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Teaching Science Mapping Research on Integration of Augmented Reality Technology and Education for Sustainable Development: A Bibliometric Analysis

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Abstract: The integration of technology and sustainability education is essential to develop students' 21st-century skills. AR and ESD offer innovative pathways to enhance science learning in addressing global challenges. However, the development of research combining AR and ESD in science education has not been comprehensively mapped. This study aims to analyze trends and directions of research on the integration of AR and ESD using bibliometric analysis. Data were collected from Scopus indexed articles published between 2015 and 2025 and analyzed using VOSviewer through performance analysis, co-authorship, keyword co-occurrence, and thematic mapping. The results show a steady increase in publications, with research clusters highlighting themes such as immersive learning, sustainability awareness, digital pedagogy, and interdisciplinary approaches. Visualization reveals AR as a powerful experiential tool for promoting ESD values in science classrooms. This study also identifies future opportunities, such as enhancing pedagogical frameworks, expanding real world applications of AR, and strengthening collaboration across education, technology, and environmental disciplines. The findings suggest that integrating AR and ESD can foster more interactive, meaningful, and sustainability-oriented science education. This study recommends further development of immersive AR based teaching strategies aligned with the goals of sustainable development.

Keywords: Augmented reality; Bibliometric analysis; Education for sustainable development; Science teaching

Introduction

Developing 21st-century skills in students is a central fokus of education. In this era, 21st-century education is undergoing significant changes in various aspects, especially in the integration of technology into learning and in preparing students with 21st-century skills. The integration of technology in education can enhance student engagement, foster collaboration between teachers and students, and improve 21st-century skills (Asrizal et al., 2024; Ismail et al., 2023; Utaminingsih et al., 2023). Skills of the 21st century such as critical and creative thinking, communication, collaboration, digital literacy, and global awareness are key competencies that students are required to develop in the current era (Akçay et al., 2024; Ginting et al., 2021; Thornhill-Miller et al., 2023). Possessing strong 21st-century skills enables students to adapt to the increasingly complex changes of the times, including rapid technological developments, challenges related to

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21st-century competencies, global issues, and future uncertainties.

Learning process should facilitate the development of students' 21st-century skills. Learning in the 21st century must align with technological developments and the realities of globalization. Educational systems should move away from conventional methods and adopt strategies that encourage active participation, meaningful engagement, and contextual understanding (Asrizal et al., 2022; Bhardwaj et al., 2025). Moreover, 21st-century education prioritizes the integration of technology in learning and strives to improve students' competencies in 21st-century skills (Asrizal et al., 2018; Mansyur et al., 2024). Project-based approaches, collaboration, creativity, problem-solving, and the integration of information technology are vital elements in this learning process. In addition, aligning instruction with real-life problems from students' surroundings is a key feature of 21st-century education.

Integrating technology and sustainability principles is a crucial aspect of 21st-century education. The use of technology in learning enhances instructional efficiency and equips students to face the challenges of a digital-based working environment (Fajri et al., 2024; Subtianah, 2023). The integration of sustainability values aims to create learning that not only focuses on knowledge transfer but also fosters awareness of social and environmental responsibility (Ferniawan et al., 2024; Setiyaningsih et al., 2024; Wamsler, 2020). The integration of sustainability values in learning can strengthen students' knowledge of relevant global problems and issues. Education for sustainable development (ESD) serves as a vital framework for guiding learning toward an understanding of both scientific knowledge and the importance of sustainability (Li et al., 2023; Mahaisavariya & Charmondusit, 2023). Through education for sustainable development, students are encouraged to think critically and actively contribute to efforts in building a sustainable future.

The independent curriculum serves as a means to develop 21st-century skills in Indonesia. It provides educators with the flexibility to design learning experiences that are tailored to students' contexts and needs (Marthawati & Setyo, 2024; Setyaningsih et al., 2023). The Independent Curriculum emphasizes meaningful learning that is relevant to students' real-life environments. Learning is encouraged to be contextual, exploratory, and collaborative, enabling students to actively construct their own knowledge (Satria et al., 2024). In addition, learning in the independent curriculum is oriented toward strengthening the Pancasila Student Profile, which encompasses creativity, independence, collaboration, and critical thinking promoting students' social and environmental awareness. Thus, the independent curriculum creates opportunities for integrating technology, sustainability, and student-centered learning approaches.

Findings from previous research indicate that students' 21st-century skills are still underdeveloped. Key competencies namely critical thinking, creative thinking, communication, and collaboration remain limited among students in Indonesia (Bilad et al., 2024; Chusni et al., 2020; Pamungkas et al., 2023). Students'limited 21st-century skills are largely due to ineffective curriculum implementation particularly the insufficient integration of technology and the lack of pedagogical approaches that foster these skills. Consequently, many graduates are not adequately prepared for the challenges of the modern workforce (Hadiyanto et al., 2022). In addition, the low level of 21st-century skills among students in Indonesia is also due to the learning process still being teacher-centered (Ilwandri et al., 2023). Learning should support the development of 21st-century skills in students. These skills are essential for preparing competent human resources and addressing the challenges of the Industrial Revolution 4.0 in the field of education (Nazifah & Asrizal, 2022).

