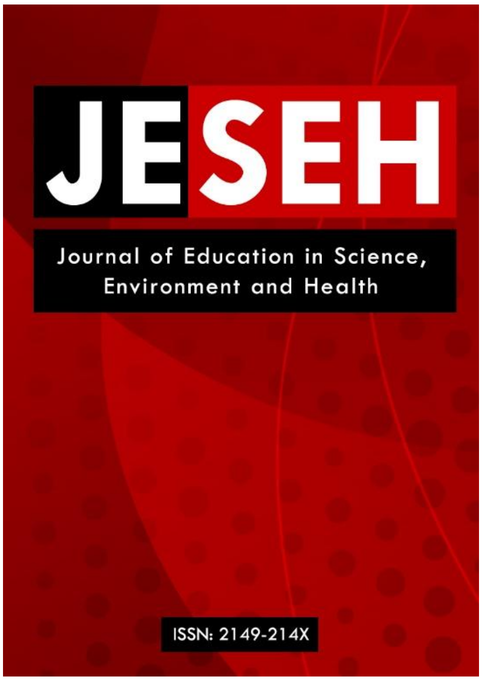

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Virtual Reality Technology in Science Education: Exploring Trends and Future Perspectives

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Abstract

The importance of virtual reality in science education is constantly increasing. For this reason, this study aims to identify current trends in science education through virtual reality (VR) themes using a bibliometric analysis of the Web of Science (WoS) database. Data analysis was conducted with VOSviewer software. Findings reveal that VR studies are primarily categorized under "Education Educational Research" and "Education Scientific Disciplines." VR technology first appeared in science education research in 2002, with publications steadily increasing over time. The most prolific and influential researchers were Lamb, Richard, and Etopio, Elisabeth, while the United States, Australia, and Türkiye had the highest academic impact. The most frequently used keywords were "virtual reality," "science education," "augmented reality," and "higher education," while recurring abstract terms included "technology," "knowledge," and "research." These results underscore the rising importance of VR technologies in science education and map the evolving research landscape, offering valuable insights for future studies and educational practices.

Introduction

Digitalization, together with rapid developments in information and communication technologies, leads to radical transformations in many areas of life. In particular, basic social areas such as communication, economy, and education have experienced significant changes under the influence of digital technologies. The replacement of traditional work and life practices with digital processes has profoundly transformed the ways in which individuals access information and interact with it. Digitalization not only changes economic and social structures but also redefines individuals' lifestyles and learning habits. Thanks to the opportunities offered by technologies, individuals and organizations can share information much faster and more efficiently and time and space limitations are largely eliminated (Castells, 2010). While Castells (2010) defines digitalization as the basic building block of the information society, Negroponte (1995) describes it as the transition from the physical world to the virtual world, and underlines that this transition has profound effects on individuals and social structures.

Education has become one of the sectors most affected by digitalization. The education technology market, which is growing every year, clearly reveals the extent of this transformation. It has been reported that by 2023, the size of the global edtech sector will exceed 250 billion dollars (HolonIQ, 2023). This trend is also supported by the fact that the number of users of online education platforms is increasing by 20% annually. In Türkiye, data from the Ministry of National Education (MoNE) for 2022 shows that the EBA platform was used by more than 20 million people. Data such as these confirm that digitalization has led to radical changes in the field of education, while also revealing its contributions to educational processes. Digital education technologies transform learning and teaching approaches into a more effective, flexible, and interactive structure. Traditional classroom practices are being replaced by online platforms, simulation-based teaching techniques, and individualized learning methods (Doğan et al., 2024). This transformation enables students to access information more quickly, while teachers can monitor student performance more efficiently (Means et al., 2009). Moreover, digitalization provides teachers with the opportunity to implement a more student-centered and interactive teaching methodology. Additionally, students can advance at their own pace using digital resources, surpassing traditional classroom boundaries (Ozdemir et al., 2017). Another significant benefit of digitalization is its ability to foster the development of collaborative learning environments. According to Siemens (2005), digital technologies empower individuals to engage in in-depth and meaningful learning experiences by providing easier access to diverse sources of information. This shift transforms learning from a solitary activity into a collaborative community experience.

One of the most notable innovations in digital education is the adoption of VR technologies. VR enables users to experience realistic scenarios by immersing themselves in computer-supported three-dimensional environments (Dalgarno & Lee, 2010). This technology has enhanced educational experience by offering an interactive and dynamic learning process. VR applications, particularly those that simplify the understanding of abstract concepts, open new horizons in education. They allow students to engage in experiences that would be challenging or impossible to achieve in a physical environment (Merchant et al., 2014). The ability of VR to support immersive learning experiences can be used to demonstrate this argument. In history classrooms, for example, students can use VR to tour ancient cities; in chemistry classes, they can safely conduct dangerous experiments; and in astronomy classes, they can conduct in-depth analyses of the solar system (Aktamıs & Arıcı, 2013; Dikyol & Isbilen, 2020; Kahveci & Sondas, 2023).

Science education, being a field that deals intensively with complex and abstract concepts, has significant potential to create a strong synergy with VR technologies. In the field of chemistry, the utilisation of three-dimensional visualisations of molecular structures or the employment of virtual environments to simulate chemical reactions has been demonstrated to facilitate students' comprehension of abstract concepts (Avcı & Taşdemir, 2019). In the context of physics courses, these technologies facilitate the experiential learning of fundamental principles, such as Newton's laws of motion, within a virtual laboratory environment (Karakaş & Ozerbas, 2020). In the field of biology, the potential for VR to facilitate detailed examination of complex biological systems, such as cellular structures and human anatomy, has been demonstrated (Azmanoglu & Topal, 2024). This technological advancement has the capacity to enhance students' understanding of these subjects. In the domain of astronomy education, the utilisation of VR applications facilitates spatial exploration of the solar system and galaxies through the medium of virtual planet simulations (Cankaya & Girgin, 2018). It is submitted that such virtual experiences make a unique contribution to science education by allowing students to experience scenarios that are not possible in the real world. These technologies have been shown to facilitate the comprehension and experience of abstract scientific concepts among students (Aktamıs & Arıcı, 2013; Merchant et al., 2014). For instance, the visualisation of chemical reactions at the molecular level or the in-depth study of cell structures are some of the unique learning opportunities that can be offered in VR environments. Furthermore, VR applications offer a particularly valuable solution for schools with limited laboratory facilities. As posited by Rutten et al. (2012), experiments that may pose a threat to the health and safety of subjects, or that require a significant financial investment in real laboratory conditions, can be conducted safely and cost-effectively in a virtual environment. Consequently, student motivation is enhanced and the development of scientific process skills is accelerated. A further significant rationale for the accelerated propagation of these technologies within the domain of science education is that they facilitate a more dynamic and interactive engagement with scientific concepts among students. Interactive and visual learning environments have been shown to facilitate the retention of scientific knowledge by promoting meaningful and in-depth learning. Research has indicated that such applications contribute to students' enhanced comprehension of scientific processes and refinement of their cognitive abilities (Jensen & Konradsen, 2018).

