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Exploring Digital Learning Media Research Trends in Education for Sustainable Development Relating to Particle Technology: A Bibliometric Analysis Approach

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ABSTRACT

This research explored digital learning media research trends in education for sustainable development (ESD) relating to particle technology through a bibliometric analysis approach. Data taken from the Scopus database for the last ten periods (2014-2024) was used in this research Data were sourced from the Scopus database for the period 2014–2024, analysed in four stages: (i) data collected, (ii) screening for relevant studies, (iii) bibliometric analysis using VOSViewer and Microsoft Excel to visualize trends, and (iv) interpretation and conclusion. A total of 4,115 documents were analysed, showing significant growth in publications since 2018, particularly during the COVID-19 pandemic (2019–2021), driven by the shift to digital learning. Key findings reveal that Learning Management Systems (LMS), e-learning platforms, and interactive applications became crucial in maintaining educational continuity during the pandemic, while ESD gained prominence as global awareness of sustainability challenges increased. Geographically, the analysis highlights significant contributions from China, the United States, and Germany, with institutions such as the Ministry of Education of the People's Republic of China leading in publication output. Research trends identified nine clusters, including particle technology and design, sustainability education, digital technology and virtual learning, and sustainable energy solutions. Emerging technologies like augmented reality, virtual simulations, and deep learning are identified as critical for integrating particle technology into ESD. This study emphasizes the need for interdisciplinary collaboration among educators, policymakers, and researchers to develop innovative digital learning tools. These findings provide a foundation for advancing sustainable educational practices to address global challenges, including clean energy, environmental management, and technological innovation.

1. Introduction

In the era of digital transformation, the use of technology in education is a key factor in improving the quality of learning and supporting the achievement of the Sustainable Development Goals (SDGs). Among the 17 SDGs, quality education (SDG 4), climate action (SDG 13), and clean energy

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(SDG 7) are the main focuses in the world of education [1,2]. These three goals are considered crucial because they contribute to the formation of a more just, inclusive, and environmentally friendly society while providing a framework for facing increasingly complex global challenges. In this context, digital learning media plays an important role as a supporting tool for educators to create a more effective and engaging learning experience for students [3]. This digital media can increase interactivity in the learning process, create a fun and innovative atmosphere, and provide flexibility in delivering material [4]. With the application of digital technology, teaching methods that were previously monotonous and traditional can be replaced with a more adaptive, interactive, and relevant approach. This not only reduces stress, anxiety, and boredom in students but also improves their understanding of complex learning concepts [5,6].

In this context, Education for Sustainable Development (ESD) offers an approach that focuses on equipping students with the knowledge, skills, and values of passion needed to face global challenges [7]. ESD supports the development of relevant competencies to build a more sustainable society, both in social, economic, and environmental aspects. In general, the integration of poverty principles into secondary education helps students understand global issues such as climate change, social inequality, and resource scarcity [8]. In supporting this approach, digital learning media plays an important role as a platform to create interactive learning, provide access to the latest information, and facilitate global collaboration between students and educators [9].

However, one of the main challenges in ESD-based learning is teaching complex concepts, such as technological particles, including nanoparticles or reaction materials, which are often abstract and difficult for students to understand [10]. The characteristics of particles on a nanoscale, which cannot be seen directly, are an obstacle to learning if only using conventional teaching methods [11]. Therefore, digital learning media such as augmented reality (AR) and virtual reality (VR) are effective solutions. AR and VR allow students to visualize particle structures and understand their interactions and reactions in three dimensions [12]. In addition, nanotechnology has great relevance in today's technological developments. The application of nanotechnology in the educational curriculum can prepare students to face future technological challenges. Knowledge of nanotechnology equips students with the skills needed to develop and apply technology at the atomic level [13]. This is very important considering the great potential that nanotechnology has in various sectors, such as renewable energy, health, and environmental protection [14].

In Indonesia, materials on particles and nanotechnology have been included in the high school curriculum. By integrating nanotechnology into education, Indonesia has the opportunity to increase its competitiveness in the global market [15]. By equipping the younger generation with knowledge and skills related to nanotechnology, Indonesia can develop skilled human resources who are ready to face global challenges. Expertise in this field not only strengthens Indonesia's position in international competition but also provides opportunities for innovation and technological solutions that can address global problems such as energy scarcity, health care and climate change [15]. Countries that have the ability to develop and implement nanotechnology have a significant competitive advantage, because this technology is a key determinant in leading the industrial revolution 4.0 and facing competition in the increasingly tight technology market [16]. Several previous studies have discussed the importance of nanotechnology in education, such as those presented in several literature [17,18], which show the challenges in teaching abstract and difficult-to-understand concepts of particles on a nanoscale. Meanwhile, ESD focuses on developing knowledge and skills to create a more sustainable society, but many ESD studies still rely on conventional methods that are less effective in understanding complex concepts [19]. On the other hand, digital learning media such as AR and VR have been shown to improve students' understanding, but the use of these technologies in the context of ESD and nanotechnology is still limited [20].

Therefore, this study aims to see and explore the development of ESD research, digital learning media, and particle technology using bibliometric analysis. By analyzing data from various scientific publications, this study attempts to identify trends, research patterns, and major contributions in the field. Bibliometric analysis allows researchers to quantitatively assess the development of literature, identify the most influential authors and institutions, and understand the dynamics of collaboration in research [21]. Bibliometric analysis of previous studies in various fields is shown in Table 1.

Table 1
Previous research on bibliometric analysis

No.	Title	Result	Ref.
1.	Using biotechnology in education to teach green chemistry: bibliometric analysis and research patterns	Using 420 finished and Scopus-indexed papers, this study employed bibliometric analysis to evaluate the developments in biotechnology education toward green chemistry from 2012 to 2022. With papers representing 42% of all publications, the analysis distinguished three major paper categories: biotechnology, education, and green chemistry teaching. The majority of sources (91%) were journals, which indicate an increase in pertinent publications. Four possible study ideas are suggested by future research trends, highlighting chances to improve biotechnology's useful application in the classroom.	[22]
2.	Techno-economic education publication analysis by computational bibliometrics.	The search focused on titles, keywords, and abstracts of 288 papers from 2017 to 2022. Publications on techno-economic education varied annually, with an increase noted in 2021. This study highlights the utility of bibliometric analysis in understanding phenomena. Its aim is to assist researchers in selecting and conducting research projects effectively.	[23]
3.	Scientific publications on geotechnics fields are analysed using bibliometric and visual methods.	This search was run on October 23, 2020 and yielded 79,185 articles. The findings indicate that Ronald Kerry Rowe is the most productive writer in geotechnical research. Furthermore, China is the largest country in the field of geotechnical research, therefore many other countries have developed cooperative links with it. The International Journal of Rock Mechanics and Mining Science is the most prolific journal for geotechnical engineering research. For keyword analysis, it generates bibliometric maps such as network visualizations, overlay visualizations, and density visualizations. Four keywords frequently appear: "displacement", "strength", "stress", and "earthquake". The bibliometric technique allows academics to detect	[24]
4.	Using the VOSviewer: Scopus database, a computational bibliometric study of research on science and Islam from 2012 to 2022	According to the findings, there were 296.20 citations on average every year between 2012 and 2021 for articles on science and Islam, with an average of 14.18 citations per piece. Every year, the state of science and Islam research continues to deteriorate. With 39 articles, the year 2012 saw the most research, and 2022 saw none. The phrases most commonly connected with scientific and Islamic research are Islam, science, Islamic worldview, education, and study. The nation’s most closely related to this study are Malaysia and Indonesia.	[25]
5.	Bibliometric analysis utilizing VosViewer, indexed by Google, to comprehend the relationship between chemistry and special needs education	Chemistry and special education are the research's major words. One thousand things were pertinent between 2017 and 2021. The search results showed that in 2017, 2018, 2019, and 2020, there were less articles pertaining to "chemistry" and "special education." But it dropped again in 2021. Scholars doing research and choosing research topics are likely to benefit from the study's conclusions.	[26]

