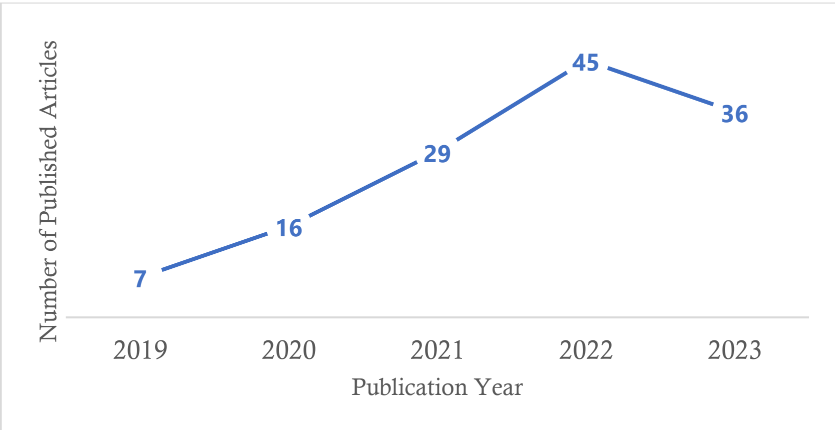

Figure 2. Development of article publications from 2019-2023

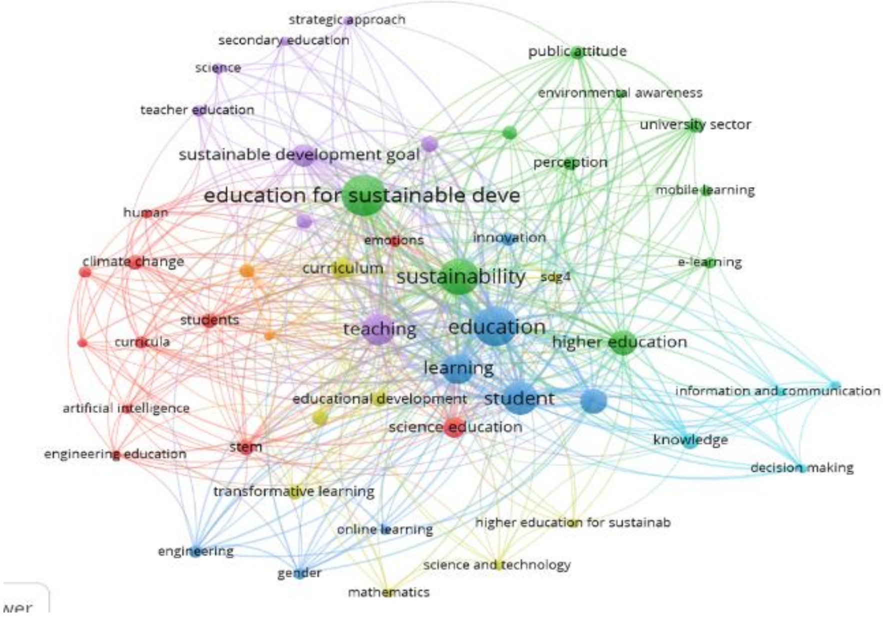

Figure 3. Publication Keywords Mapping

The VOSviewer analysis resulted in a visualization shown in Figure 3 depicting the network of research keywords. There are 7 clusters, 468 connections, and has a link strength of 1008 that enrich the research topic about the implementation of education for sustainable development in science classrooms. Each cluster is represented by circles and connecting lines with different colors, grouping the topics based on their characteristics (Astuti et al., 2023). The size of the circles in the mapping indicates the frequency of keyword mentions. The larger the circle, the more often that keyword appears (Indriyanti et al., 2023).

Cluster 1 is represented by a group of red circles consisting of 11 keywords, namely "artificial intelligence," "climate change," "curricula," "emotions," "engineering education," "health education," "human," "science education," "STEAM," "STEM," and "students." In Cluster 1, the most frequently mentioned keyword is "science education," with 13 total occurrences, 22 connections, and has a link strength of 50. Cluster 2 is shown by visualization of green circles consisting of 10 keywords, including "e-learning," "education for sustainable development," "environmental awareness," "higher education," "mobile learning," "perception," "public attitude," "sustainability," and "university sector." In Cluster 2, the most frequently mentioned keyword is "education for sustainable development," with 49 total occurrences, 37 connections, and has a link strength of 120.