Augmented reality (AR) is one of the solutions for integrating technology in education. This technologyprovides a realistic visualization of learning concepts (Akçayır & Akçayır, 2017). Moreover, augmented reality is suitable for educational integration as it merges real and virtual elements, provides real-time interaction, and displays objects in a three-dimensional format (Hajirasouli & Banihashemi, 2022; Prananta et al., 2024). Studies have shown that integrating augmented reality into learning can increase student motivation and engagement, while also making it easier and more enjoyable to present complex concepts (Egista & Mustofa, 2025; Lu et al., 2021). Furthermore, Ashari (2023) states that augmented reality facilitates the comprehension of abstract and complex concepts by enabling their representation through structured visual objects.

Several studies have shown that the integration of augmented reality has a positive impact. The use of augmented reality in learning is considered promising for enhancing 21st-century skills. This is because augmented reality technology encourages students to explore, think creatively, and work collaboratively in solving problems (Alkhabra et al., 2023; Bakri et al., 2023; Wibowo, 2022). Moreover, the integration of augmented reality into education has the potential to improve students' creative thinking abilities by providing deep and immersive learning experiences (Buditjahjanto & Irfansyah, 2023; Huang & Musah, 2024). Thus, augmented reality is regarded as an

effective tool for connecting scientific concepts to real-world contexts, making it highly suitable for integration with the education for sustainable development framework.

Education fors sustainable development integration supports 21st-century skills in students. This integration seeks to cultivate environmental consciousness, a sense of social responsibility, and ethical values that support sustainable development among learners (Najwa & Suhartini, 2023; Tafese & Kopp, 2025b). In the context of science education, education for sustainable development promotes learning that is not only concept-oriented but also action-oriented in addressing sustainability issue (Baptista et al., 2025). A contextual, participatory, and transformative pedagogical approach is required to enable students to connect scientific knowledge with real-life challenges. Such integration serves as a strategic solution for equipping students with essential 21st-century skills such as critical thinking, creativity, and collaboration (Alali, 2024; González-salamanca et al., 2020). Accordingly, the integration of education for sustainable development strengthens the role of science education in shaping a generation that is environmentally conscious and actively engaged in contributing to sustainable development.

Despite the growing number of studies on augmented reality and education for sustainable development individually, research focusing on their integration in science education remains limited. The integration of augmented reality and education for sustainable development holds significant potential in enhancing both conceptual understanding and sustainability-oriented thinking among students. Therefore, a systematic and comprehensive mapping of studies on the integration of augmented reality and education for sustainable development is necessary. Such a study can reveal the landscape of current research, highlight dominant themes and emerging directions, and uncover gaps that need further exploration. This can provide a strong basis for developing future research agendas aligned with transformative 21st-century science education.

Bibliometric analysis serves as an effective method to examine the development of scientific publications in this field. It allows researchers to identify research patterns, trends, and impacts within a specific domain (Passas, 2024). By employing bibliometric tools, this study explores how the integration of augmented reality and education for sustainable development has evolved over the past decade, who the key contributors are, which topics dominate, and what opportunities exist for future inquiry. The findings will guide stakeholders'researchers, educators, and policy makers toward more strategic, collaborative, and impactful research directions.

This study aims to map the research landscape on the integration of augmented reality and education for sustainable development in science education. Through bibliometric analysis, this study analyzes publication growth, network visualizations (co-occurrence), overlay maps to reveal emerging themes, and density visualizations to identify potential research clusters. This research contributes not only by synthesizing current developments but also by highlighting the urgency of immersive and sustainability oriented pedagogical innovations that meet the needs of 21st-century learning.

Method

This study employs a bibliometric analysis method. This method utilizes a quantitative approach to describe, evaluate, and monitor published research outputs, ensuring more objective and transparent results while minimizing the biases commonly found in qualitative methods (Zupic & Čater, 2015). This approach is quantitative and systematic, allowing for an objective analysis of relevant literature. Through this method, patterns of collaboration, keyword distribution, and the dynamics of scientific publications within the studied topic can be identified.

The data in this study were obtained from the Scopus database. Scopus was chosen as the primary data source due to its extensive coverage of globally reputable scientific journals. The search was conducted by selecting articles published between 2015 and 2025. The data were limited to specific document types, including journal articles, conference papers, conference reviews, and review articles. A systematic selection process was carried out to ensure the relevance to the research topic and the quality of the data analyzed.

Keywords were carefully selected to ensure that the retrieved literature was relevant to the research topic. The keywords used in the search process included a combination of terms such as "augmented reality" AND "education for sustainable development." The search was conducted using boolean operators AND to broaden or narrow the scope of results as needed. The selection of keywords was carried out strategically to ensure that the collected articles reflected the connection between augmented reality technology and the goals of sustainable education.