6.	Using Vosviewer to compute bibliometric analysis and map visualization on "pharmacy" and "special needs" research data from 2017 to 2021	The mapping analysis using the VOSviewer tool shows that the terms "school," "pharmacy education," "special needs," "patient," and "student" are related to the term’s "pharmacy" and "special needs" and have the highest total link strength. Research on "special needs" and "pharmacy" is often associated with the term "student," particularly with connection strength 603. A research problem or concern in the areas of "pharmacy" and "special needs" can be identified with the aid of this study.	[27]
7.	Bibliometric Analysis using VOSviewer to Gain an Understanding of "Science Education" for "Students with Special Needs"	A study covering the period from 2013 to 2022 was conducted using the number of publications gathered up to 1000 linked articles. The quantity of publications pertaining to scientific education has declined. Nonetheless, there was a rise in the quantity of science education-related publications in 2020, but they decreased the following year.	[28]
8.	A bibliometric examination of nutritional research mapping for endurance sports	A total of 1724 strong links are associated with the term Endurance; 119 strong links are associated with the term Sport; 118 strong links are associated with the term Exercise; 120 links are associated with the term Nutrition; 106 links are associated with the term Endurance Sport; 86 links are associated with the term Sports Nutrition; and a total of 791 strong links are associated with the term Endurance Sport.	[29]
9.	Using Vosviewer, a bibliometric examination of sports science research development	The study's findings demonstrate that the field of instrumentation has grown significantly between 2006 and 2016, with 181 articles (30.68%) reaching their peak in 2018. This growth was indexed on Google Scholar. Authors Davids and Araujo are regarded as productive in the field of sports science research.	[30]
10.	Water hyacinth and ecosystem: A bibliometric literature evaluation on research trends from the Scopus database	The results indicate that there have been sporadic variations in the number of articles published during the course of the last 23 years (2000–2023), which may be categorized into three distinct eras. 2000–2008 and 2009–2015 were designated as the pioneering and growing periods, respectively. In the meanwhile, the acceleration phase will last from 2016 to 2023. There were discovered to be four clusters based on the data visualization results. More often than not, the term "water hyacinth" is used, particularly in 2016. The University of California is the most fruitful affiliate publishing article. India is the most producing nation at the moment. Moreover, the majority of prolific authors Kanna, S. and Dube, T.are Indian.	[31]

Different from other studies using bibliometric analysis in the field of ESD and digital media, which generally focus more on general educational technology trends or research collaboration analysis without linking aspects of particle technology. Existing studies tend to discuss e-learning platforms, learning simulations, or ESD implementation. The research gap of our study is to explore the role of particle technology in supporting sustainable education and innovative solutions in the field of science. Although there is an increase in research on digital learning media and ESD teaching, the focus on the application of particle technology in supporting sustainable development is still very rare.

The novelty of this study lies in the bibliometric analysis approach used to identify and analyse global research trends related to digital learning media, ESD and particle technology. This study not only evaluates the development of publications from a temporal and collaborative aspect but also maps keywords and research topics that have not been widely explored. With this approach, this study offers a significant contribution to filling the literature gap, especially regarding the interconnectedness of digital technology, sustainability education and particle technology, as well as opening up opportunities for interdisciplinary research in the future. Thus, this study is expected to provide valuable insights for researchers, educators, and policymakers in encouraging educational innovation that supports the sustainability and effective use of particle technology.

2. Literature Review
2.1 Particle Technology
2.1.1 Basic concept particle technology

Particle technology is a term that refers to the field of science and technology related to the characterization, formation, processing and utilization of particles [32]. This technology deals with systems in which one or more components are in the form of particles. Particle technology encompasses the study of the properties, behaviour, and applications of particles at various scales, especially the micro and nano scales. The terms particle, powder and particulate solid are often used interchangeably; thus, particle technology is often referred to as powder technology. Recently, the scope of particle technology has been expanded to include systems containing nanoparticles, aerosols, liquid droplets, emulsions, and bubbles [33]. Nanoparticles, which are very small in size (1–100 nanometers), offer unique properties such as high surface area, greater chemical reactivity, and special optical or magnetic capabilities [34]. These advantages allow particle technology to be used in a variety of sustainability-based solutions, including in education and industry. One of the prominent characteristics of nanomaterials is the large surface area compared to macroscopic materials (bulk materials) which are micro-millimeter in size. For example, imagine a sugar cube measuring 1 cm^3 (Figure 1), then we cut the cube into eight parts, then the surface area increases. This means that with the same total mass and volume, it can increase the surface area of a material by reconstructing it into a smaller material. This illustrates the analogy of why nanometer-sized materials are very reactive. Because all reactions of the material with the environment occur on its surface [35].

The range of particulate systems of industrial importance is vast, as are the processes involving particulate systems. Most industrial practices involving energy, chemicals, petroleum, agriculture, food, minerals, pharmaceuticals, environmental and advanced materials utilize particles or powders, in their process operations. Therefore, an understanding of particle science and technology is essential to ensure successful particle synthesis and handling, particulate process design and operational friendliness.

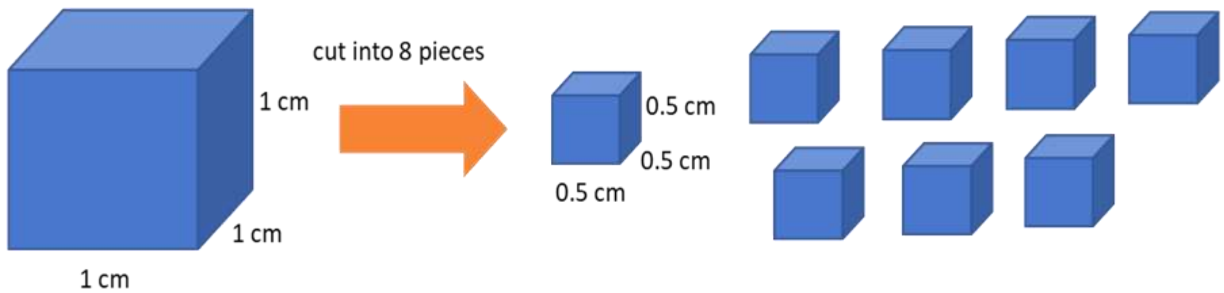

Fig. 1. Particle breakdown illustration

2.1.2 Particle properties

Several particle properties are the basis for understanding their characteristics:

i. Particle size is one of the main properties, usually measured in nanometer (nm) or micrometer (µm) scales. This size affects surface area, reactivity, and optical properties, where small particles tend to have higher reactivity. In addition, particle shape is also important, with variations such as spherical, flat, or irregular. This shape affects the flowability, density of the arrangement, and aerodynamic properties of the particles [36].