Cluster 3 is portrayed by a series of blue circles consisting of 8 keywords, including "education," "engineering," "gender," "innovation," "learning," "student," and "sustainable education." In Cluster 3, the most frequently mentioned keyword is "education," with 46 total occurrences, 45 connections, and has a link strength of 189. Cluster 4 is symbolized by yellow circles consisting of 8 keywords, such as "curriculum," "educational development," "higher education for sustainability," "mathematics," "science and technology," "SDG4," "STEM education," and "transformative learning". In Cluster 4, the most frequently mentioned keyword is "curriculum," with 12 total occurrences, 27 connections, and has a link strength of 51.

Cluster 5 is marked by purple circles consisting of 8 keywords, including "COVID-19," "science," "secondary education," "strategic approach," "sustainable development goals," "teacher education," "teacher training," and "teaching." In Cluster 5, the most frequently mentioned keyword is "teaching," with 29 total occurrences, 43 connections, and has a link strength of 140. Cluster 6 is displayed by light blue circles composed of 4 keywords, such as "decision making," "information and communication," "knowledge," and "spatiotemporal analysis." In Cluster 6, the most frequently mentioned keyword is "knowledge," with 8 total occurrences, 18 connections, and has a link strength of 30.

Lastly, Cluster 7 is illustrated by the orange circles consisting of two keywords, namely "interdisciplinary" and "interdisciplinary approach." In Cluster 7, the most frequently mentioned keyword is "interdisciplinary approach," with 6 total occurrences, 18 connections, and has a link strength of 32. Based on these results, it is evident that each cluster has similar characteristics, supporting and interrelated with each other.

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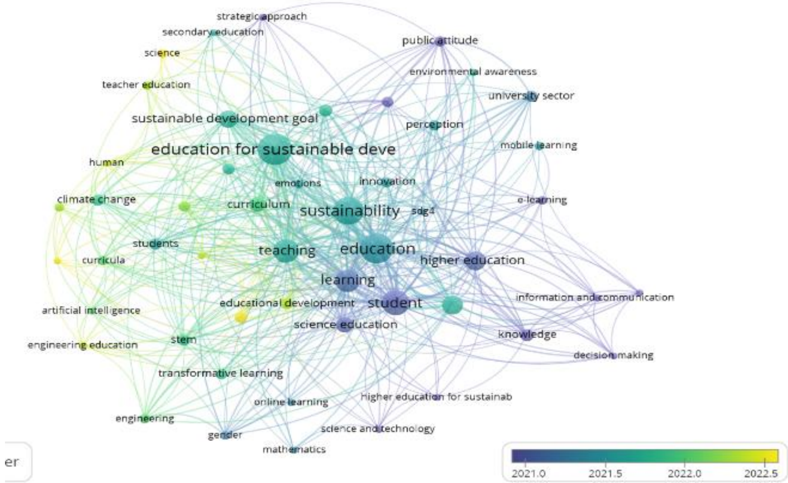

