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# The Development of Virtual Reality Research in Science Education (2008–2024): A Web of Science–Based Bibliometric and Descriptive Content Analysis

## *Fen Eğitiminde Sanal Gerçeklik Araştırmalarının Gelişimi (2008–2024): Web of Science Tabanlı Bibliyometrik ve Betimsel İçerik Analizi*

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**ABSTRACT**

This study aims to reveal the development of virtual reality (VR) research in science education between 2008 and 2024. A total of 58 peer-reviewed articles, selected from the Web of Science Core Collection database in accordance with the PRISMA flow, were analyzed using bibliometric approaches (VOSviewer, CiteSpace, bibliometrix) and descriptive content analysis. The bibliometric findings indicate a marked increase in publications after 2015, with studies predominantly concentrated in the fields of biology and physics, while remaining limited in disciplines such as chemistry and earth sciences. Results of the descriptive content analysis reveal that research has mostly focused on fully immersive (HMD-based) applications; has been conducted with small- and medium-sized samples; and that the diversity of measurement tools has restricted generalizability. By examining the distributions of science disciplines, VR types, research purposes, and measurement approaches, the study identifies gaps in the literature and proposes priority directions for future research. The findings highlight the need for large-scale, theory-driven, and low-cost/accessible VR solutions to be evaluated in alignment with curricula, particularly in the contexts of chemistry, earth sciences, and teacher education.

**Keywords** Virtual reality, science education, bibliometric analysis, descriptive content analysis.

**ÖZET**

Bu araştırmanın amacı, 2008–2024 yılları arasında fen eğitimi alanında gerçekleştirilen sanal gerçeklik (SG) araştırmalarının gelişimini ortaya koymaktır. Web of Science Core Collection veri tabanından PRISMA akışına uygun olarak seçilen toplam 58 hakemli makale, bibliyometrik analiz yaklaşımları (VOSviewer, CiteSpace, bibliometrix) ve betimsel içerik analizi kullanılarak incelenmiştir. Bibliyometrik bulgular, 2015 yılından sonra yayın sayısında belirgin bir artış yaşandığını, çalışmaların ağırlıklı olarak biyoloji ve fizik alanlarında yoğunlaştığını, kimya ve yer bilimleri gibi disiplinlerde ise sınırlı kaldığını göstermektedir. Betimsel içerik analizi sonuçları, araştırmaların çoğunlukla tam daldırımlı (başa takılan ekran [HMD] tabanlı) sanal gerçeklik uygulamalarına odaklandığını, küçük ve orta büyüklükteki örneklemlerle yürütüldüğünü ve ölçme araçlarının çeşitliliğine ilişkin sınırlılıkların bulguların genellenebilirliğini kısıtladığını ortaya koymaktadır. Araştırmada fen disiplinleri, sanal gerçeklik türleri, araştırma amaçları ve ölçme yaklaşımlarının dağılımları incelenerek alanyazındaki boşluklar belirlenmiş ve gelecekteki araştırmalar için öncelikli yönelimler önerilmiştir. Bulgular, özellikle kimya, yer bilimleri ve öğretmen eğitimi bağlamlarında, öğretim programlarıyla uyumlu, geniş ölçekli, kuramsal temellere dayanan ve düşük maliyetli/erişilebilir sanal gerçeklik çözümlerinin değerlendirilmesi gerektiğini vurgulamaktadır.

**Anahtar Kelimeler** Sanal gerçeklik, fen eğitimi, bibliyometrik analiz, betimsel içerik analizi.

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## 1. Introduction

Science education aims to enable individuals to understand the world through scientific reasoning and to apply this knowledge in daily life. In this context, fostering scientific thinking, enhancing problem-solving skills, and deepening conceptual understanding are among the fundamental objectives of science education (Bybee, 1997; NRC, 2012). However, although science education is based on student-centered approaches, various challenges encountered during the implementation process often hinder the achievement of intended outcomes (Balbağ, Leblebicier, Karaer, Sarıkahya, & Erkan, 2016). At this point, inadequate infrastructure, lack of teacher preparedness, and shortage of materials emerge as the main factors limiting the effective realization of student-centered learning (Babatunde, 2025; Omowumi et al., 2024). These barriers negatively affect students' participation and motivation, thereby reducing the efficiency of the learning process. Consequently, the need for innovative and interactive instructional tools that can strengthen experiential learning is steadily increasing (Makransky, Petersen, & Klingenberg, 2020). In recent years, technologies such as Virtual Reality (VR) have offered promising opportunities to enrich science teaching and to make especially abstract concepts more concrete and comprehensible (Meyer, Omdahl, & Makransky, 2019).