VR in the Context of Türkiye

In recent years, there has been a notable surge in scholarly interest in the utilization of VR technologies within the domain of science education. A plethora of studies have indicated that the utilization of VR in the domain of science education has the potential to facilitate students' conceptual understanding, enhance their scientific process skills, and augment their motivation for learning, thereby contributing to an improvement in their academic achievement (Aktı Aslan, 2019; Bilen & Zor, 2024;Küçüksavcı, 2017; Makransky & Lilleholt, 2018; Merchant et al., 2014). In scientific disciplines such as chemistry, biology and physics, VR has been shown to be an effective tool in making abstract concepts more understandable (Aktamıs & Arıcı, 2013; Boz, 2019; Yagcı & Şenturk, 2023). Significant research has been conducted on the use of VR in science education in the Turkish context. For instance, in the study conducted by Aktamıs and Arıcı (2013), it was emphasized that VR applications are not only an effective method in increasing students' academic achievement in astronomy courses, but also in ensuring the retention of learned information. A study undertaken by Cankaya (2019) concluded that the integration of augmented reality applications, incorporating virtual elements, into secondary school science courses was associated with enhanced student achievement and motivation. Demir (2019) conducted a study to ascertain the attitudes of pre-service teachers towards VR technologies, revealing that VR technology can be considered an effective method to increase the interest and motivation levels of pre-service teachers towards their courses. The study also expressed the importance of integrating these technologies into teacher education programmes. The findings of this study demonstrate that VR can serve as an effective educational tool in the domain of science, contributing to both the instruction and the learning processes. Furthermore, it has been demonstrated that VR applications have a beneficial impact on science education processes in general (Jensen & Konradsen, 2018).

When literature is examined, there are also studies that systematically compile and review the use of VR technology in education. A bibliometric analysis of 307 postgraduate theses conducted in Türkiye between 1996 and 2020 was the basis of a recent study which found that VR and augmented reality topics have become increasingly prominent in postgraduate thesis studies in Türkiye in recent years (Gsncan, 2022). In their methodological analysis of studies on the applications of virtual and augmented reality technologies in the field of education in Türkiye Kapucu and Yıldırım (2019) sought to address this paucity of research. The research findings revealed that these studies largely focus on the discipline of computer education and have shown especially a significant increase in recent years. The investigation revealed a predominance of qualitative research approaches, with student groups being examined and techniques such as scales and t-tests being extensively utilised in the analysis processes. The findings of these studies generally took the form of descriptive results and frequently included various suggestions for future research. It is also stated that there is a more intense interest in studies on the integration of augmented reality into education. Turgut and Denizalp's (2021) study constitutes a comprehensive examination of the trends in research on VR technologies in the field of education in Türkiye. The findings revealed that studies on the use of VR have shown a significant increase, especially in recent years, and that ready-made content is generally preferred. A review of the extant literature reveals a preponderance of quantitative methodologies, with a judicious selection of samples for the purpose of study and the utilization of questionnaires and interview forms as the primary data collection instruments. Furthermore, it was observed that predominantly predictive statistical techniques were utilised in data analysis processes.

Systematic review methods, including meta-analysis, bibliometric analysis, and content analysis, are imperative tools for the analysis of research trends within a specific field, the meticulous examination of data, and the interpretation of results within a broader context. These methods play a crucial role in measuring and evaluating the efficiency of research techniques used in disciplines such as education and science (Borenstein et al., 2009; Krippendorff, 2018; Moed, 2005). A review of the extant literature reveals a paucity of studies that systematically examine VR in the field of education. This phenomenon is particularly pronounced in the context of science education, where the subject is addressed, resulting in a notable escalation in the perceived limitations within the relevant domain.

Purpose of the Study

The aim of this study is to determine the research trends by examining the scientific studies on VR in science education, based on the Web of Science (WoS) database. To this end, answers to the following sub-questions will be sought:

1. Which categories do studies on VR fall into?
2. How do research trends change over the years?
3. What is the distribution of prominent researchers and their publication profiles?
4. What are the most cited researchers and their citation distribution?
5. What is the structure of the analysis of bibliographic matches of the studies?
6. What are the trends of the countries that stand out according to the number of citations?
7. What are the trends of the most commonly used keywords in studies?
8. What is the structure of the conceptual network formed by the most commonly used words in article abstracts?

In line with these questions, scientific productivity, interaction networks and conceptual trends in the field will be analyzed in detail.

Importance of the Study

In recent years, there has been a noticeable increase in the number of academic studies on VR applications in science education. This increase is closely related to the growing recognition of the innovative and effective possibilities offered by VR technology in education. Especially in science education, VR applications, which facilitate the understanding of abstract concepts, enrich educational processes by providing students with active learning opportunities. This is frequently emphasized in the literature (Aktamıs & Arıcı, 2013; Makransky & Lilleholt, 2018; Merchant et al., 2014). However, there is a significant gap in literature regarding a comprehensive review of academic studies on this subject. Considering the rapid advances in technology and transformations in educational approaches, there is an ongoing need to systematically evaluate more recent academic studies. In this context, the bibliometric analysis method stands out as a powerful tool for revealing trends in VR applications in science education, identifying existing research gaps, and analyzing scientific studies produced in this field (Moed, 2005; Yılmaz, 2021).

Studies show that significant improvements are achieved in student achievement, motivation and conceptual understanding levels in VR supported science education (Aktamıs & Arıcı, 2013; Aktı Aslan, 2019; Bilen & Zor, 2024; Kucuk- Avcı, 2017; Makransky & Lilleholt, 2018; Merchant et al.) However, the limited number of systematic reviews of these studies creates an important gap in literature. This deficiency makes it difficult to reveal the effects of rapidly developing technological innovations and changing educational approaches on science education. For example, Makransky and Lilleholt (2018) state that technological advances constantly offer new opportunities in education and that these innovations should be analyzed in depth in literature. Similarly, in Türkiye, it can be said that this situation limits scientific awareness in the field. In this context, the need for more up-to-date and systematic bibliometric analysis studies is evident (Irwanto et al., 2022). This study aims to reveal, by examining the existing literature in detail, how VR technologies are applied in science teaching and research trends in this field in line with current data. By addressing dynamic research trends and emerging themes, this bibliometric analysis aims to provide a comprehensive roadmap for researchers and educators. In addition, the main goal of the study is to evaluate the developments in the local context and to reveal new research opportunities in this field, with a special emphasis on VR-oriented studies in science education in Türkiye.