Figure 4. Keywords Mapping Based on Publication Year

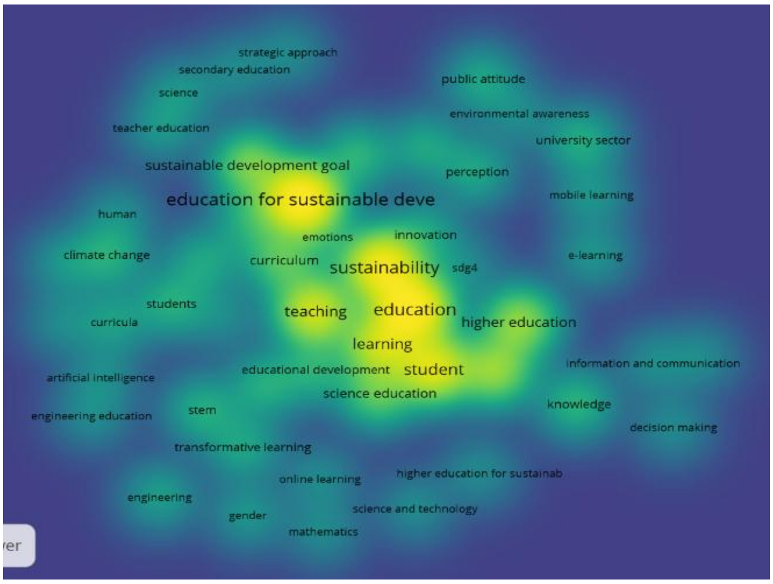

Figure 5. Keywords Density

Figure 4 provides an overview of the novelty of research keywords based on the publication year of the articles (2019—2023). The colors represent the average number of publications each year (Septiyanto et al., 2022). The brighter the circles' color and surrounding networks, the more recent the research. Conversely, darker colors indicate older research. From Figure 4, it can be concluded that research topics concerning STEM education, science education, health education, engineering education, interdisciplinary approaches, educational development, human studies, STEAM education, and teacher education are relatively new or fairly recent, and have the potential to continue evolving in the future. Particularly, topics highlighted in the brightest color include STEM, science, and health education. Therefore, sustainability values inherent in education for sustainable development can be integrated through STEM education, science education, and health education.

Meanwhile, the density of the mapped keywords is shown in Figure 5. The brighter the color, the higher the density or number of research conducted on that theme (Astuti et al., 2023). The analysis results indicate that keywords such as education for sustainable development, education, learning, students, and teaching have been extensively studied. In contrast, keywords with dimmer or darker colors represent topics that have the potential for future research development. They have not been extensively studied, especially concerning their relationship with education, sustainability, and education for sustainable development. Examples: strategic approaches, secondary education, gender, science and technology education, decision-making, and artificial intelligence.

From Figures 6 and 7, innovative new research topics can be formulated. The lines connecting one keyword to another indicate research relationships from published articles. Longer distances may indicate less explored connections between these contexts. Figure 6 depicts the research network on the keyword "education for sustainable development," suggesting potential novelty when connected with gender, for instance, how spatiotemporal analysis skills can impact "education for sustainable development", and so forth. The same applies to other keywords such as environmental awareness or artificial intelligence. On the other hand, Figure 7 illustrates the research network on the keyword "science education," with potential novelty in several topics such as decision-making, information and communication, public attitudes, environmental awareness, health, engineering, artificial intelligence, and so forth. If these keywords intersect with "education for sustainable development" and "science education," the potential for linking them becomes greater.

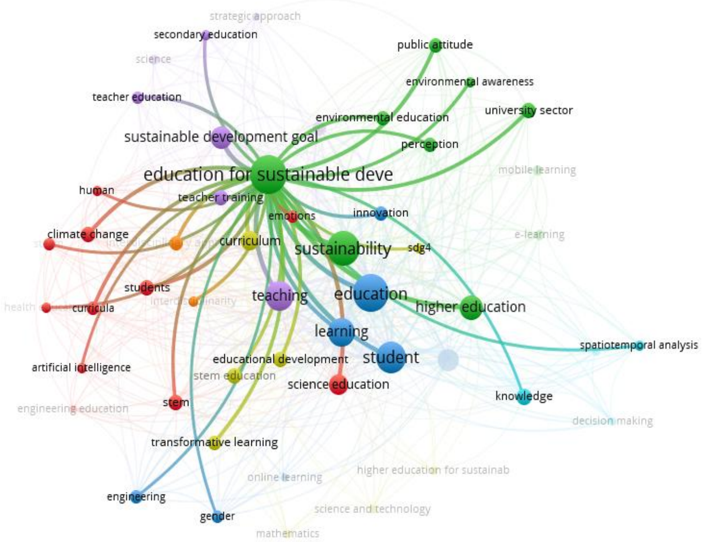

Figure 6. Research Network on the Keyword "Education for Sustainable Development"