In this context, VR technology not only provides students with a visual experience but also enables users to directly interact with virtual objects in three-dimensional environments. In this way, abstract and complex scientific concepts can become more comprehensible and concrete (Merchant, Goetz, Cifuentes, Keeney-Kennicutt, & Davis, 2014; Radianti, Majchrzak, Fromm, & Wohlgenannt, 2020). When students are immersed in a VR environment, they are able to simulate, explore, interact with, and modify the objects around them. Furthermore, through avatars that represent them, they experience a sense of presence in the environment, receive real-time feedback from instructors, and engage in an authentic learning experience (Monahan, McArdle, & Bertolotto, 2008). VR platforms can encompass not only digital representations of real-world spaces but also entirely imaginary scenarios that are impossible in the physical world. For instance, entering the nucleus of an atom or walking on the surface of the Sun is impossible in reality; however, in a designed VR environment, such experiences can be realized, allowing users to interact with objects, move, communicate with other users, create objects, and even play games (Zinchenko et al., 2020).

With these features, VR is regarded as a powerful alternative for overcoming the limitations faced by science education. Its potential to increase student motivation, concretize abstract concepts, and enrich the learning experience has led to growing interest in this technology. From a technical perspective, VR is a technology that enables interaction with computer-simulated environments through devices such as head-mounted displays (HMDs), controllers, or desktop systems (Chen, 2018; Slater & Sanchez-Vives, 2016). It provides students with an interactive and immersive sensory experience (Araiza-Alba et al., 2021) and, depending on the hardware used, is generally classified as immersive (IVR) or non-immersive. Non-immersive VR provides experiences via standard screens with limited interaction, whereas IVR, through devices such as Oculus Quest or HTC Vive, creates a fully enveloping and embodied learning environment (Eutsler & Long, 2021; Makransky, Borre-Gude, & Mayer, 2019).

This classification has particularly led to the prominence of immersive virtual reality (IVR) applications in science education. IVR provides students with opportunities to engage in realistic simulations, safely explore complex experiments, and grasp abstract concepts more effectively (Johnson-Glenberg et al., 2011; Makransky et al., 2020). By

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supporting both visual and physical interaction, it contributes to the development of deeper understanding and fosters lasting motivation toward learning (Radianti et al., 2020). Moreover, IVR enables the safe examination of phenomena that are dangerous or difficult to access directly; this not only enriches the learning experience but also enhances students' interest in science (Cheng & Tsai, 2019; Han, 2021; Hite et al., 2019; Zhao et al., 2020).

Although IVR applications offer significant opportunities in science education, the findings in the literature are not always consistent. Indeed, while some studies show that VR enhances learning outcomes, others point to mixed results due to logistical constraints and short-term effects (Makransky, Borre-Gude, & Mayer, 2019; Munafo, Diedrick, & Stoffregen, 2017; Radianti et al., 2020). Moreover, most existing research has been conducted with small samples, leaving uncertainties regarding effect sizes (Akbay & Deniş Çeliker, 2023; Coban, Bolat, & Goksu, 2022). A large portion of the literature has focused on biology and physics topics, whereas applications and assessment designs in chemistry and earth sciences remain relatively limited (Sviridova, Yastrebova, Bakirova, & Rebrina, 2023). The current findings therefore necessitate a systematic search for an answer to the question: *"Which type of VR, with which science topic and pedagogical design, is most effective for whom?"*

This study, covering the period 2008–2024, maps VR research in science education in a comprehensive manner at two levels: (i) at the bibliometric level, focusing on publication dynamics, keyword networks, and thematic/conceptual structures; and (ii) at the content level, examining research purposes, methodological and sample characteristics, measurement instruments, and the types of VR employed. In doing so, it goes beyond the predominantly field-general syntheses of previous reviews in the literature by identifying gaps in the distributions of science disciplines, VR types, research purposes, and measurement approaches, and by specifying priority directions for future research.