This study follows systematic steps to ensure clarity in the analytical process. The research procedure was carried out through five stages as proposed by Irawan et al. (2024). The process began with data collection from the Scopus database, followed by article

selection based on inclusion criteria, data processing, bibliometric analysis, result visualization, and insight interpretation. Each stage was designed to ensure valid outcomes aligned with the research focus. This process guarantees that only relevant articles meeting scientific criteria were analyzed. The research framework is presented in the form of a diagram to facilitate a clearer understanding of the workflow throughvisual representation.

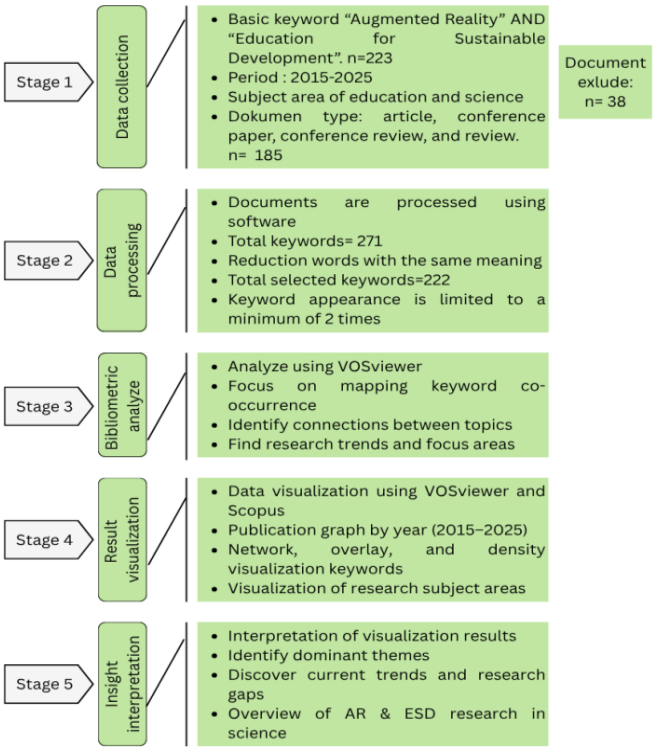

Figure 1. Steps in bibliometric analysis research

This study utilized several software tools to ensure accurate and valid data visualization. The data processing was conducted using Microsoft Excel and Notepad. This stage included a keyword reduction process, which involved merging keywords with similar meanings but different variations in spelling. The visualization and interpretation of the processed data were carried out using VOSviewer. This software was selected due to its ability to produce interactive and easily interpretable visualizations. The outputs generated by VOSviewer served as the basis for interpreting trends and patterns within the analyzed literature data.

Data analysis was carried out by processing metadata obtained from Scopus. The data were then imported into VOSviewer for analysis based on keyword occurrences and relationships among documents. The results were visualized in the form of network visualization, overlay visualization, and density visualization to facilitate the identification of thematic clusters and dominant research trends. Interpretation was conducted descriptively to explain the visual findings. The visualized results such as research development and subject areas were derived from the data analysis conducted using Scopus.

Result and Discussion

The first result of this study is the analysis of research trends over the past ten years. The data visualization was generated from a Scopus analysis using the keywords "augmented reality" and "education for sustainable development." This graph provides an overview of the dynamics of research growth from year to year. The pattern also reflects the influence of technological advancements, global education policies, and sustainability issues that have gained attention over the past decade.