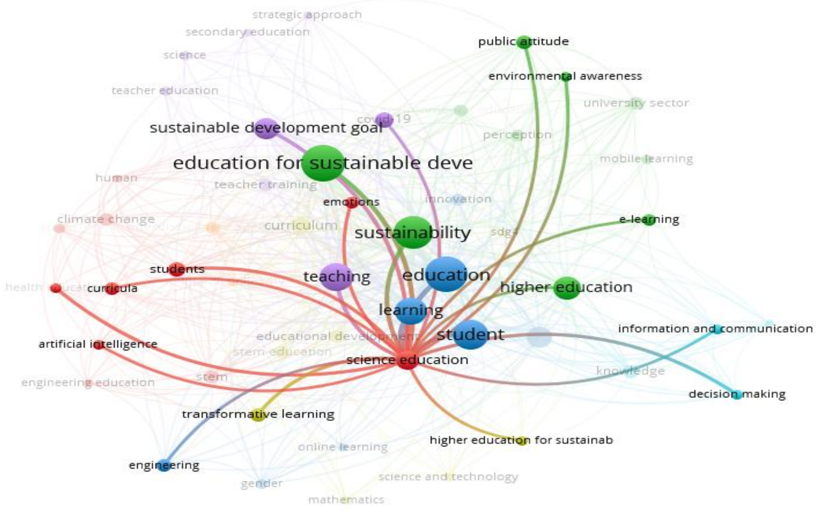

Figure 7. Research Network on the Keyword "Science Education"

The Strategies for Implementing Education for Sustainable Development in Science Classrooms

In science learning, sustainability values can be embedded explicitly or implicitly. Several research findings support the implementation of education for sustainable development in science learning, as indicated in Table 2. These 10 articles are sourced from various Scopus-indexed journals, with research conducted in different countries, predominantly in Asia, followed by Europe, and lastly, America. This outcome contrasts with research suggesting that America typically contributes the most to STEM-related research when mapped bibliometrically (Septiyanto et al., 2022). The accurate reason for this discrepancy was that several irrelevant sources on the topic discussed were eliminated in the analysis and synthesis stages. Additionally, the analyzed articles were published only from 2021 to 2023.

Table 2. Synthesis of 10 articles on strategies for teaching continuing education in science classes

Author(s)	Title	Country	The Strategies and The Subjects	Research Findings
Ali et al. (2021)	A STEM model to engage students in sustainable science education through sports: A case study in Qatar	Qatar	STEM and interdisciplinary learning (Science)	(1) The fundamental thinking skills, including critical thinking, inquiry, and hypothetic-deductive reasoning of students, significantly improved following the implementation of STEM learning that integrated science and sports subjects in a program aimed at enabling students to design sports equipment based on science principles; (2) Students' understanding and perspective regarding the importance of STEM in everyday contexts, such as sports, increased; (3) Students' interest in future STEM-related careers heightened.
Azhar et al. (2022)	Students' Attitude and Perception	Malaysia	Implementing sustainability programs in every	(1) USM students showed a high awareness of the university's sustainability program, displaying

Author(s)	Title	Country	The Strategies and The Subjects	Research Findings
	towards Sustainability: The Case of Universiti Sains Malaysia		university activity and course	positive attitudes that vary based on individual characteristics, and responding well to the program; (2) Students' attitudes towards the sustainability program at USM are related to their perceptions of the program.
Costa et al. (2023)	Physics of Sound to Raise Awareness for Sustainable Development Goals in the Context of STEM Hands-on Activities	Portugis	STEM learning, hands-on activity with the workshop framework, and integrating SDGs into the material content of the subject (Physics)	(1) There was an increase in teachers' knowledge regarding content material on the topic of sound, awareness of the impact of noise pollution on health, understanding of SDGs, prioritization of teaching SDGs, and confidence levels after conducting practical activities using a workshop approach; (2) In addition to teachers, students also experienced an increase in knowledge, actively engaged in learning, and felt positive emotions during the activities.
Zidny et al. (2021)	Exploring Indigenous science to identify contents and contexts for science learning in order to promote education for sustainable development	Indonesia	Adapting scientific knowledge from local wisdom (ethnoscience) into curriculum (Chemistry, Biology, and Physics)	(1) There are six themes of Baduy local wisdom that can be integrated into the science curriculum, encompassing agriculture, health, natural dyes, household cleaning materials, renewable energy, and astronomy; (2) The implementation of traditional knowledge in science education can equip students with local wisdom values and interdisciplinary thinking, and foster a sustainable attitude that respects nature.
Acharya (2023)	Gardening at School for a New Good Life: Entrepreneurship for Sustainable Education in the Public Schools in Nepal	Nepal	Interdisciplinary learning, hands-on activity, and integrating SDGs into the material content of the subject (Biology)	Students acquire content knowledge about factors influencing mushroom growth, scientific literacy skills through observation and mushroom cultivation, and entrepreneurial skills by selling harvested mushrooms in the local market.
Zidny & Eilks (2022)	Learning about Pesticide Use Adapted from Ethnoscience as a	Indonesia	Adapting scientific knowledge from local wisdom (ethnoscience) into curriculum,	(1) Students' perceptions of ethnochemistry-based chemistry learning with online chemistry laboratory activities involving the Green Star Metric—adopted from Baduy local knowledge—are