In recent years, several reviews (Chang, Kuo, & Du, 2023; Lampropoulos & Kinshuk, 2024; Oje, Hunsu, & Fiorella, 2025; Yang et al., 2024) have focused on different dimensions. For example, Chang, Kuo, and Du (2023) developed a digital literacy framework; Lampropoulos and Kinshuk (2024) examined gamification and motivation dimensions; and Matovu et al. (2023) addressed design–implementation–evaluation processes. Yang (2024) presented a meta-analysis particularly on practical skills, while Oje (2025) systematically evaluated pedagogical design principles. However, these studies have not comprehensively addressed interdisciplinary comparisons, methodological designs, and measurement approaches within the context of science education. The purpose of the present study is to address this gap and to reveal the trends in the field from a multidimensional perspective. In this regard, the following research questions were formulated, and the scope of the study was structured around these questions.

**R1.** What are the annual publication trends, thematic focuses, and conceptual network structures of VR research in science education between 2008 and 2024?

**R2.** What distribution do the methodological approaches, sample types, sample sizes, and data collection instruments of these studies exhibit?

**R3.** What are the distributions of virtual reality types and science disciplines in VR research in science education?

**R4.** Which dimensions (e.g., cognitive achievement, motivation, self-efficacy, presence) are covered by the measurement instruments used in VR research in science education, and how do these reflect the research trends in the field?

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## 2. Method

This study is based on a two-phase research design covering the years 2008–2024, with data obtained from the Web of Science (WoS) Core Collection dataset. In the first phase, bibliometric analysis conducted through VOSviewer, CiteSpace, and bibliometrix software mapped annual publication trends, thematic focuses, and conceptual network structures. The bibliometric method provides an effective approach for making the structure and evolutionary development of a research field visible through citation patterns and network relationships (Cheng, Wang, Xie, & Yan, 2023). In the second phase, descriptive content analysis was employed to systematically code research designs, sample characteristics, data collection instruments, types of VR used, and measurement dimensions. This integrated method provides a comprehensive overview of publication dynamics, methodological trends, and the distributions of science disciplines and VR types in science education research.

### 2.1. Scope and Time Frame

The year 2008 was chosen as the starting point of the study, as this marks the period when peer-reviewed articles with a VR focus in the context of science education began to be visibly published in the WoS Core Collection. To test the robustness of the selected time frame, the sub-periods 2010–2024 and 2015–2024 were also examined, and it was confirmed that the main trends remained unchanged. The final search was conducted on September 18, 2024, and thus the year 2024 includes only articles published up to that date.

### 2.2. Data Source and Limitations

In this study, the WoS Core Collection was used as the primary data source. This choice was based on the high accuracy of citation data provided by WoS, its standardization, and its strong compatibility with the bibliometric tools employed (VOSviewer, CiteSpace, bibliometrix). Accordingly, the findings offer a WoS-based global perspective; however, other databases such as Scopus or ERIC were not included. This limitation may be addressed in future research through cross-validation.

### 2.3. Data Retrieval and Search Strategy

The literature search was conducted in the Web of Science (WoS) Core Collection on September 18, 2024, covering the period from 2008 to 2024. The search strategy combined virtual reality-related terms with keywords associated with science education, including STEM, earth science, natural science, science learning, and science teaching. The selection process was reported using the PRISMA 2020 framework (Page et al., 2021).

As illustrated in Figure 1, the initial search identified 240 records. The documented screening criteria included document type (articles), language (English), publication years (2008–2024), WoS subject categories (Education & Educational Research and Education, Scientific Disciplines), and the SSCI, SCI-EXPANDED, and ESCI indexes. Following the initial filtering stage, 68 records remained. Subsequently, one duplicate record and nine records considered outside the research scope were excluded, resulting in a final dataset of 58 articles. The original documentation does not provide a separate numerical breakdown for each initial filter. Therefore, the reduction from 240 to 68 records is reported as a combined filtering stage.