Method

In this research, the method of bibliometric analysis, which is defined as an attempt to manage big information through conceptualization that shows the trends and structural composition of scientific research in a field (Passas, 2024), was used, analyzed, and evaluated with VOSviewer visualization software. VOSviewer is defined as software that can create bibliometric maps by establishing network connections between items such as scientific publications, researchers, and keywords; analyze the relationships between them; and present these maps with network, layer, and density visualizations (Van Eck & Waltman, 2023; Zhang et al., 2023). By using this software, the aim is to obtain detailed profiles of research on VR technology until 2025 and thus guide future research trends in the related field.

Obtaining and Analyzing Data

The Web of Science (WoS) database, which includes three major citation indexing databases SCI, SSCI, and A&HCI, is a widely used source of scientific evidence in different disciplines (Jia & Mustafa, 2023; Sarkar et al., 2022). It also holds an important place as the first bibliographic database (Pranckute, 2021). For this reason, the WoS database was preferred in the study to create the dataset within the scope of the research. Web of Science was accessed on 06.02.2025 from the university database, to which the researcher was affiliated, and the framework was created using the contents as criteria within this context.

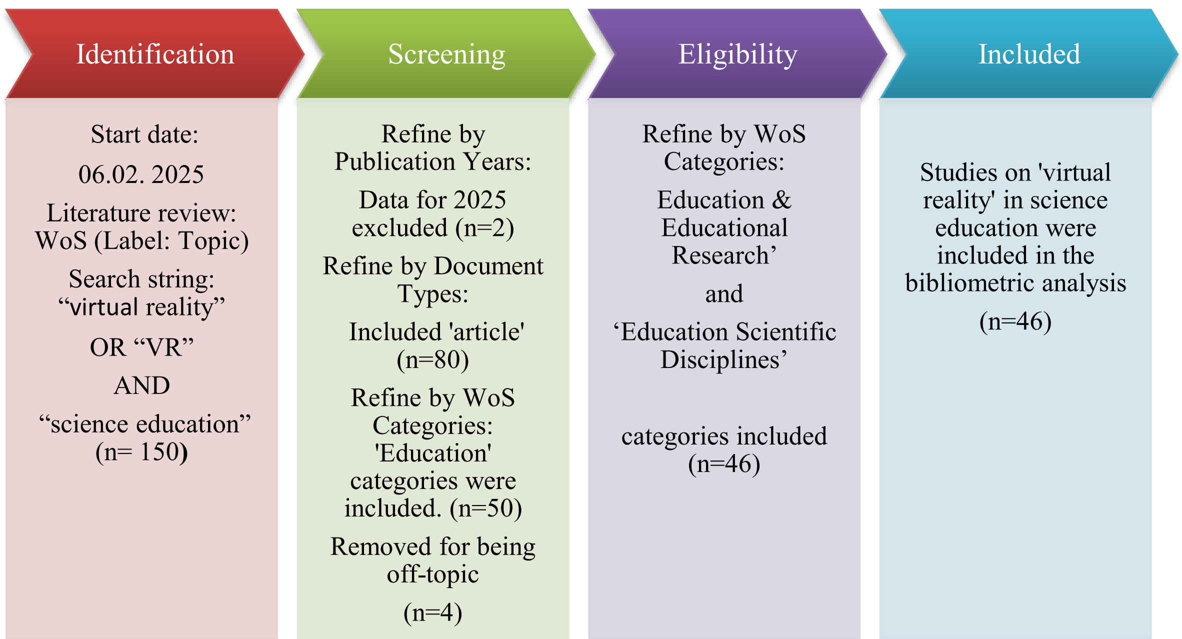

Figure 1. Flowchart followed in the creation of the dataset

In the WoS database, 150 studies were reached with the keywords “virtual reality” or "VR" and “science education” under the title of “topic”. Considering that the data flow for 2025 continues, the aim was to examine the studies until December 2024, and to determine the trend dynamics. In this context, 148 studies were identified. In the next stage, only the studies in the article type were included (n=80). The categories of ‘Education & Educational Research’ and ‘Education Scientific Disciplines’ in the WoS database were selected (n=50). The articles that were out of the subject were removed (n=4). As a result, a total of 46 articles were identified and analyzed. The process followed in obtaining the dataset of the study is presented in Figure 1, which includes the PRISMA flow diagram (Moher et al., 2009).

Results

Breakdown of the Top Ten WoS Categories of VR Technology Applications

Although the categories 'Education & Educational Research' and 'Education Scientific Disciplines' were included in the scope of the research, it was considered to examine the categories that include VR technology from a holistic perspective. In this context, when the WoS database is examined, VR applications are found to be included in 41 categories in total. The distribution of the first ten categories is given in Figure 2. When the results obtained are analyzed, VR applications are mostly categorized under the category of 'Education Educational Research' (f=45).

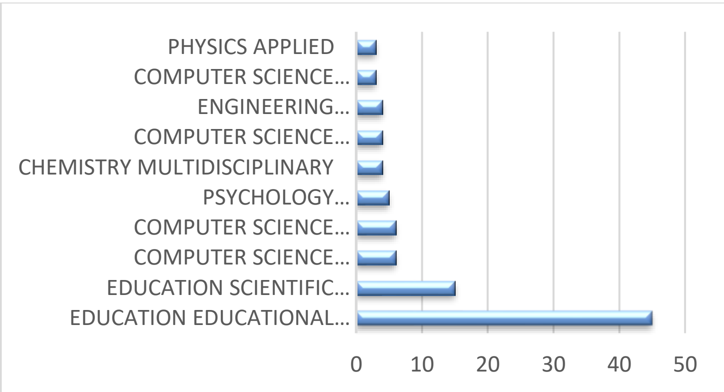

Figure 2. Breakdown of the top ten WoS categories of VR technology applications

Changes in Research Trends by Year

According to the results provided by the WoS database, the changes in VR technology applications in science education over the years appear in Figure 3. When the data in Figure 3 are analyzed, it is seen that VR technology in science education has been included in the studies since 2002. According to the results obtained, the trend shows that studies on VR technology increased with each passing year.