Author(s)	Title	Country	The Strategies and The Subjects	Research Findings
	Contribution to Green and Sustainable Chemistry Education		interdisciplinary learning, virtual hands-on activity, and integrating SDGs into the material content of the subject (Chemistry)	generally positive; enhancing their motivation to understand chemistry content within the context of traditional culture; encouraging them to acknowledge the diversity of natural science sources; and eliciting a sense of satisfaction; (2) Students' knowledge of Green Chemistry increases after experiments demonstrate outcomes aligned with sustainability principles and energy efficiency.
Kulshreshtha et al. (2022)	Foldscope Embedded Pedagogy in Stem Education: A Case Study of SDG4 Promotion in India	India	STEM learning, curriculum development, hands-on activity, using a new laboratory tool (Biology)	(1) The positive response of students to practical-based learning supplemented with a foldable microscope called foldscope indicates the effectiveness of this tool in supporting field-based learning, self-directed learning, and overcoming barriers related to the difficulty of accessing proper laboratory facilities, to achieve Quality Education goals (SDG4); (2) Students' learning motivation increases with the incorporation of foldscope-based learning.
Mulero et al. (2022)	Studying Forests in an Open Schooling Project	Catalonia, Yunani, Lithuania, Polandia, and Portugal	Implementing sustainability projects, interdisciplinary learning, transdisciplinary learning, and STEM learning (Chemistry and Biology)	(1) Teachers encounter difficulties in integrating the Open Schooling Project into the curriculum and struggle to communicate with teachers from other disciplines (teachers participating in the project have backgrounds in Chemistry, Biology, Mathematics, Engineering, and English), resulting in a greater inclination towards extracurricular rather than intracurricular approaches; (2) Students' perceptions of this project are influenced by gender, with female students tending to have a more positive outlook; (3) The implementation of the Open Schooling Project specifically in Catalonia involves various subjects and integrates SDGs into each content area.
Han et al. (2023)	Building a sustainable model of integrated STEM education: investigating	Amerika	STEM learning, interdisciplinary learning, teacher training (Biology and Physics)	(1) The teacher training program known as TRAILS has proven to be effective in the long term, as evidenced by consistently improving student outcomes, with a significant increase in critical thinking skills; (2) Learning with the D-BAIT method implemented

Author(s)	Title	Country	The Strategies and The Subjects	Research Findings
	secondary school STEM classes after an integrated STEM project			by teachers who have undergone TRAILS training includes providing basic knowledge, engaging experts, and collaborating students from different disciplines to actively participate in learning; aiming to create functional bait products by adopting principles of science and engineering.
Abdur-rahman et al. (2023)	Impacts of integrating the engineering design process into STEM maker space on the renewable energy unit to foster students' system thinking skills	Indonesia	STEM-PBL learning with the integration of the Engineering Design Process (Science)	(1) Integrated STEM-PBL learning with Engineering Design Process (EDP) significantly enhances students' system thinking abilities compared to regular STEM-PBL, as each step in the EDP facilitates students in systematically developing their thinking patterns; (2) This approach also enables students to be more focused in problem-solving, develop product designs, and realize the role of technology in daily life.

Sustainable education aims to prepare for envisioned futures while enhancing the quality of present-day life (Nuwangi et al., 2023). Through sustainable education, it is anticipated that leaders and decision-makers who possess key sustainable competencies will emerge and be inclined to apply them within their respective domains in preparation for confronting uncertain possibilities (UNESCO, 2017). Consequently, sustainable education integrated into science learning should be holistic and imparted to students across all educational levels.

Elementary school students are reported to experience increased positive emotions and highly engage in learning activities by integrating sustainability values into science subjects such as Physics and Biology (Acharya, 2023; Costa et al., 2023). Direct experiential learning is fostered by encouraging students to participate in physical activities, leading to more enduring knowledge retention. Emphasizing entrepreneurial skills (Acharya, 2023) in learning also adds value to support economic sustainability as one of the pillars of sustainable education while simultaneously achieving Sustainable Development Goals 1 and 2 (no poverty and zero hunger).