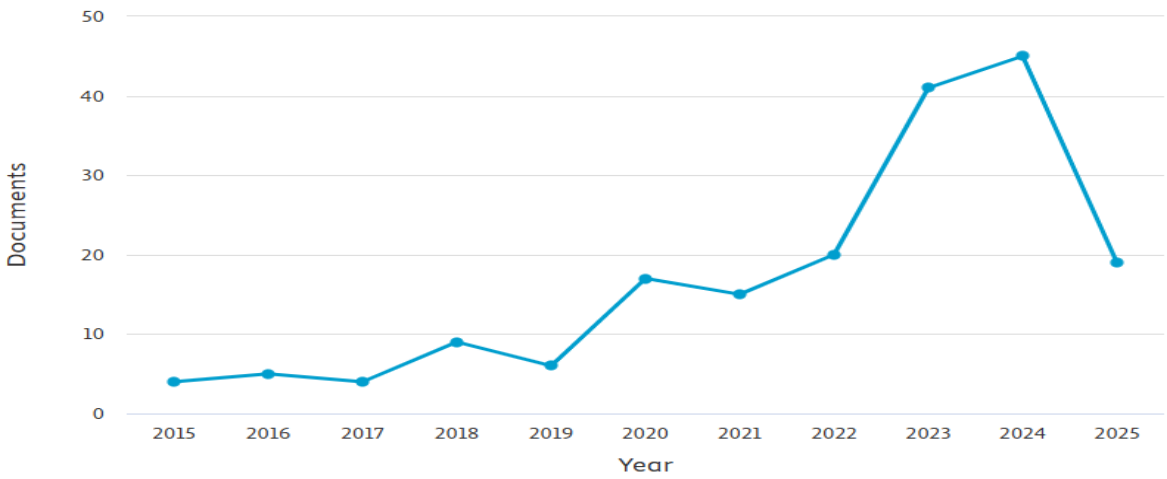

Figure 2. Distribution of publication growth from 2015-2025

Figure 2 presents the trend of scientific publication growth examining the integration of augmented reality and education for sustainable development in science education during the period 2015–2025. A significant increase in the number of publications is observed, particularly after 2018, reflecting the growing interest of the academic community in the use of augmented reality for sustainable education. This upward trend aligns with findings from the study by Anesti & Irwanto (2025), hich revealed a notable surge in publications related to augmented reality in education since 2015, suggesting that AR is regarded as one of the key technologies in educational innovation. Furthermore, research by Sulastri (2025) highlights that in the context of higher education, the use of augmented reality has rapidly expanded, with the United States and China emerging as the main contributors to scientific publications in this area. This trend reflects the increasing adoption of augmented reality technology across global educational institutions.

The study by Ozyurt & Ozyurt (2024) identified that since 2015, there has been a growing research interest in augmented reality in education, particularly in the context of interactive learning and immersive learning experiences. This indicates that augmented reality is not only a popular research topic, but also regarded as an effective approach to enhancing student engagement and understanding. In addition, another study by Tafese & Kopp (2025a) emphasizes the importance of education for sustainable development in higher education and shows that the integration of technologies such as augmented reality can strengthen the achievement of sustainable development goals through education. These findings support the view that the increasing number of publications in the field of augmented reality and education for sustainable development reflects a global effort to combine innovative technologies with the pursuit of sustainable education. Overall, the upward trend in publications over the years indicates that the integration of augmented reality in education for sustainable development has become a central focus in educational research, highlighting the need for innovative and sustainable learning approaches.

The second finding of this study involves the network visualization analysis. In this visualization, each node represents a keyword, and the links between them indicate co-occurrence relationships. The colors signify clusters that group related topics. This network map facilitates the identification of dominant research themes and emerging directions in the field.

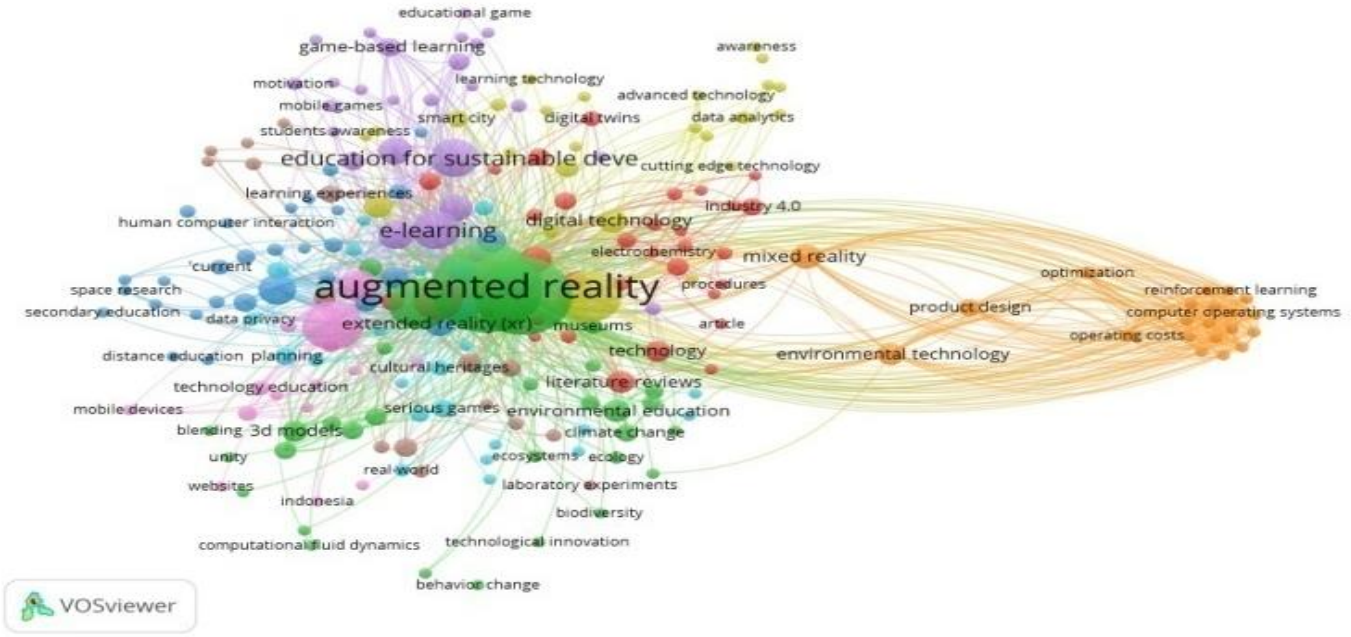

Figure 3. Network visualization of research trends in augmented reality and education for sustainable development

Based on the bibliometric analysis shown in Figure 3, which was conducted on keyword co-occurrence data, the term "augmented reality" emerged as the most strongly connected keyword within the analyzed literature. This indicates that the topic serves as a central focus in research integrating technology and sustainable education. In addition, several other keywords also demonstrated significant relevance, including "sustainable development goals (SDGs)," "education," "e-learning," "education for sustainable

development," "learning systems," "curricula," and "teaching." The presence of terms such as "virtual reality," "engineering education," and "students" further enriches the thematic network in this research mapping.