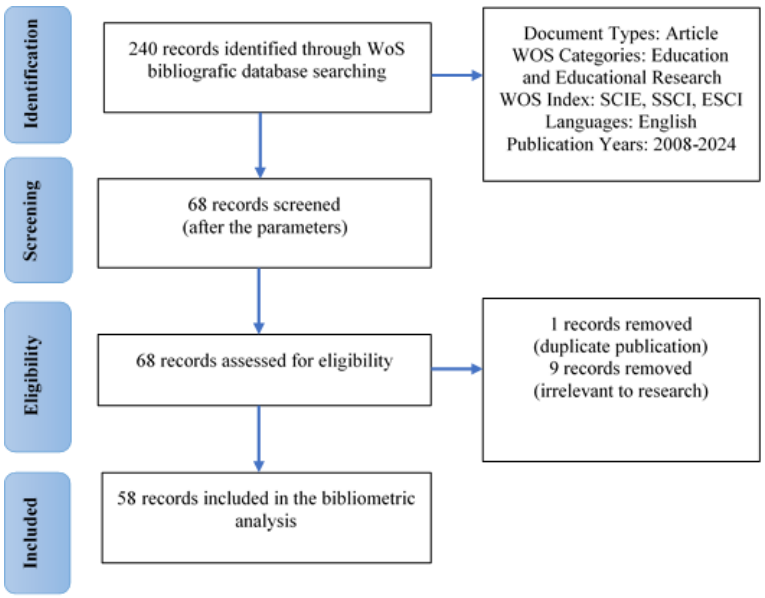
The complete search query used in the Web of Science Core Collection was as follows:

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TS=("virtual reality" OR "VR") AND TS=("learning for science" OR "education in science" OR "scientific project*" OR "science reading" OR "science center*" OR "science game*" OR "teaching science" OR "elementary science" OR "science class*" OR "earth science" OR "natural science" OR "science education" OR "science course*" OR "science learning" OR "learning science" OR "science teaching" OR "science content*" OR "science laborator*" OR "STEM").

**Figure 1**

*PRISMA flow diagram for data collection*




### 2.4. Data Analysis and Coding Reliability

The data analysis process was conducted using VOSviewer (1.6.20), CiteSpace (6.4.R1), and R (bibliometrix package, biblioshiny application). VOSviewer was employed for generating maps based on network data, while CiteSpace was used to examine citation patterns and keyword bursts.

Within the scope of content analysis, a publication review form was developed by the researchers, and information such as year, author, method, sample, data collection instrument, subject area, variables examined, and type of VR used was systematically coded from the articles. The coding process was carried out in two stages: first, a trial was conducted on a pilot set of 10 articles, and the coding manual was revised based on the results obtained. Subsequently, 20% of all articles were coded independently by two researchers; the resulting Cohen's $\kappa = 0.82$ indicated a high level of reliability. Coding discrepancies were resolved through discussion among the researchers.

In the tables and figures used in the study, the "*" symbol indicates cases where a single article included more than one sample group.

## 3. Findings

In this section, the findings are presented in accordance with the research questions (R1–R4) of the study. First, publication trends and thematic/conceptual structures (R1) are reported, followed by methodological characteristics and sample features (R2), the distributions of VR types and science disciplines (R3), and measurement instruments and variables examined (R4).

### 3.1. Publication Trends, Thematic Focuses, and Conceptual Structures (2008–2024)

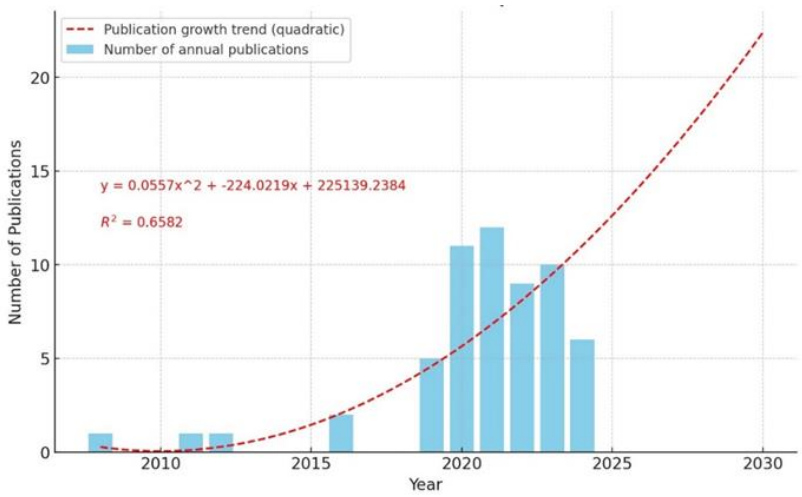
This section presents the findings related to the first research question—"What are the annual publication trends, thematic focuses, and conceptual network structures of VR research in science education between 2008 and 2024?" Within the scope of the bibliometric analysis, results concerning annual publication and citation trends, bibliographic coupling, keyword co-occurrence, citation bursts, and thematic structures are reported.