Moreover, sustainable education holds significant potential to be incorporated into secondary education, including both lower and upper secondary levels. Six studies have addressed sustainable education learning in secondary school science classes, indicating that research at this level predominates over other educational levels. Research at the secondary school level often practices project-based interdisciplinary learning, either by addressing topics connected to multiple subjects' content or by combining students with diverse academic backgrounds in the process (Abdurrahman et al., 2023; Ali et al., 2021; Han et al., 2023; Mulero et al., 2022). Additionally, the research explores the integration of ethnosciences from the local wisdom of the Baduy community in Banten into the curriculum of both lower and upper secondary education, which can be integrated into various subject content such as Chemistry, Biology, and Physics—covering topics like agriculture, health, natural dyes, household cleaning materials, renewable energy, and astronomy (Zidny et al., 2021). Other research involves hands-on meaningful learning activities intersecting with research at the elementary school level (Acharya, 2023).

At the university level, particularly for STEM-related disciplines, research on sustainable education is integrated in the form of socio-scientific issues in laboratory practicals to offer compelling self-directed learning experiences, problem-focused learning, and to complement theoretical knowledge with scientific method skills (Kulshreshtha et al., 2022; Zidny & Eilks, 2022). Furthermore, sustainability programs integrate sustainable education into all university courses and activities (Azhar et al., 2022). These university sustainability programs support the creation of a sustainable university climate. Moreover, sustainable education can contribute to teachers developing themselves and their content and pedagogical competencies (Costa et al., 2023; Han et al., 2023).

Implementing sustainable education in science learning can be grouped into several types of strategies. First, the application of STEM learning is believed to attract interest and increase students' motivation to pursue careers in the field in the future; it also hones various skills while supporting the enhancement of key sustainability competencies such as critical thinking, systems thinking, creativity, and collaboration (Abdurrahman et al., 2023; Ali et al., 2021; Costa et al., 2023; Han et al., 2023; Kulshreshtha et al., 2022; Mulero et al., 2022). Second, interdisciplinary learning integration, ranging from interdisciplinary to transdisciplinary and multidisciplinary approaches. Interdisciplinary learning is recommended to achieve sustainability, as real-life problems that need solving are multidimensional (Nuwangi et al., 2023; UNESCO, 2017). Moreover, interdisciplinary learning is also related to STEM learning, which fundamentally involves collaborating across multiple disciplines in the learning process. Such learning can contribute to increasing collaboration levels, which, besides being a 21st-century skill, are also key sustainability competencies.

Third, activity-based practical learning, whether in the field, in the laboratory, or online (Abdurrahman et al., 2023; Acharya, 2023; Ali et al., 2021; Costa et al., 2023; Kulshreshtha et al., 2022). Fourth, the integration of sustainability values into the content of science subjects or courses, including Biology, Physics, and Chemistry (curriculum development) (Azhar et al., 2022; Kulshreshtha et al., 2022; Zidny et al., 2021; Zidny & Eilks, 2022), which can be done by adapting local or ethnoscientific knowledge (Zidny et al., 2021; Zidny & Eilks, 2022), or the use of specific tools to enhance learning interest and facilitate the development of new skills (Kulshreshtha et al., 2022). Finally, strategies for implementing sustainable education in science learning in classrooms involve teachers in specialized training to enhance their abilities as educators, thereby growing with their students (Costa et al., 2023; Han et al., 2023).

4. Conclusion

Over the five years from 2019 to 2023, the trend in sustainable education research in science classroom learning has shown a steady increase, reaching its peak in 2022 before experiencing a slight decline in 2023. Among the top 10 publications with the highest citations, most articles were published in the journal Sustainability, with a dominance of research articles from 2020. Bibliometric analysis using VOSviewer visualized seven clusters of keywords, each consisting of several. The most frequently mentioned keywords include “science education,” “education for sustainable development,” and “education.” However, when examined based on publication time, keywords such as STEM, science, and health education were identified as emerging topics recently and could potentially further develop. Finally, in terms of density, keywords such as strategic approaches, secondary education, gender, science and technology, decision-making, and artificial intelligence are identified as topics with relatively few studies and high novelty. Meanwhile, the analysis of literature studies concludes that several strategies can be used to teach sustainable education in science classroom learning, including implementing STEM education, interdisciplinary approaches, practical learning, integrating sustainable values into the curriculum, and providing teacher training or participation.

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