The data visualization reveals that "augmented reality" functions as a central node in the network of topics related to sustainable education. This finding reflects the integration of technology-based approaches in learning practices that emphasize sustainability. In particular, the concept of "education for sustainable development" emerges as a critical bridge between the application of innovative technologies and the achievement of 21st-century educational goals, highlighting the development of awareness, values, and social responsibility (UNESCO, 2020).

The analysis of the network structure indicates the presence of three dominant clusters: The innovative technology cluster, which includes augmented reality, virtual reality, extended reality, and immersive technology. This cluster forms the primary foundation for creating simulation and visualization-based learning experiences (Radianti et al., 2020); The education and sustainability cluster, which consists of terms such as education, education for sustainable development, SDGs, and environmental sustainability, highlights the importance of integrating sustainability principles into the educational system (Bozkurt, 2020); and The Learning Design Cluster, which includes terms such as learning systems, curricula, and instructional design, reflects the strengthening role of pedagogy in designing adaptive and contextual learning experiences. The strong interconnections among topics in this analysis indicate a close relationship between augmented reality technology and the educational framework for sustainability. These findings open opportunities for further exploration in developing immersive technology-based learning models that not only support the achievement of the SDGs but also enhance the implementation of education for sustainable development in science education.

Based on the network visualization presented in Figure 3, it can be concluded that the integration of augmented reality within the framework of education for sustainable development holds great potential in supporting science learning oriented toward sustainable living. Through the use of innovative technologies, the learning process becomes not only more engaging and interactive but also equips students with relevant understanding and values to face global challenges critically and responsibly. Future research is expected to move toward the design of instructional strategies that comprehensively integrate sustainability values by making optimal use of advancements in educational technology.

The third result of this study is the overlay visualization analysis of the data. The color of each node indicates the average publication year when the corresponding keyword was frequently used. This visualization provides an overview of research trends and the shifting focus of studies over time.

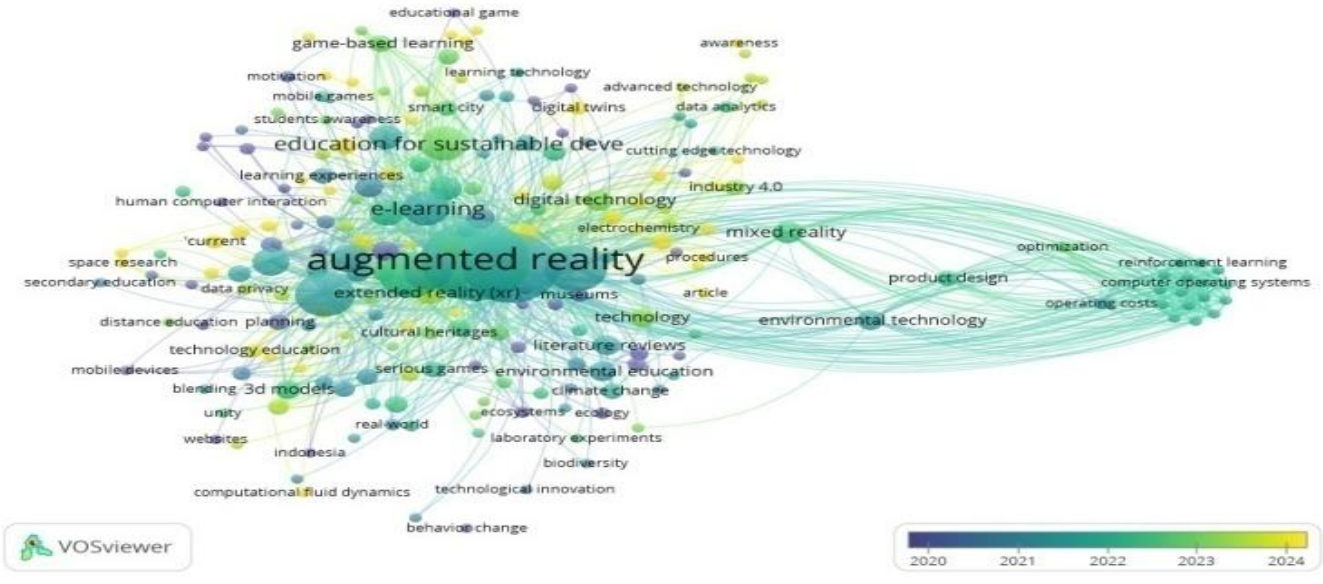

Figure 4. Overlayvisualization of research trends in augmented reality and education for sustainable development