ii. Density, both real and bulk density, determines the mass per unit volume and greatly influences the stability, transport, and mixing of the material. Another property is flowability, which reflects the ability of particles to flow as a mass, influenced by shape, size, and humidity. The electrical charge of the particles is also of interest, especially in electrostatic applications, where particles can be charged due to friction or triboelectrification [36].
iii. Flowability refers to the ability of particles to flow as a mass. This property is influenced by several factors, such as particle size, where large particles tend to have better flowability due to lower interparticle friction. Particle shape also plays an important role; spherical particles have better flowability than flat or irregular particles. Moisture is also a significant factor, as wet particles tend to clump together, reducing their flowability. This flowability property is important in a variety of industries, such as pharmaceuticals for tablet production, food for powders, and metallurgy for metal powders [37].
iv. Chargeability is the ability of a particle to store or acquire an electric charge. Factors that influence this property include particle size and material, with small particles having a higher surface area to volume ratio, and therefore more readily becoming charged. Friction between particles through triboelectrification can also generate charge, while the environment, such as humidity and type of medium (liquid or gas), affects the distribution of charge. This charge is important in applications such as electrostatic separation for purification of materials and the stability of colloids or suspensions of particles in liquids [37].
v. Interparticle interactions describe how particles affect each other through physical and chemical forces. Physical forces, such as weak van der Waals forces and electrostatic forces due to electric charge, can attract or repel particles. Meanwhile, chemical forces, such as covalent or ionic bonds, allow particles to bond to each other. The effects of these interactions can cause particles to clump together if the attractive forces between particles are strong enough. Interparticle interactions are very important in determining the stability of suspensions and composite material formulations [37].
vi. Permeability is the ability of a particle or collection of particles to be passed by a liquid or gas. Factors that affect permeability include the size of the interparticle pores, where large or irregular particles create larger spaces that increase permeability, and packing density, where denser packing reduces permeability. This property is very important in applications such as filters, nano membranes, and other porous materials, where it is used to determine the material's ability to transport fluids [37].

2.1.3 Particle characterization

Various techniques are used for particle characterization, including microscopy techniques such as Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Atomic Force Microscopy (AFM) which provide detailed images of the morphology and internal structure of the particles. Dynamic Light Scattering (DLS) is used to determine the particle size distribution through the analysis of light scattering due to Brownian motion. Laser Diffraction measures the particle size distribution based on the angle and intensity of light reflected by the particles. Nanoparticle Tracking Analysis (NTA) tracks the movement of individual particles to determine the size distribution and concentration. X-Ray Diffraction (XRD) is used to identify the crystalline structure and phase composition, while Fourier-Transform Infrared Spectroscopy (FTIR) analyzes the chemical bonds and functional groups on the particle surface. In addition, additional techniques such as BET Surface Area

Analysis and Zeta Potency Analysis are also used to measure the specific surface area and surface charge as well as the stability of colloidal dispersions [38,39].

2.2. Digital Applications Used in Particle Technology Learning to Support Sustainable Development-Based Education (ESD)

2.2.1 E-learning platforms

E-learning platforms are a key tool in supporting modern learning, including in the implementation of ESD and teaching technology articles. Figure 2 shows several e-learning platforms that support the learning process, such as Moodle, Canvas, Google Classroom and Blackboard. These platforms provide flexible virtual spaces to deliver learning materials in various formats, such as text, interactive videos, quizzes and discussion forums. In the context of technology particles, e-learning platforms enable the delivery of materials related to basic theories, such as nanoparticle structures, particle reactions and their applications in sustainable materials. In addition, these platforms support the use of reflective videos and interactive quizzes designed to spread students' understanding of complex topics, such as particle-based coating materials or clean energy storage. With these features, e-learning platforms become very effective tools in supporting ESD-based learning, while encouraging students' understanding of the concept of desire and advanced technology [40,41].

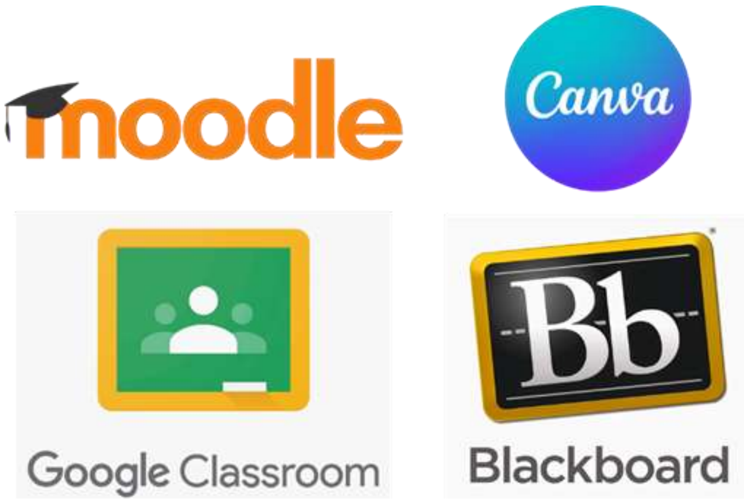

Fig. 2. E-Learning platforms

2.2.2 Simulation software

Computer-based simulation tools allow students to study particle behaviour and its applications in virtual environments that closely approximate real-world conditions. Figure 3 shows some commonly used software, such as COMSOL Multiphysics, ANSYS Fluent and MATLAB Simulink, to model particle systems in a variety of contexts, including pollutant dispersion, particle interactions in fluids, and thermal reactions of nanomaterials. In ESD applications, these simulations help students understand desirable concepts, such as the use of nanoparticles in air filtration systems or wastewater treatment. In addition, these simulations provide safe, experiment-based learning experiences, reduce reliance on expensive physical laboratories, and encourage practical solution-based learning. With their interactive features, computer-based simulation tools are an essential tool in preparing students for the challenges of modern technology and global migration [42,43].

Fig. 3. Simulations software

2.2.3 Virtual reality (VR) application

VR creates an immersive learning environment, allowing students to interact directly with particle simulations in real-world scenarios. This technology, through devices such as the one shown in Figure 4, Oculus Rift or Google Expeditions VR, provides an immersive and realistic learning experience. In particle technology learning, VR allows students to explore virtual laboratories where they can conduct experiments related to nanoparticle reactions, material efficiency or waste treatment processes. In ESD applications, VR becomes a powerful tool to visualize sustainability solutions, such as material analysis in thermal energy storage. By eliminating the limitations of a physical laboratory, VR provides a hands-on learning experience that is safer, cheaper and more effective [44,45].