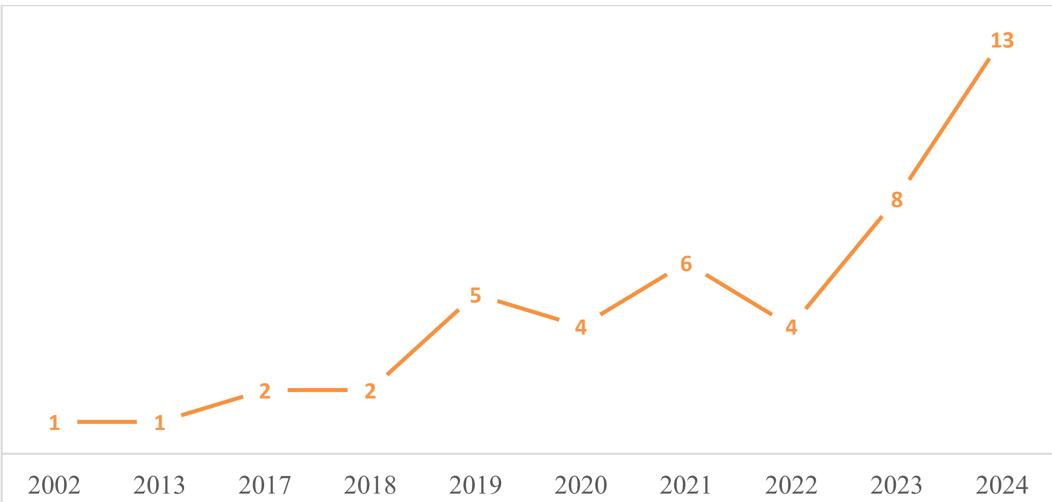

Figure 3. Changes in VR technology applications over the years

Featured Researchers and Publication Profiles

According to the WoS database results, the total number of researchers working on VR technology in the field of science education was determined to be 145. The top ten researchers and their publication profiles are given in Figure 4. The researcher who conducted the most academic studies on VR technology in science education was Lamb, Richard (*f*=4), followed by Etopio, Elisabeth (*f*=3).

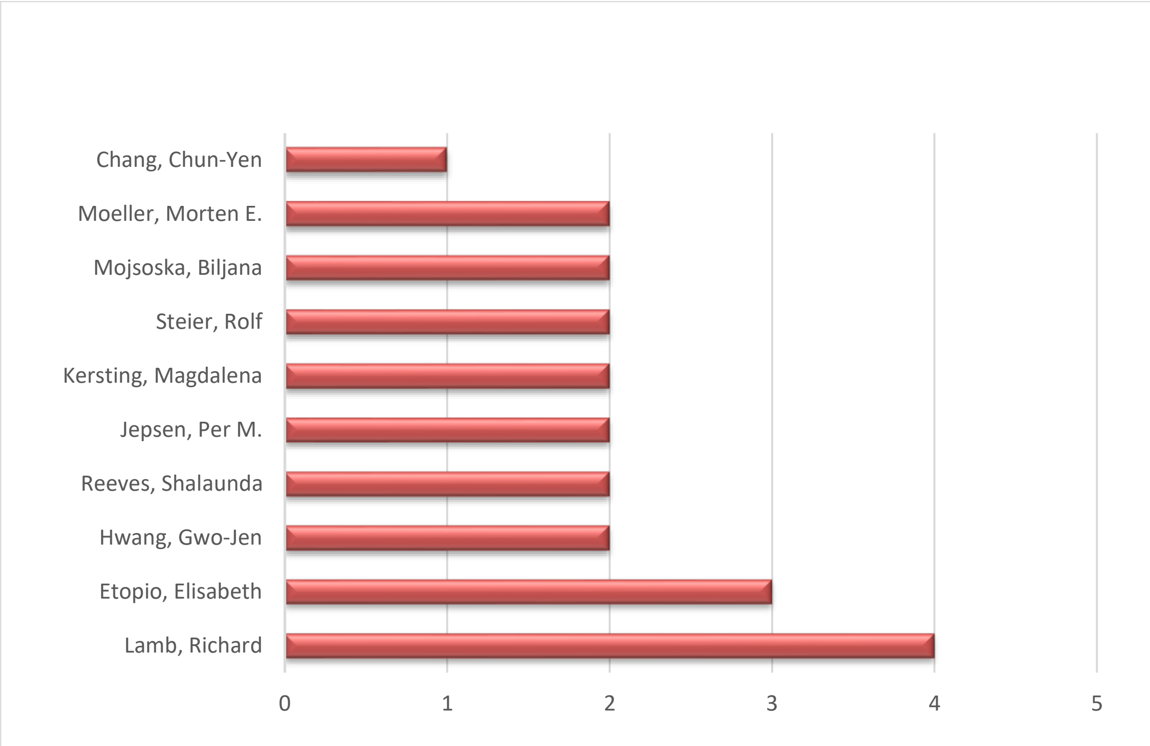

Figure 4. Featured researchers and publication profiles

Most Cited Researchers and Citation Distribution

In order to identify the most cited authors and the network interaction between them, at least two publications and at least two citation criteria were used. The findings obtained as a result of the VOSviewer analysis are presented in Table 1 and Figure 5.

Table 1. Most cited researchers and citation distribution

Author	NoD	NoC
Lamb, Richard	4	127
Etopio, Elisabeth	3	100
Jepsen, Per Meyer	2	26
Mojsoska, Biljana	2	26
Pande, Prajakt	2	26
Crippen, Kent J.	2	26
Reeves, Shalaunda M.	2	26
Kersting, Magdalena	2	25
Steier, Rolf	2	25
Hwang, Gwo-Jen	2	8

Note. NoD: Number of Documents, NoC: Number of Citations

The results of the analysis show that the most cited authors are Lamb, Richard and Etopio, Elisabeth. It is seen that these most cited authors are included in the citation network with Jepsen, Per Meyer, Mojsoska, Biljana and Pande, Prajakt.