The overlay visualization in Figure 4 highlights the development of research through the keywords frequently appearing in studies that link augmented reality with education for sustainable development. The keyword "augmented reality" has an average publication year of 2021.82, indicating its dominant role

in the related literature. Meanwhile, "virtual reality" appeared earlier with an average year of 2020.37, reflecting its foundational role in the application of immersive technologies in education, as previously discussed in various studies. The keyword "education for sustainable development" has a more recent average publication year, indicating the growing attention to sustainability-oriented education in the context of technology. Additionally, "immersive learning" and "science education" are among the most recent keywords, reflecting a new direction in research that emphasizes the direct application of immersive technology in science education grounded in sustainability values.

The overlay visualization in Figure 3 illustrates the shifting focus of research development over time. Initially, studies emphasized technological aspects such as augmented reality and virtual reality as innovative learning tools to enhance students' motivation and understanding of abstract concepts. The use of these technologies saw a significant increase in science education, particularly in visualizing complex scientific ideas. Over time, the research focuses gradually shifted toward the integration of sustainability issues, as reflected in the rising frequency of keywords such as "education for sustainable development" and "SDGs," which serve as the foundation of value-based global education. According to UNESCO (2020) the roadmap for education for sustainable development highlights the importance of education that promotes holistic social and environmental transformation. The emergence of keywords like "STEM" and "science education" indicates that recent research has begun to focus on more applied and contextual approaches to science education in addressing global challenges. In this context, immersive technologies play a role in providing learning experiences that are more realistic, deep, and reflective.

Overall, the overlay visualization reveals a shift in focus from purely technological development toward more meaningful and integrated pedagogical implementation within the context of sustainable education. This presents opportunities for the development of innovative learning strategies that are not only effective in content delivery but also value-driven and impactful in fostering students' sustainability awareness.

The fourth result of this study is the density visualization analysis of the data. Density visualization illustrates the level of concentration or intensity of keyword usage within the document set. Brighter colors indicate keywords that appear more frequently and are more central to the research. This visualization helps identify the core keywords within the field of study.

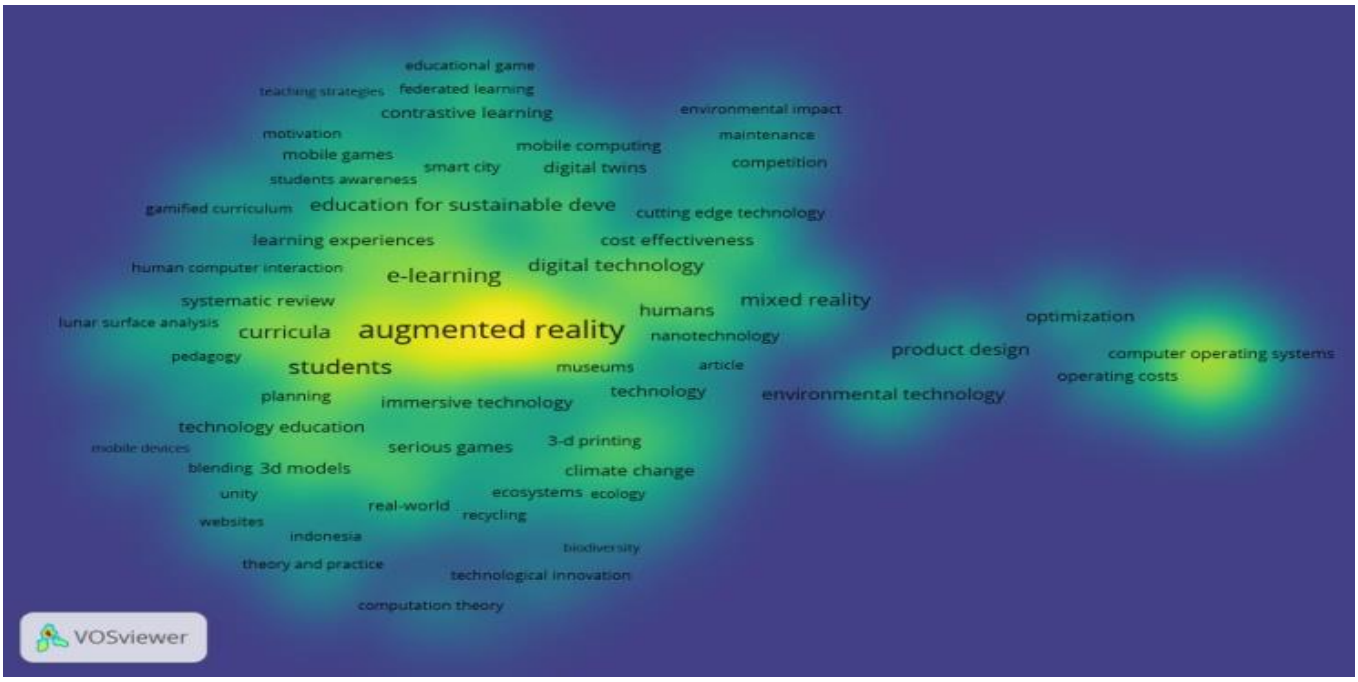

Figure 5. Density visualization of research trends in augmented reality and education for sustainable development