Fig. 4. Virtual reality application

2.2.4 Augmented reality (AR) application

AR brings virtual elements into the real world, allowing students to visualize particle technology concepts in a more interactive and contextual way. This technology, as shown in Figure 5 through the Merge Cube, Zappar AR, Vuforia, Assemblr applications, gives students the opportunity to manipulate models of nanoparticle structures or study particle reactions in sustainable systems. In ESD-based learning, AR can be used to illustrate complex processes, such as air filtration using nanoparticles or sustainable material design in energy storage systems. This technology provides a direct visual experience that allows students to see and understand abstract mechanisms more concretely. By presenting interactive models, AR not only enhances students' understanding of difficult concepts but also encourages deeper engagement in the learning process [46,47].

Fig. 5. Augmented reality (AR) application

2.2.5 Interactive video and animation

Interactive videos and animations are very effective media to explain dynamic processes in particle technology. Through platforms such as Edpuzzle, Kahoot! or TED-Ed, as seen in Figure 6, educators can deliver complex materials in a more interesting and easy-to-understand form. In particle technology learning integrated with ESD, animated videos can be used to illustrate processes such as particle movement in fluids, thermal reactions of nanoparticles, or the effects of nanomaterials in water filtration. The advantage of this media is its ability to combine visual, audio and interactive elements so that students can learn in a flexible way and be directly involved in the learning process. Animations that explain the application of sustainable materials in clean energy can also enhance students' understanding of the contribution of this technology to sustainability [48].

Fig. 6. Interactive video and animation

2.2.6 Big Data Analysis and Artificial Intelligence (AI)

Big data and AI provide great opportunities to improve the effectiveness of particle-based learning in the context of ESD. Through applications such as IBM Watson, ChatGPT, Gemini, Google Classroom Analytics (Figure 7), educators can analyze learning data to understand students' learning patterns, identify their difficulties, and provide more personalized recommendations. In particle-based learning, AI can be used for the effectiveness of particle simulations or to customize nanoparticle-based learning modules to students' needs. This technology can also be used to identify the impact of learning on students' understanding of poverty issues, such as waste management or clean energy. By leveraging AI's ability to generate in-depth analysis, educators can create more adaptive and relevant ESD-based learning [50].

Fig. 7. Big data analysis and artificial intelligence (AI)

3. Methodology

In order to conduct the bibliometrics analysis for this research, there are several stages carried out, namely as follows:

i. Data collection
The collected data were obtained from the Scopus database used (https://scopus.com, last visited on July 3, 2024). The Scopus web search was conducted using the following keywords: " (TITLE-ABS-KEY (“Education for Sustainable Development” OR "ESD”) OR TITLE-ABS-KEY (“Technology particle" OR "technology in sustainable development" OR "nano-particles technology”) OR TITLE-ABS-KEY (“digital learning media" OR "E-learning platform" OR "digital educational tools”). The Scopus document search includes journal articles in the last ten years 2014-2024.

ii. Screening
At this stage, 5,000 documents were obtained from the Scopus Database. Furthermore, filtering was carried out based on abstracts, use of English, and types of documents limited to journals, leaving 4,511 documents. Data from the Scopus Database were then stored in RIS and CSV formats, which were used in the next stage.

iii. Bibliometric analysis
The next stage involves conducting bibliometric network analysis and creating maps using visualization tools such as VOSviewer and Microsoft Excel. Microsoft Excel is utilized to generate simple charts and graphs, such as line graphs, to illustrate the distribution, annual publications, and trends. Meanwhile, VOSviewer was used for network visualization to detect patterns and trends in the data, including identifying the most prominent authors, institutions, papers, and potential future research themes [51,52]. VOSiewer offers both network visualization and overlay visualization for a comprehensive analysis. Additional information on the use of VOSviewer software for data analysis and visualization can be found elsewhere [51].

iv. Interpretation and conclusion
At this stage, the results of the bibliometric analysis are interpreted to identify trends, collaboration patterns, and research contributions in the analysed topic. Through VOS viewer, network visualization is carried out to map the relationships between the most influential authors, institutions, and journals. The collaboration network shows the institutions or authors that have a key role in advancing research on this topic. Overlay visualization provides an overview of future trends, including the identification of emerging research topics. Then, the conclusions of this analysis are then summarized to provide a comprehensive overview of research contributions, future development directions, and implications for education policy and sustainable practice.

4. Results and Discussion

4.1 Publications Trends

Figure 8 shows the trend in the number of publications over the past ten years (2014-2024) relevant to the topics of “Digital Learning Media," “Education for Sustainable Development (ESD),” and “Particle Technology." Based on Figure 8 in 2014-2017, the number of publications was relatively stable at around 260-280 documents. This shows that research interest in this topic is still limited, especially since there has been no significant push from the development of digital technology and sustainable education policies. The increase began to be seen in 2018, when the number of publications rose from 200 documents to more than 500 documents in 2020. This spike coincided with the increasingly widespread implementation of technology in education and the increasing attention to ESD. After peaking in 2021 with around 550 documents, the trend fluctuated slightly in 2023 before finally increasing again to reach 600 documents in 2024, indicating that this topic remains relevant and continues to grow. In addition, the sharp increase that occurred between 2019 and 2021 is closely related to the COVID-19 pandemic. The pandemic accelerated the transition from conventional learning to digital learning. Media such as Learning Management Systems (LMS), e-learning platforms, and various interactive applications became the main solutions in maintaining the continuity of education during the crisis. At the same time, the pandemic increased the relevance of ESD by driving global awareness of the importance of sustainable education in addressing environmental, health, and technological challenges.

In practice, digital learning integrated with the ESD concept opens up opportunities for broader access to education, especially during the pandemic. The use of digital media supports innovative interactive learning methods, allowing students to understand global issues in more depth. On the other hand, particle technology is important to teach students because it plays a crucial role in improving their understanding of complex and abstract scientific concepts. Through this technology, students can learn how particles interact in various natural phenomena and technological processes visually and practically [53]. This allows students to more easily understand concepts such as chemical reactions, fluid dynamics, pollutant dispersion, and nanotechnology, which are often difficult to explain with conventional approaches. Particle-based simulations through digital learning help stimulate students' analytical and imaginative thinking because they can see visual representations of scientific theories in real-world contexts [54].

The relevance of technology particles in the ESD framework is increasingly strong, along with the need to understand and address global ecosystem challenges. This technology makes a significant contribution to improving students' understanding of issues such as climate change, clean energy, and waste management. This understanding helps foster critical awareness of climate change and sustainable development issues. In addition, the integration of technology particles encourages 21st-

century skills such as technological literacy, critical thinking, and collaboration, which are highly needed in the modern workplace that is increasingly dependent on technology. Furthermore, studying technology particles can inspire students to pursue careers in advanced technology and science fields, such as nanotechnology, chemical engineering, environmental engineering, and clean energy development. With an understanding of how particles work in various technological applications, students can contribute to creating innovative solutions to real-world problems [55]. Therefore, teaching technology articles in schools and universities is not only important for improving scientific and technological literacy, but also for preparing a young generation that is competitive, innovative, and able to face global challenges in realizing sustainable development.