#### *3.1.1. Annual Publication Trends*

The annual volume of publications is an important indicator reflecting the level of interest in a research field. Figure 2 presents the distribution of publications on VR in science education between 2008 and 2024.

**Figure 2**

*Annual publications and growth trend of VR in science education (2008–2024)*




When Figure 2 is examined, it is observed that the number of annual publications remained low between 2008 and 2015, with some years showing no publications at all. This indicates that during this period, virtual reality had not yet attracted sufficient attention in the context of science education, or that studies on the use of this technology in education were limited. A marked increase is evident after 2015, with a particularly notable rise between 2019 and 2021. This increase can be associated with the growing interest in integrating virtual reality into science education, the wider availability of suitable hardware, as well as the impact of remote/blended learning practices. The sharp rise in publication numbers in 2020 and 2021 shows that the topic had become popular among researchers. The year 2024 appears lower due to the coverage extending only up to September. The red dashed line represents the quadratic trend fitted to the annual publication counts. The coefficient of determination ($R^2 = 0.6582$) indicates that the fitted model accounts for approximately 65.8% of the observed variation in annual publication counts. However, this value alone does not establish the statistical significance of the publication trend or provide a reliable basis for predicting future publication numbers. Furthermore, because the 2024 data include only publications indexed up to September 18, comparisons involving this year should be interpreted cautiously. Overall, the findings suggest an increase in research activity on virtual reality in science education during the analyzed period, particularly after 2015.

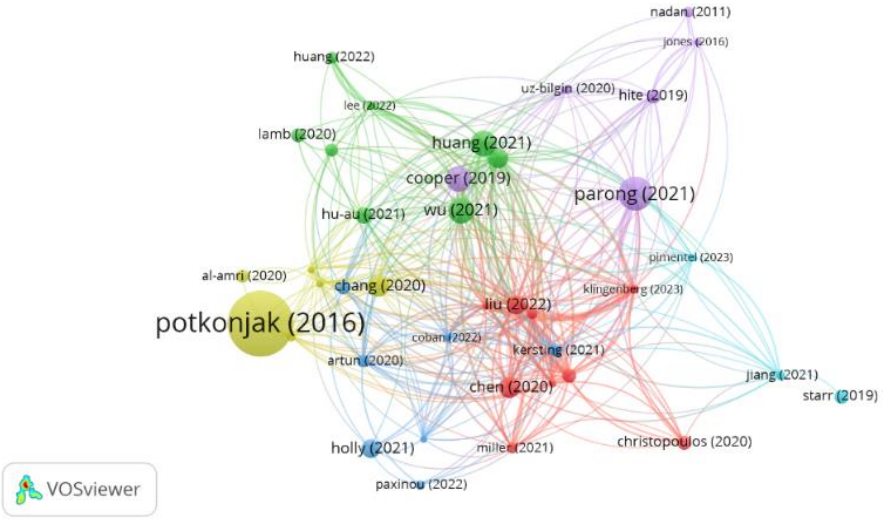
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### 3.1.2. Bibliographic Coupling

The bibliographic coupling of documents reveals which studies are more centrally positioned in the literature and uncovers the citation backbone of the research field. This analysis takes into account the total link strength among articles and makes the strong nodes visible, with the findings presented in Figure 3.

**Figure 3**

*Bibliographic coupling of the documents (Overlay Visualization – Weights: Citations)*




When Figure 3 is examined, it is seen that studies with high link strength (e.g., Potkonjak, 2016; Parong, 2021; Wu, 2021; Huang, 2021) stand out as central nodes in the literature. These studies facilitate transitions across clusters and contribute to the thematic coherence of the field. In the bibliographic coupling visualization, node sizes represent citation counts; Potkonjak (2016) stands out with 447 citations, followed by Parong (2021) with 121 and Cooper (2019) with 71 citations.