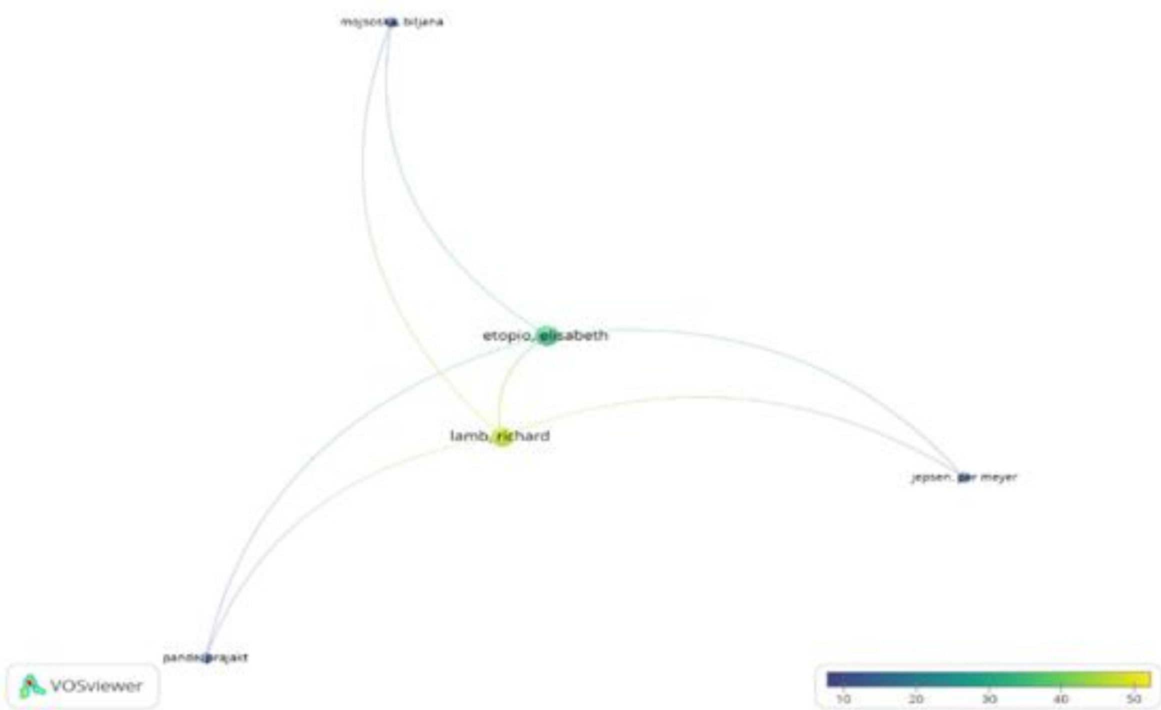

Figure 5. Most cited researchers and citation distribution

Analysis of Bibliographic Matches of Studies

An analysis was conducted to determine the bibliographic matches of the studies on VR in science education. The results of the analysis, made with the criterion of publishing at least 1 work and receiving 5 citations to determine the map of citations to a common work cited by two independent sources are given in Figure 6.

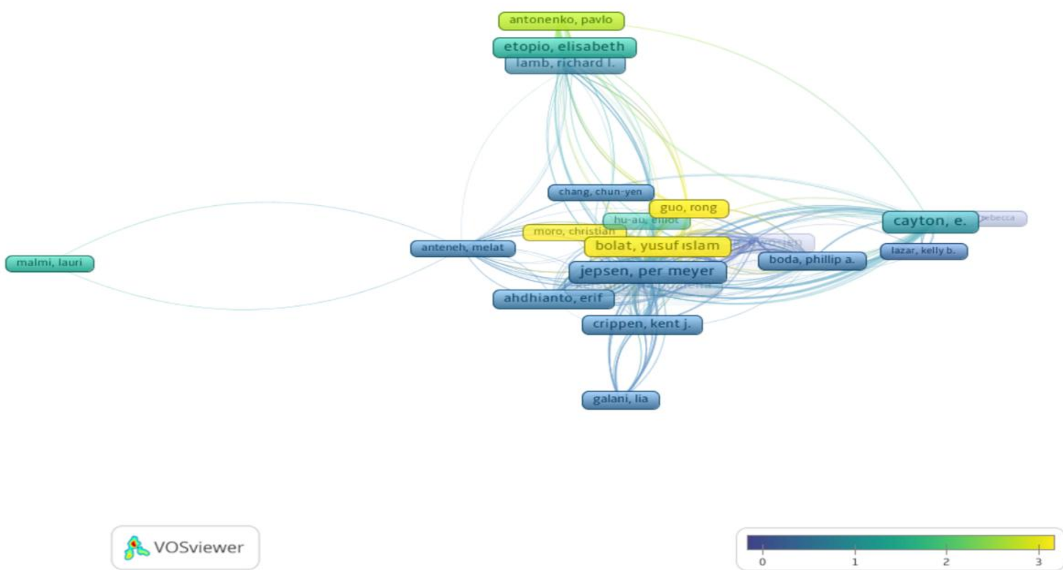

Figure 6. Bibliographic matching of studies on VR in science education

The authors with the highest number of bibliographic matches are Etopio, Elisabeth (100 citations and 685 total link strength), and Lamb, Richard (92 citations and 395 total link strength). On the other hand, other noteworthy names in the bibliographic match map are Jepsen, per Meyer (26 citations, 735 total link strength) and Bolat, Yusuf Islam (77 citations and 566 total link strength).

Prominent Countries by Citation Count

In order to identify the prominent countries according to the number of citations, fifteen countries and a total of 54 publications were identified based on analysis using the criterion that a country has received at least one citation. The profile of the first ten countries that stand out from these results is presented in Table 2 and Figure 7.

Table 2. Prominent countries by citation count

Country	NoD	NoC	TLS
USA	22	284	7
Australia	3	110	6
Türkiye	5	109	0
Peoples rChina	3	86	4
Taiwan	7	48	3
South Korea	2	39	2
Finland	1	34	0
Denmark	3	32	4
Norway	2	25	3
Chile	1	22	5

Note. NoD: Number of Documents, NoC: Number of Citations, TLS: Total Link Strenght

The most cited countries are the United States (USA), Australia, and Türkiye, respectively. Although Türkiye ranks third among the most cited countries, it is not reflected in the VOSviewer analysis result in Table 2 because of lack of total link strength.