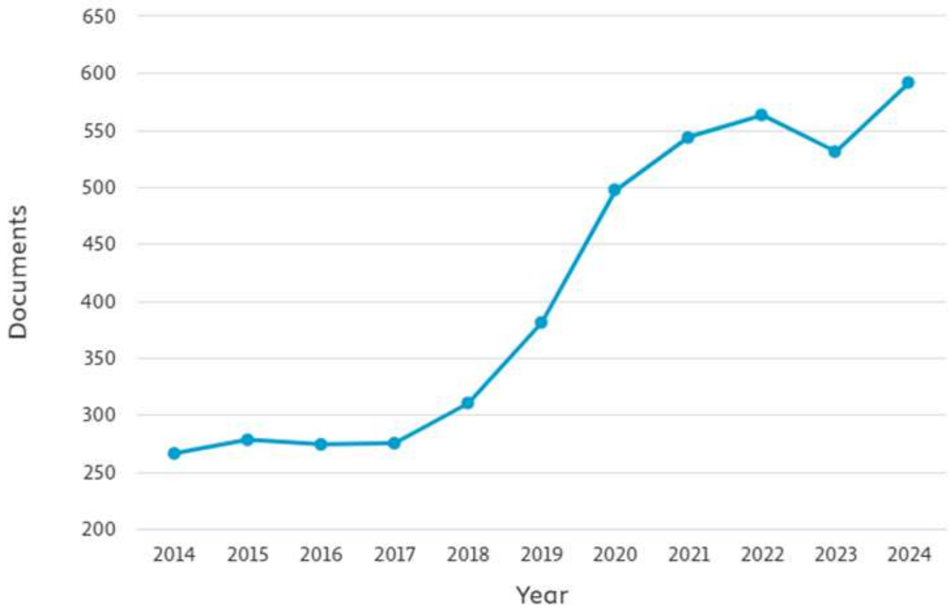

Fig. 8. Publication trends per year

4.2 Articles with the Most Citation

Table 2 presents article data based on the highest number of citations on the topics of “Digital Learning Media”, “ESD”, and “Particle Technology”. From the data in Table 2, the article “Online teaching and learning in higher education during the coronavirus pandemic: Students’ perspective” by Coman *et al.,* [56] has received many citations with a total of 613 citations over the past ten years (2014-2024). This shows that research such as that conducted by Coman *et al.,* [56] provides important insights into the online learning experience during the COVID-19 pandemic, which can be a foundation for educators to design more effective and student-centered online learning models. A high number of citations indicates the relevance of the topic discussed as well as the quality of the research recognized by the scientific community. In addition, a high number of citations also reflects the relevance of the topic discussed as well as the quality of the research recognized by the scientific community. Articles that are frequently cited are generally considered important references for other researchers and indicate that the results of the research have broad applications, especially in developing more innovative and sustainable educational practices.

As shown in Table 2, the articles with the highest number of citations reflect a strong research trend in the use of digital technologies for education and sustainability. The dominance of studies published in 2020 confirms that the COVID-19 pandemic has been a major driver of accelerating digital transformation in the education sector. Topics such as e-learning, artificial intelligence, big data, and ESD are of primary concern, indicating the urgent need to create more adaptive, inclusive, and sustainable education systems. This research provides important implications for educators to improve digital literacy competencies, for policymakers to support educational technology infrastructure, and for educational institutions to integrate sustainability into technology-based curricula.

Table 2
List of articles with the highest number of citations

No.	Topics	Authors	Year	Citation	Ref.
1	Online teaching and learning in higher education during the coronavirus pandemic: Students' perspective	Coman, C., Țîru, L. G., Meseșan-Schmitz, L., Stanciu, C., Bularca, M. C	2020	613	[56]
2	Sustainability in higher education in the context of the un DESD: A review of learning and institutionalization processes	Wals, A. E.	2014	349	[57]
3	Effects of different interactions on students' sense of community in e-learning environment	Luo, N., Zhang, M., Qi, D.	2017	82	[58]
4	Adapting the technology acceptance model to evaluate the innovative potential of e-learning systems	Persico, D., Manca, S., Pozzi, F.	2014	178	[59]
5	A survey of artificial intelligence techniques employed for adaptive educational systems within e-learning platforms	Colchester, K., Hagras, H., Alghazzawi, D., Aldabbagh, G	2017	184	[60]
6	Energy-storage-based low-frequency oscillation damping control using particle swarm optimization and heuristic dynamic programming	Sui, X., Tang, Y., He, H., Wen, J.	2014	182	[61]
7	Five trends of education and technology in a sustainable future	Burbules, N. C., Fan, G., Repp, P.	2020	131	[62]
8	Analysis of student behavior in learning management systems through a Big Data framework	Cantabella, M., Martínez-España, R., Ayuso, B., Yáñez, J. A., Muñoz, A.	2019	128	[63]
9	E-learning platforms as leverage for education for sustainable development	Donath, L., Mircea, G., Rozman, T.	2020	18	[64]
10	Educational sustainability through big data assimilation to quantify academic procrastination using ensemble classifiers	Abidi, S. M. R., Zhang, W., Haidery, S. A., Rizvi, S. S., Riaz, R., Ding, H., Kwon, S. J.	2020	14	[65]

4.3 Authors and Countries with the Most Publications

Table 3 shows the authors' contributions to the topics of "Digital Learning Media," "(ESD)" and "Particle Technology" from various countries. Based on Table 3, the author with the highest number of publications is Ker, M.D., from Taiwan with 42 publications, followed by Jin, X., from China with 35 publications and Koo, Y.S., from South Korea with 34 publications. Taiwan shows a significant contribution to research productivity, with three authors included in the list, namely Ker, M.D., Lin, C.Y. and Chen, S.L. Meanwhile, China dominates this list with four authors, namely Jin, X., Liu, Z., Wang, Y. and Du, F. Meanwhile, South Korea only has one contributing author, namely Koo, Y.S., with

34 publications. From the European side, Austria is represented by Pommerenke, D. with 30 publications. Meanwhile, India is represented by Shrivastava, M. with 25 publications.

Table 3
Authors with the most publications

No.	Authors	Number of Documents	Nation
1.	Ker, M.D.	42	Taiwan
2.	Jin, X.	35	China
3.	Koo, Y.S.	34	South Korea
4.	Liu, Z.	33	China
5.	Pommerenke, D.	30	Austria
6.	Lin, C.Y.	39	Taiwan
7.	Chen, S.L.	27	Taiwan
8.	Wang, Y.	27	China
9.	Shrivastava, M.	25	India
10.	Du, F.	21	China

Furthermore Figure 9 complements the information from Table 3, which highlights the individual contributions of authors from several countries. Based on Figure 9, China dominates with 977 documents, followed by the United States with 506 documents, then Germany (313 documents), Japan (297 documents), and South Korea (296 documents). This significant contribution is in line with the productivity of individual authors in Table 3, where authors such as Jin, X., Liu, Z., Wang, Y. and Du, F. are from China, which confirms China's position as a global leader in the production of scientific publications in the field. This dominance reflects the strategic policy of the Chinese government in encouraging scientific research and technological innovation, especially in digital education and sustainability. Meanwhile, India, with 273 documents and individual contributions from Shrivastava, M. followed by France and Spain, have lower publications with 150 and 233 documents, respectively.