The density visualization in Figure 5 shows the intensity of keyword interconnections within the literature related to the topics of "augmented reality" and "education for sustainable development." In the displayed map, areas in bright yellow indicate keywords with very high frequency and strong

interconnections, while green and blue areas represent lower levels of association. The keyword "augmented reality" occupies a central position with the highest density, marked by a bright yellow color, indicating that this topic is the primary focus within the research domain. According to Figure 5, keywords such as "students," "curricula," "e-learning," and "education for sustainable development" appear in high-density zones (yellow-green), signaling strong connections between augmented reality technology and educational contexts. Other keywords like "immersive technology," "serious games," "digital technology," "STEM," and "climate change" are located in green and blue areas, reflecting emerging thematic relationships that are not yet dominant. Meanwhile, terms such as "product design," "optimization," and "computer operating systems" appear more isolated in bluish-green zones at the edges of the map, indicating that although these topics are relevant, they have more limited connections to the core of the study.

This visualization result shows that research on augmented reality in education has evolved with a strong focus on its application in the learning process, particularly in areas related to curriculum development, e-learning, and sustainable education. The high density around the keywords "augmented reality" and "students" reinforces previous findings that position augmented reality technology as a strategic tool to enhance contextual and interactive learning experiences (Radianti et al., 2020).

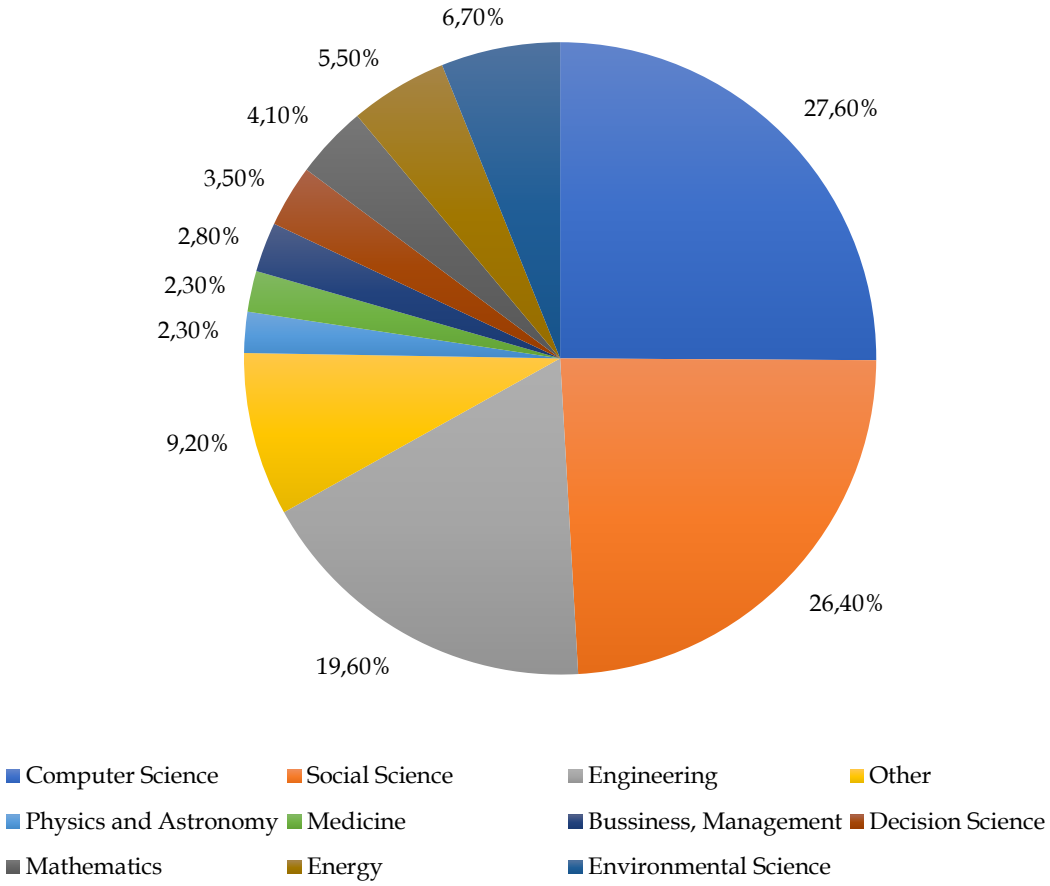

Figure 6. Subject area research augmented reality and education for sustainable development