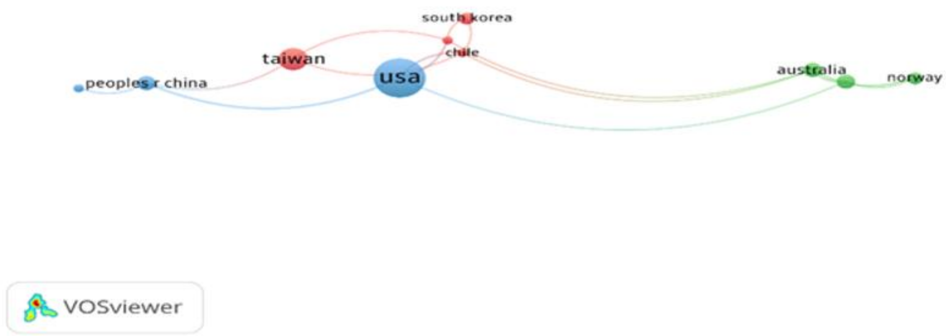

Figure 7. Prominent countries by citation count

Trends of the Most Commonly Used Keywords in Research

The results of the analysis conducted to identify the most used and recently prominent keywords within the scope of VR technology in the field of science education are presented in detail in Table 3 and Figure 8.

Table 3. Trends of the most commonly used keywords

Keyword	*f*
Virtual reality	31
Science education	19
Augmented realty	5
Higher education	4
Extended realty	3
Engagement	2
Astronomy education	2
Immersive learning	2
Teacher preparation	2
Gender	2

Note. f: Frequency

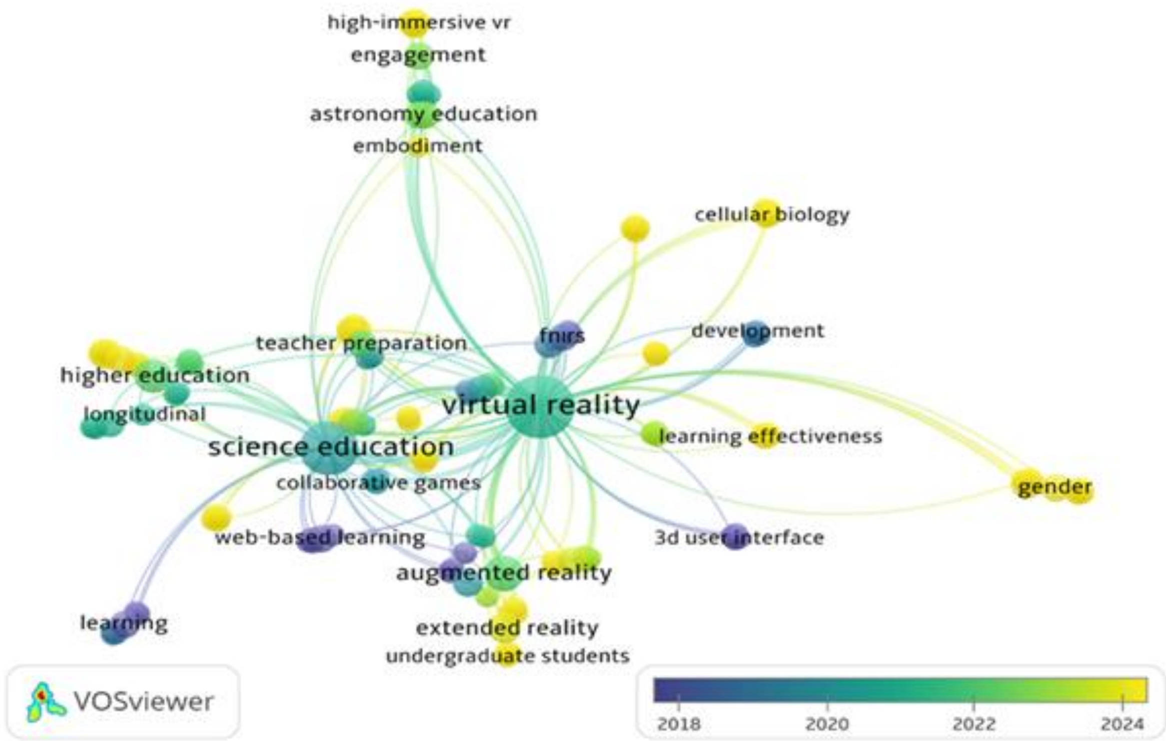

Figure 8. Trends of the most used keywords

According to Table 3, the most frequently used keywords are 'virtual reality', 'science education', 'augmented reality', and 'higher education'. In recent years, the concepts of 'extended reality', 'undergraduate students', 'gamified VR', 'cellular biology', 'education technology', 'high-immersive VR', 'self-study', 'constructivism', 'gender', 'virtual laboratory', 'experiential learning', were also found to be the subject of studies with virtual reality.

Conceptual Network Structure of the Most Commonly Used Words in Article Abstracts

'Abstract field' was selected and analyzed by determining the frequency of repetition of terms that were repeated at least five times. 1464 terms were identified, and 42 terms were found to meet the criteria. The results of the analysis are presented in Table 4 and Figure 9.

Table 4. Conceptual network structure of the most commonly used words in abstracts

Words in Abstracts	*f*
Technology	22
Knowledge	17
Research	17
Application	13
Difference	12
Analysis	12
Science	10
Data	9
Participant	9
İmpact	9
Way	9
System	8
Ability	8
Framework	7
Role	7
Attention	6
VR environment	6