This analysis highlights the authors' important role in generating methods and information that promote sustainable practices in international educational institutions. The diversity of their geographical publications reflects the complex and interconnected nature of global challenges such as climate change and the energy crisis, which are addressed through ESD approaches, digital learning media, and particle technologies [66]. The research encourages the application of technologies such as adaptive e-learning, particle-based science simulations, and big data analytics to create more inclusive, interactive, and contextual learning. The contributions of countries such as China, Taiwan, South Korea, Austria and India demonstrate the importance of global collaboration to integrate technological innovations in education, providing significant impact for educators in adopting modern learning methods and for policymakers in designing education policies that support digital transformation and sustainable development. Thus, this research provides a foundation in building a young generation that is able to face global challenges and contribute to the achievement of the SDGs.

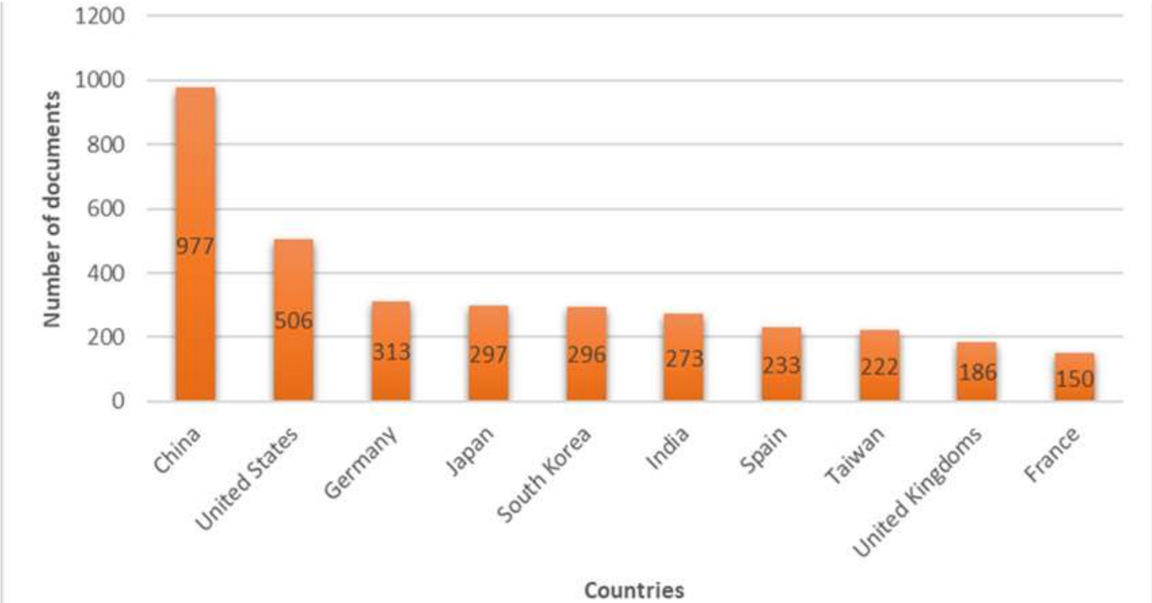

Fig. 9. Countries with the most publications

4.4. Affiliation with Leading Contribution

Table 4 presents the documents with the highest contribution to research based on affiliation. Based on Table 4, the highest contributor is the Ministry of Education of the People's Republic of China with 80 documents, followed by the University of Electronic Science and Technology of China with 69 documents, the Chinese Academy of Sciences with 69 documents. Then, seven other institutions have less than 60 articles. It is usually found that institutions affiliated with the highest contributing authors show the highest productivity. The three most productive institutions are from China, the country's need for advanced technologies to support various sectors, including digital education, particle technology and ESD. The focus of these studies is related to domestic challenges such as education modernization, waste treatment, clean energy and environmental sustainability. Strong support from the government and collaboration between universities and industry have created a productive research ecosystem, making China a leader in technological innovation that contributes significantly to achieving the SDGs [67].

Tabel 4
Affiliation with Leading Contribution

Affiliations	Documents
Ministry of Education of the People's Republic of China	80
University of Electronic Science and Technology of China	69
Chinese Academy of Sciences	69
CNRS Centre National de la Recherche Scientifique	58
National Chiao Tung University	56
National Taiwan Normal University	42
Missouri University of Science and Technology	39
Peking University	38
Zhejiang University	36
Dankook University	33

4.5 Trending Research Subject Area

Figure 10 is research related to topics based on subject areas. Engineering, Computer Science, Materials Science, and Environmental Science dominate with a proportion of more than 11%. This is because topics such as “Digital Learning Media,” “(ESD),” and “Particle Technology” are closely related to technology development, material innovation and the implementation of sustainable solutions that require an interdisciplinary approach. Engineering dominates because this field is the foundation for the development of new technologies, including particle technology, simulation-based learning tools, and digital infrastructure solutions that support education and sustainability. Computer Science plays a key role in the development of e-learning platforms, big data analytics, AI-based adaptive learning, and visualization technology, which support digital and interactive educational transformation [68].

Meanwhile, Materials Science contributes greatly because research in this topic often focuses on the development of environmentally friendly materials, nanotechnology and particle technology for applications in clean energy, waste treatment and increasing industrial efficiency. Environmental Science also has a significant role because sustainability and climate change mitigation issues are global priorities. Research in this field often combines particle technology and materials-based innovation to address environmental issues, such as air pollution, clean water treatment and renewable energy production [69].