In Appendix, Figure A1, bibliographic couplings among the documents are visualized according to total link strength. Elme (2022), with a link strength of 111, is the most central study in the network. Klingenberg (2023) and Pande (2021), both with a link strength of 99, also emerge as key connection hubs. This indicates that these studies establish strong relationships in the literature, thereby contributing to the thematic integrity of the field.

### 3.1.3. Citation Bursts

Citation bursts indicate the periods in which the most influential studies on virtual reality in science education came to the forefront and highlight thematic concentrations in the literature. This analysis was conducted using the CiteSpace tool on the references within the dataset, and the six strongest citation bursts between 2008 and 2024 were identified. The findings are presented in Appendix, Figure A2.

When Appendix, Figure A2 is examined, it is observed that during the 2017–2022 period, anatomical learning (Jang, 2017), embodied interaction (Johnson-Glenberg, 2017), and immersive VR applications in the STEM context (Pellas, 2020) emerged as key focal areas. In addition, cognitive interaction in learning processes (Johnson-Glenberg, 2018; Jensen, 2018) and the experiential dimension of virtual reality (Bailenson, 2018) drew attention with strong citation bursts. These findings reveal that in recent years, VR research has shown a tendency toward pedagogical

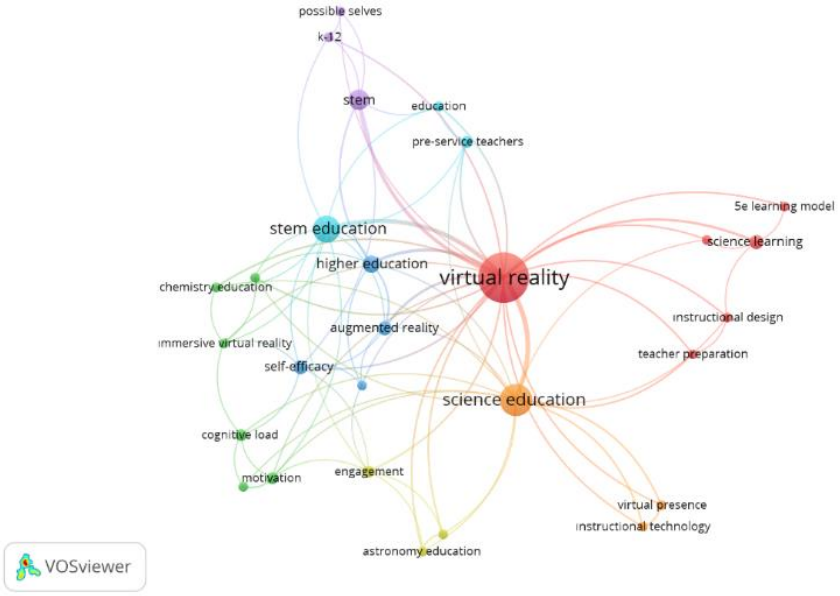
diversification and interdisciplinary expansion, and has been embraced as a transformative approach to the learning process.

### *3.1.4. Keyword Co-Occurrence Analysis (Thematic Focuses)*

The keyword co-occurrence analysis demonstrates the topics around which VR research in science education is clustered and highlights the themes that stand out. This analysis is based on the frequency and co-usage of concepts employed in the studies, with the findings presented in Figure 4.

**Figure 4**

*Co-Occurrence of the keywords (Overlay Visualization)*




When Figure 4 is examined, it is observed that concepts such as *virtual reality, science education, STEM, motivation, presence, biology,* and *learning outcomes* stand out. These clusters reveal that the studies are grouped around three main axes:

1. Cognitive and affective learning outcomes (e.g., achievement, motivation, self-efficacy).
2. Disciplinary contexts (particularly biology and physics).
3. Technological and experiential factors (e.g., presence, immersion, usability).

The density distribution of the keywords is presented in Appendix, Figure A3. This visualization illustrates the frequency and dominance of concepts in the literature through color intensities. When Appendix, Figure A3 is examined, it is evident that the six keywords with the strongest citation bursts reflect the focal points of research. In particular, *cognitive load* emerged in 2022 with the strongest burst strength and maintained its influence until 2024. This indicates that cognitive load has become a critical research topic in VR applications. In contrast, the concepts *augmented reality* and *virtual presence* remained limited to short-term bursts, whereas *instructional technology* and *environment* have shown a resurgence in recent years.