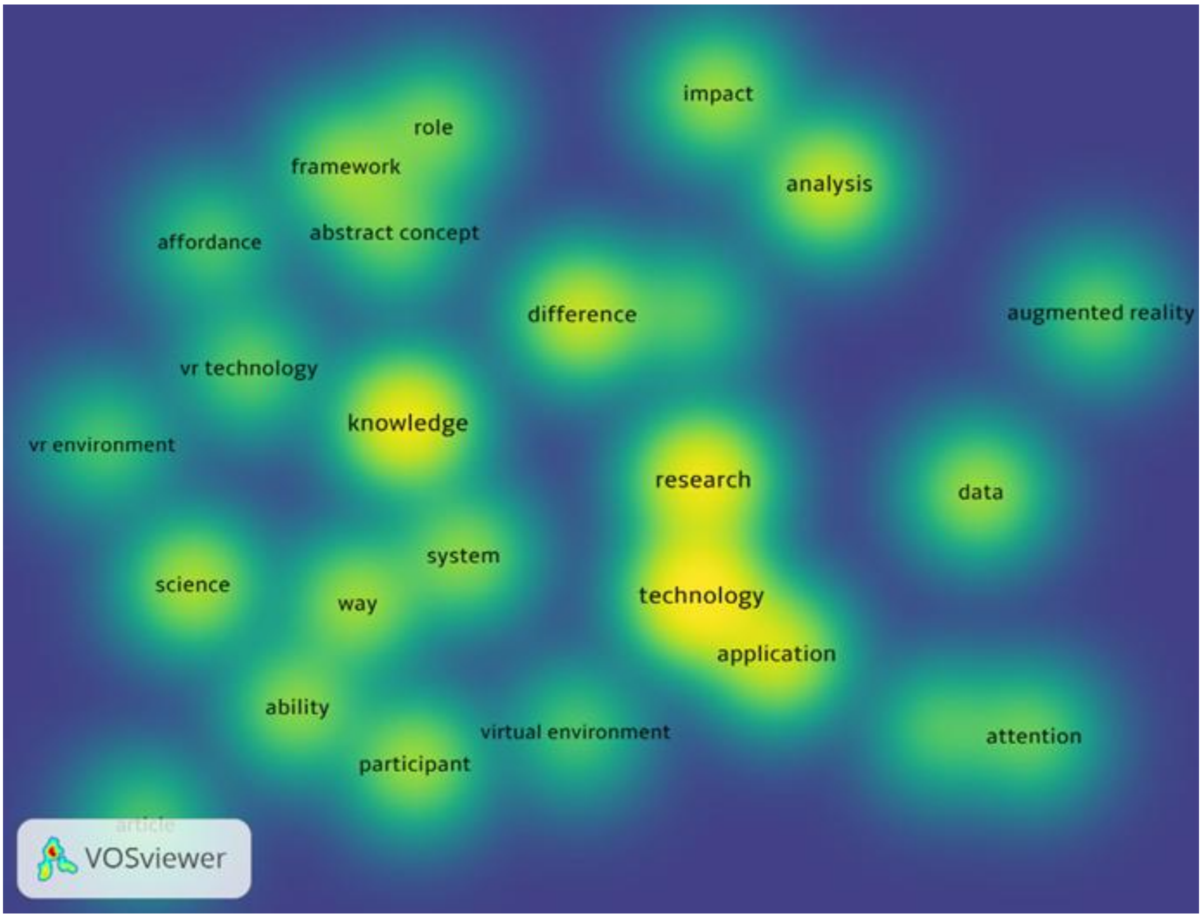

Figure 9. Conceptual network structure of the most commonly used words in abstracts

According to the results of the analysis, the most frequently used words in abstracts are 'technology', 'knowledge' and 'research'. In the VOSviewer analysis, the 'overlay visualization' method shows that the terms 'application', 'framework', 'ability', and 'impact' stand out among the words that frequently appear in research abstracts in recent years.

Conclusion and Discussion

By reviewing scientific literature on VR in science education using the Web of Science (WoS) database, this study seeks to detect research trends in the field. The data demonstrated that VR applications were dispersed across 41 distinct categories. "Education Scientific Disciplines" and "Education Educational Research" are notable names among these categories. According to this study, VR technology is becoming more and more popular in the field of education and is crucial to educational research (Dede, 2009; Merchant et al., 2014). Applications that utilize VR are mostly focused on educational and educational research, according to a number of bibliometric evaluations. For instance, a bibliometric study of graduate theses in Türkiye on augmented reality and VR revealed that these subjects have grown in popularity recently and are primarily focused on teaching (Guncan, 2022). Additionally, a different bibliometric analysis of the idea of the Metaverse in education revealed that the majority of the research on this subject is focused on education and related fields (Karakus & Seckin, 2024).

According to the study's results, VR technology has been the subject of scientific education research since 2002, and the amount of research in this area continues to increase over time. Since the early 2000s, VR technology has been more popular and available in educational settings thanks to improvements in computer hardware and a decline in the cost of VR systems (Kahveci & Sondas, 2023). Applications like augmented reality have made it possible to concretize abstract notions in science education through interactive learning environments, which are a result of the growing significance of the constructivist learning method (Aktamıs & Arıcı, 2013; Cavas et al., 2004; Dede, 2009). Meanwhile, academics are focusing more closely on STEM education and using VR technology in the classroom because of the growing interest in this area (Merchant et al., 2014). Furthermore, research on VR-based education has significantly increased because of funding in the US, Europe, and Asia

(Radianti et al., 2020). By giving students, the chance to experience intricate processes in a risk-free setting, VR applications enhance experiential learning and support science education in this regard (Aktamıs & Arıcı, 2013; Makransky & Lilleholt, 2018).

Based on the study's findings, there were 145 researchers who studied VR technology in scientific education in total. The scholars with the greatest number of studies, citations, and bibliographic matches were found to be Richard Lamb and Elisabeth Etopio. This demonstrates their proficiency in the area and the significance of the work they have done in exposing the possibilities of VR technology in science instruction. It demonstrates that both researchers have a significant academic impact on their disciplines and that other academics regularly cite their work. In their joint research, Lamb and Etopio thoroughly investigated the usefulness of VR applications in science education as well as their impact on students' acquisition of scientific ideas and scientific writing techniques (Lamb et al., 2019). They underlined that pre-service science teachers can effectively apply their theoretical knowledge through VR (Lamb & Etopio, 2020).

Lamb and Etopio are in the same citation network as Jepsen, Per Meyer, Mojsoska Biljana, and Pande Prajakt, according to another significant study finding. Yusuf Islam, Per Meyer and Bolat, and Jepsen are further noteworthy names in the bibliographic matching map, following Lamb and Etopio. An essential method for observing the concentration and interplay of knowledge in an area is the mapping of academic networks (Gonzales-Aguliar et al., 2023). This suggests that these authors work together academically, either directly or indirectly, or that they study related topics. Furthermore, the names that are garnering interest in the citation network may be used as a possible point of reference to direct further research. Researchers can better observe current trends in literature and formulate their own research questions within this framework by looking at the works of these authors. In addition to helping detect research gaps and scientific production, these citation network analyses are a valuable tool for determining which themes are prevalent in the academic area and which scholars concentrate on these subjects (Moed, 2005).

The analysis's findings indicate that, based on the quantity of citations, the United States, Australia, and Türkiye stand out. Large-scale research initiatives and significant resources in VR technologies have made the US a leader in this field. Prior study indicates that the United States is a global leader in VR applications and technology-oriented educational research (Mikropoulos & Natsiz, 2011; Slater & Wilbur, 1997). By using VR in the classroom, Australian institutions are also contributing significantly to the creation of visual and interactive learning experiences (Johnson et al., 2015). This is arguably one of the primary causes of the nation's rising citation count. Citations have increased considerably in Türkiye in recent years, primarily as a result of the incorporation of technology into science instruction. Innovative technologies like VR and their application in education are attracting more and more attention from academics in Türkiye (Muz & Yuce, 2023). Nevertheless, Türkiye's low link strength in the VOSviewer study suggests that there are few all over the world collaborations and that studies mostly have a local or regional impact, even with the high number of citations. This implies that in order to make a greater global contribution to the scholarly literature on VR and scientific education, Türkiye needs to expand its partnerships.