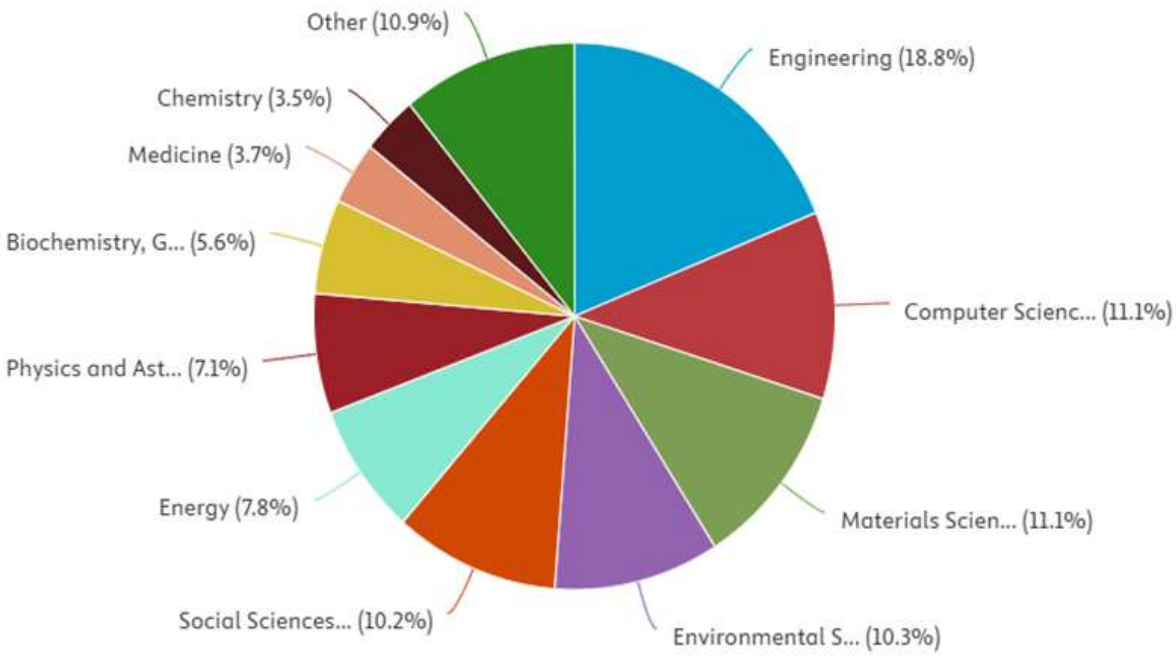

Fig. 10. Distribution of research documents by subject area

4.6 Mapping Visualization

Figure 11 shows a network visualization based on keyword co-occurrence using VOSviewer, which groups keywords into 9 main clusters with different colors, namely Cluster 1 (red), Cluster 2 (green), Cluster 3 (dark blue), Cluster 4 (yellow), Cluster 5 (purple), Cluster 6 (light blue), Cluster 7 (orange), Cluster 8 (brown), and Cluster 9 (pink). The clusters indicate the research focus related to ESD, particle technology, and digital learning media, with the size of the circle reflecting the frequency of keyword occurrence and the connecting lines depicting the relationship between topics. The following is an explanation of each cluster:

i. Cluster 1 (Particle Technology and Design):
The focus of this cluster includes keywords such as technology, coating, design, optimization, investigation and sensor. This theme relates to the development of particle technology, sustainable material design, and technology optimization in various applications such as energy storage and environmental efficiency. This research shows the role of advanced technology in supporting sustainability and clean energy-based solutions.

ii. Cluster 2 (Analysis, Evaluation, and Learning Model)
The dominant keywords are analysis, model, impact, platform and evaluation. This cluster focuses on evaluation and analysis methods related to digital learning media and platform technology to measure the impact and effectiveness of learning. Research in this cluster can be used to improve the implementation of digital technology in education.

iii. ClESD
This theme highlights the importance of curriculum development, sustainability competencies, and teaching practices at the higher education level to support the achievement of SDGs.

iv. Cluster 4 (Teacher Readiness and Competence)
Keywords such as teaching, competency, teacher education, and readiness emphasize the role of educators in the readiness to adopt ESD technology and practices. This research can help improve teachers' technological literacy and skill development in teaching sustainability concepts.

v. Cluster 5 (Curriculum and Environmental Education)
Keywords such as curriculum, environmental education, school, and community indicate a focus on the integration of environmental education in formal and non-formal curricula. This is important in forming students' awareness of sustainability issues from an early age.

vi. Cluster 6 (Digital Technology and Virtual Learning)
This cluster involves keywords such as augmented reality, distance, learning, and achievement. The focus is on the implementation of e-learning technology and virtual media such as augmented reality to increase the effectiveness of the learning process.

vii. Cluster 7 (Sustainable Energy)
Keywords such as energy storage, thermal energy, and long-term outcome indicate research related to clean energy and energy storage technologies, which are relevant to sustainable solutions in energy resource management.

viii. Cluster 8 (Performance Evaluation and Network)
This theme includes keywords such as network, performance, and student performance, which emphasize the evaluation of learning performance through digital technology and data-based networks.

ix. Cluster 9 (Experimentation and Technology Development)

Keywords such as experiment, mechanism and innovation refer to experimental research to develop new technologies, especially in the field of particles and materials.

Figure 12 shows a keyword co-occurrence-based overlay visualization using VOSviewer, depicting research trends related to ESD, technology particles, and digital learning media from 2019 to 2022. The colours in the network indicate the temporal evolution of research topics, where purple represents early topics that emerged in 2019, green for topics that developed in 2020–2021, and yellow shows the latest trends in 2022. Research trends evolved from an initial focus on ESD integration in educational curricula, with keywords such as higher education, curriculum and teaching in the early years 2019. As the development progressed, the focus shifted to the use of digital platforms and analysis of the impact of technology on learning, as seen from keywords such as platforms, analysis, and dominant models in 2020–2021. The latest trends in 2022 highlight advanced technologies such as deep learning, thermal energy storage, and optimization, which are closely related to innovative technology particles for clean energy solutions and sustainability.