Based on the density visualization in Figure 5, the appearance of "education for sustainable development" and "e-learning" in high-density zones also reinforces that the integration of technology and sustainability values has become a dominant trend. This aligns with the roadmap outlined by UNESCO (2020) which emphasizes the importance of transforming education through the integration of values, skills, and technology. The frequent co-occurrence of these keywords indicates that researchers are increasingly aware of the urgent need to address global challenges through educational innovation. In particular, science education appears to be a strategic domain where both technological advancement and sustainability values can intersect meaningfully. Meanwhile, the moderate density of keywords such as "immersive technology" and "serious games" indicates future research opportunities to optimize experiential learning

approaches that promote active and reflective engagement. These approaches have the potential to enhance students' motivation, engagement, and long-term retention of scientific concepts. In addition, the integration of immersive tools can support the development of 21st-century skills such as critical thinking, collaboration, and systems thinking. Keywords appearing on the periphery, such as "product design" and "computer systems," suggest potential for interdisciplinary exploration with fields of technology and engineering, although these topics have not yet become main stream. Their peripheral position implies that these themes are emerging but still underexplored within the core discourse. Overall, the density visualization reveals that research in the field of augmented reality and sustainable education remains wide open for further development, particularly in linking pedagogical aspects, technological innovation, and transformational values in science and global education.

The fifth result of this study is the subject area visualization. This visualization displays the distribution of academic disciplines represented in the analyzed documents. Each color or category reflects the dominant fields of study contributing to the related publications. This information is useful for understanding the contributions of various disciplines to the topic of augmented reality and sustainable education.

Based on the subject area distribution shown in Figure 6, research integrating augmented reality and education for sustainable development is dominated by two main fields: Computer Science (27.6%) and Engineering (19.6%). This indicates that, technically and methodologically, the development of augmented reality remains highly dependent on disciplines related to computer science and both software and hardware engineering. Social Sciences account for the third largest share (16.4%), followed by Environmental Science (6.7%) and Energy (5.5%). Meanwhile, contributions from Mathematics, Decision Science, Physics and Astronomy, as well as Medicine are relatively small, each comprising less than 5%. The "Other" category represents 9.2%, including fields such as design, the arts, or interdisciplinary studies.

The dominance of the Computer Science and Engineering fields indicates that research on augmented reality and education for sustainable development remains heavily focused on technological development and the implementation of computing-based systems. This is understandable, as augmented reality requires technical infrastructure such as visualization algorithms, sensors, machine learning, and adaptive user interfaces (Radianti et al., 2020). However, the significant role of the Social Sciences indicates a shift toward the use of technology within social and educational contexts, particularly to support behavioral transformation and the promotion of sustainability values. This context is highly relevant to value-based pedagogical approaches, such as those promoted by education for sustainable development (UNESCO, 2020).

Social Sciences contribute the third largest share (16.4%), indicating a growing interest in studying augmented reality not only as a technological product but also as a medium to transform human behavior and learning environments. This is relevant to value-based educational frameworks such as education for sustainable development, which promote the internalization of sustainability values through learner centered and participatory approaches (UNESCO, 2020; Wamsler, 2020).

The presence of Environmental Science (6.7%) and Energy (5.5%) reflects growing applications of augmented reality in climate education, environmental awareness, energy transition, and simulation of ecological phenomena supporting findings by Baptista et al. (2025) and Tafese & Kopp (2025b). Meanwhile, smaller contributions from Mathematics, Physics and Astronomy, Decision Sciences, and Medicine (each < 5%) suggest that the use of augmented reality and education for sustainable development integration in these fields remains limited or unexplored. These findings underscore the multidisciplinary nature of augmented reality and education for sustainable development research. They also reveal opportunities to expand into underrepresented fields, particularly in science education and healthcare education, where sustainability issues and immersive technologies could intersect meaningfully to develop future-ready competencies.

Conclusion

This bibliometric analysis identifies five key findings regarding the integration of augmented reality and education for sustainable development in science education. First, research in this area has shown significant growth and relevance within the context of 21st-century learning. Second, the thematic clusters mapped reveal a synergy between technology, pedagogy, and transformational values. Third, overlay visualizations point to current trends emphasizing augmented reality as an experiential medium that fosters sustainability awareness. Fourth, the limited real-world classroom implementation highlights the need for further exploration and stronger pedagogical design. Fifth, subject area analysis confirms the multidisciplinary nature of this field, with dominant contributions from computer science, engineering, and

social sciences. These findings underscore the transformative potential of augmented reality and education for sustainable development integration in shaping innovative, reflective, and sustainability-oriented learning models.

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Author Contributions
All authors have contributed with their respective tasks which are equally important for the completion of the writing of this paper. A.F. contributed in collecting data, compiling paper drafts, processing data, and analyzing; A. contributed as a guide for the implementation of research up to the paper's authorship, idea designer, and review of paper drafts; H.A. contributed to guiding how to collect data, process data, and how to visualize it.

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Conflicts of Interest
In making the paper, the authors found no conflicts. The research implementation ran smoothly according to procedures with legal permits. Research implementation does not interfere with conducive learning in class because the research material is in accordance with the curriculum used in schools.

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