VR and augmented reality technologies have found many applications in the field of science education, and there is an increasing interest in their use, particularly at the higher education level (Mikropoulos & Natsis, 2011). The study's findings indicate that the studies on the use of VR technology in science education are focused around the themes of "virtual reality" and "science education." Other prominent keywords in the literature involve "augmented reality" and "higher education”. Alongside these themes, phrases like "gamified VR," "extended reality," and "high-immersive VR" have started to appear in recent years, referring to emerging technologies that further broaden the use of VR in education. This result demonstrates interest in research on gamified and interactive technology applications. Research on "gamified VR" applications in particular highlights how these technologies affect students' academic performance, motivation, and engagement. Research in this area indicates that gamification techniques based on VR can significantly alter the way that lessons are taught (Bouchrika et al., 2019; Lampropoulos & Kinshuk, 2024). The applications of VR technologies to provide concrete form to abstract and complicated subjects like "cellular biology" is another significant scientific area. This highlights how VR technology can help students learn by bringing complicated scientific ideas to life (Dede, 2009). Students can also gain theoretical information through real-world applications in virtual environments thanks to ideas like "virtual laboratory" and "experiential learning”. Especially in experimental and practice-based fields such as science, interactive learning tools are known to help students better comprehend the subject matter (Bogusevschi et al., 2020). Other remarkable methods in VR-based education are "self-study" and "constructivism." According to constructivist learning techniques, this research demonstrates that VR technology may support individual learning processes (Aktamıs & Arıcı, 2013; Sarıoglu, 2019). Specifically, ideas like "high-immersive VR" and "extended reality" (XR) enable students to learn more deeply by simulating real-world interactions. Research in this context reveals that these technologies have a significant impact on both individual and group learning processes in education (Cheng & Tsai, 2020; Dalgarno & Lee, 2010). Simultaneously, the association of the concept of "gender", a social phenomenon, with the utilisation of VR applications in educational contexts can be regarded as a methodology for the examination of the impact of gender disparities on VR-based applications and educational learning processes (Basaran, 2010; Cakır et al., 2022; Tuzun et al., 2016). In this context, this association can provide a novel research domain for the comprehension and analysis of gender inequalities in the application of educational technologies. In accordance with the findings obtained, it was determined that the keywords frequently encountered in the abstracts of the studies on VR technology in science education were "technology", "knowledge" and "research". This situation suggests that there is an increasing interest in integrating VR technologies into teaching processes in the field of science education. Research into understanding the impact of these technologies on knowledge acquisition and learning processes is gaining momentum (Mikropoulos & Natsis, 2011). Furthermore, the "overlay visualization" method employed in the VOSviewer analysis reveals a notable increase in the utilization of terms such as "application", "framework", "ability" and "impact" in abstracts over recent years. "Overlay visualization" is a visualization method that facilitates the tracking of conceptual changes and developments in a particular research area by means of analysing the usage trends of certain terms over time (Van Eck & Waltman, 2010). This finding can be considered an indicator of a growing academic interest in the potential of VR applications in education, with a particular focus on implementation processes, methodological configurations, and strategies, and impact analysis (Bailenson, 2018; Lampropoulos & Kinshuk, 2024; Ozeren et al., 2021). The term "impact" has seen a surge in interest, particularly in research examining the impact of VR applications on student achievement and learning processes (Aktamıs & Arıcı, 2013; Ceylan & Kalaycı, 2024; Dikmen & Bahadır, 2021). When synthesised, these findings indicate an ongoing intensive research effort to enhance the efficacy of VR applications in science education and to facilitate their integration into educational processes.

Recommendations

In consideration of the constraints imposed by the current study, the following recommendations for subsequent research are proposed, drawing upon the findings obtained. The present study is constrained in its scope to the utilisation of VR technology in the domain of science education, as evidenced by the utilisation of scientific publications that have been indexed in the WoS database. While WoS incorporates prominent citation indexing databases such as SCI, SSCI, and A&HCI, it would be advantageous to investigate studies from additional major databases, including ERIC, Google Scholar, and SCOPUS. Furthermore, the evaluation of research conducted in Türkiye would contribute to a more comprehensive understanding of the country's potential in this field.

In order to enhance the effective use of VR technology in the sphere of science education, it is recommended that future research encourage interdisciplinary collaborations and conduct in-depth examinations of the long-term effects of VR applications. Concurrently, the formulation of strategies aimed at enhancing accessibility and inclusivity is poised to assume a pivotal role in addressing the multifaceted learning requirements of diverse groups. Concrete, data-driven studies exploring the integration of VR technology into the differentiated instruction approach embraced by current curricula could provide valuable insights. The execution of such research would facilitate the identification of methodologies for the utilisation of VR in the pedagogy of scientific subjects, the enhancement of educational processes, classroom interactions, and the promotion of students' active participation in a more efficacious manner. Furthermore, studies focusing on advanced applications, such as the "gamification of VR" and "extended reality," could create important opportunities for the enhancement of interactive and immersive learning experiences.

In this context, the establishment of professional development programmes for educators would be essential to enable the effective use of VR technology. These programs should offer both theoretical and practical content, equipping teachers to integrate VR's interactive, experiential learning opportunities into their curricula. Furthermore, the establishment of VR laboratories within educational institutions, the enhancement of accessibility, and the implementation of sustainable support mechanisms for technological infrastructure would substantially augment students' experiential learning processes.

From a policymaking perspective, the augmentation of financial resources to facilitate the development of VR-based content, in conjunction with the promotion of international collaborative initiatives, has the potential to enhance the global impact of research outcomes, particularly in nations such as Türkiye, which demonstrate considerable promise in the domain of VR research. Given Türkiye's strong position in the international academic literature, strategic support for VR-based educational projects could provide a competitive advantage on a global scale. The development of teaching materials tailored to the local context, aligned with cultural and pedagogical needs, has the potential to expand the reach of VR technology to a broader student population and to promote greater educational inclusivity.

In conclusion, the effective integration of VR technology within the domain of science education is contingent upon the establishment of a robust and concerted collaborative network encompassing educators, policymakers, and researchers. The recommendations presented herein offer a comprehensive and strategic roadmap for stakeholders, guiding the more effective implementation of VR technologies in science education practices.

Scientific Ethics Declaration

* The authors declare that the scientific, ethical, and legal responsibility of this article published in the JESEH journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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