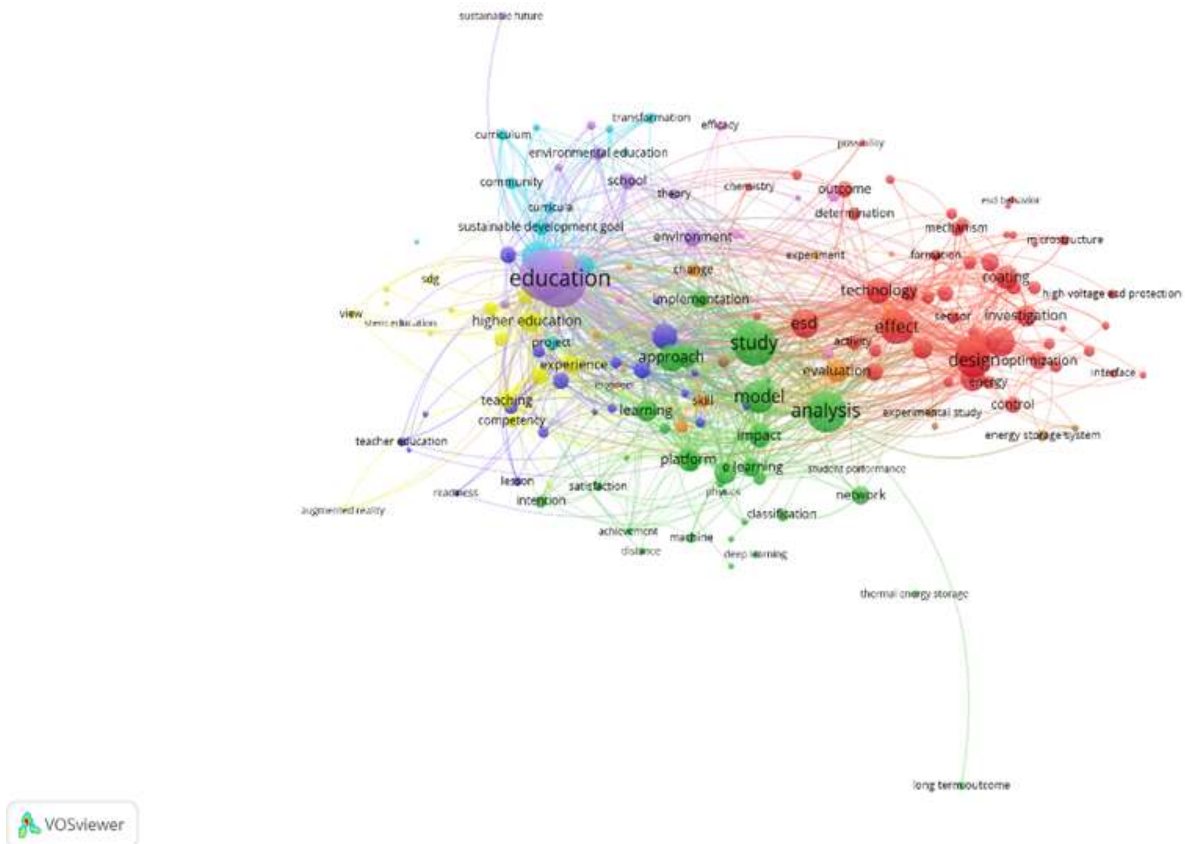

Fig. 11. Network visualization

Based on the results of the visualization analysis above, several important topics were found that have not been widely discussed but have a high urgency to be explored further. One of them is the integration of technological particles in digital learning media. Research on technological particles, such as nanoparticles, is still limited to the development of sustainable materials and has not been linked to its implementation in ESD and Science, Technology, Engineering and Mathematics (STEM) learning through e-learning platforms or virtual simulations. The use of augmented reality and virtual learning to model technological particles can help students understand complex concepts, such as reacting materials, energy storage, and nanotechnology, in a more visual, interactive, and practical way. At the same time, evaluation of learning performance based on big data and AI also needs to be further developed [70]. Although several studies have focused on performance analysis, in-depth exploration of the use of AI and big data analysis to measure the effectiveness of educational availability is still very limited. This technology has the potential to help educators understand student learning patterns, broadcast the effectiveness of ESD-based curriculum, and design more personalized and adaptive learning interventions according to student needs. In addition, there is still a gap in interdisciplinary collaboration between ESD, digital technology, and technological particles. The integration of these three elements can create innovative and holistic solutions that not only support environmental sustainability but also contribute to solutions to global learning problems such as clean energy, waste management, and the development of environmentally friendly technologies [71].

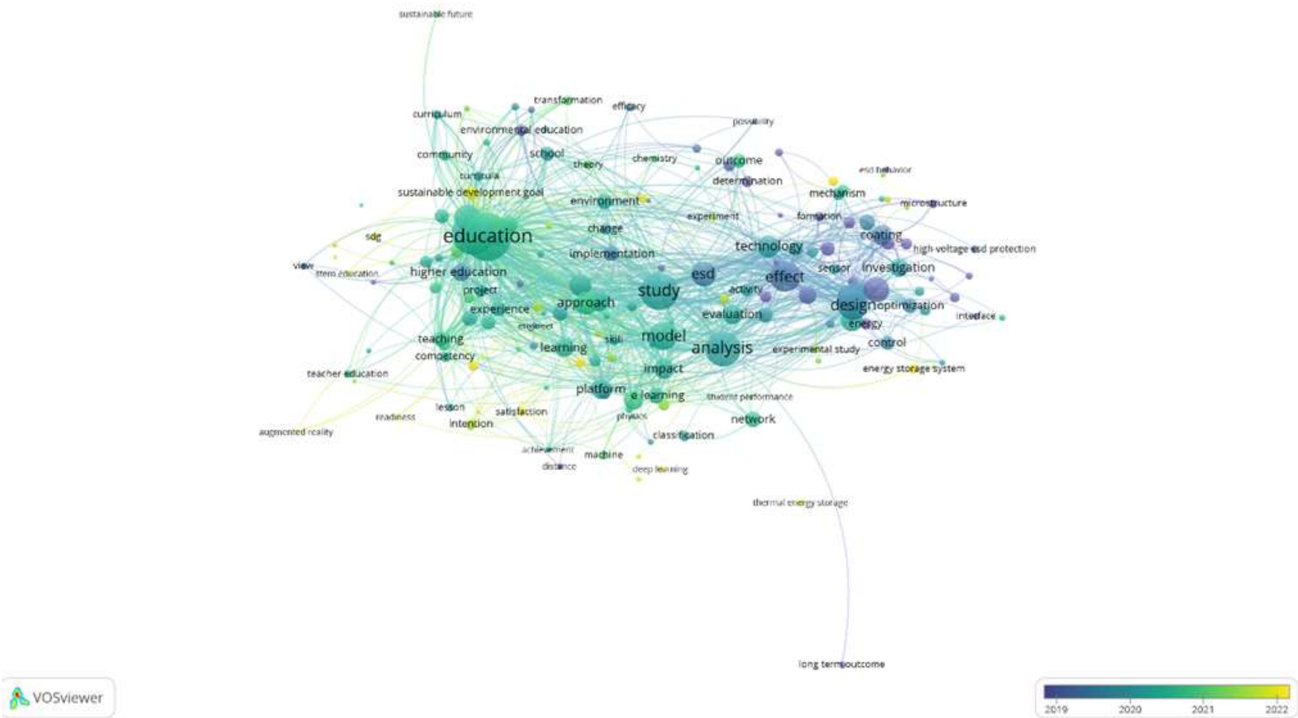

Fig. 12. Overlay visualization

The implications of the results of this visualization include several important aspects. For educators, the integration platform for e-learning and digital technology enables a more effective and interactive learning approach, especially in teaching the concept of academic education (ESD). Educators also need to improve technological literacy to support modern technology-based teaching methods. For policymakers, these results can be the basis for formulating policies that encourage the development of digital infrastructure in education, investment in research on technology particles and clean energy, and the integration of ESD into the national education curriculum. Meanwhile, for researchers, these results open up opportunities to explore areas of research that have not been widely developed, such as the application of technology particles in renewable energy innovation and waste management, as well as in-depth analysis of the impact of digital technologies such as immersive learning in education. Thus, the integration of ESD, digital learning media, and technology particles has great potential to encourage innovation in sustainable education and contribute to global solutions in the fields of technology, clean energy and the environment. Collaboration between educators, policymakers, and researchers is key to realizing educational transformation that is more adaptive and relevant to future challenges.

5. Conclusions

The research has successfully explored EESD, digital learning media, and particle technology through a bibliometric analysis of research trends from 2014–2024. Publications increased significantly during the COVID-19 pandemic, driven by the adoption of e-learning, LMS, and interactive technologies that support sustainability. Countries such as China, United States and Germany dominate the contributions, with nine main clusters, including particle technology, sustainability education and clean energy. Based on the visualization analysis, there are important topics that have not been widely explored, such as the integration of particle technology in digital learning media. Research on nanoparticles still focuses on sustainable materials and has not touched on their application in ESD and STEM learning through e-learning platforms or virtual simulations. Technologies such as augmented reality and virtual learning can help students understand complex concepts, such as material reactions, energy storage, and nanotechnology, in a more visual, interactive, and practical way. This research highlights the need for collaboration between educators, policymakers, and researchers to improve technological literacy, develop digital infrastructure, and create ESD-based innovations. The integration of digital media and particle technology in education offers great potential to support sustainability, clean energy, and global environmental solutions.

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