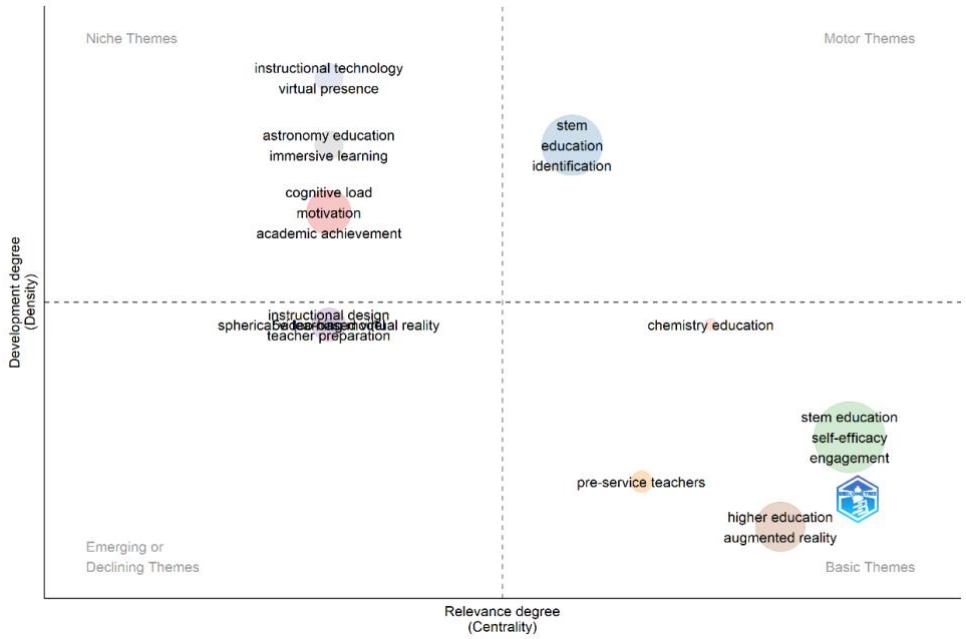
These findings indicate that VR research in science education has focused on both pedagogical variables and technological integration. However, the still limited diversity of keywords suggests that conceptual expansion in the field remains at an early stage.

### 3.1.5. Thematic Map and Conceptual Structures

The thematic map analysis identifies the positions of keywords based on their density and centrality values across clusters, thereby revealing the conceptual structure of the field. The findings are presented in Figure 5.

**Figure 5**

*Thematic map for the period 2008–2024*




When Figure 5 is examined, it is observed that the themes are clustered into four main regions:

***Motor (core) themes:*** *STEM education* and *identification* are the most central and well-developed topics of the field. This finding indicates that STEM has been extensively addressed in VR research in science education.

***Niche themes:*** Topics such as *instructional technology, virtual presence, astronomy education, immersive learning, cognitive load, motivation,* and *academic achievement* are well-developed but exhibit low centrality, representing areas of specialized interest.

***Emerging or declining themes:*** *Instructional design, global video studies,* and *teacher preparation* fall into this category, suggesting that these areas are either still in the process of maturing or beginning to lose research interest.

***Basic themes:*** Concepts such as *pre-service teachers, STEM education, self-efficacy,* and *engagement* hold central positions but display relatively low levels of development. This suggests that while these areas are significant, they carry greater potential for further research.

The findings reveal that variables such as *motivation, self-efficacy,* and *learning outcomes* are at the core of VR research in science education, while areas such as *teacher education* and *earth sciences* remain secondary. Overall, the thematic map indicates that the field is still in a maturation process and that some emerging themes may become more prominent in the coming years.

In order to further reveal the conceptual structure, a Multiple Correspondence Analysis (MCA) was conducted using the Biblioshiny package in R, and the resulting keyword clusters are presented in Appendix, Figure A4. Two main clusters stand out:

***Red cluster:*** This cluster encompasses cognitive and motivational variables related to students' learning processes. Within this cluster, concepts such as *cognitive load, self-efficacy, motivation,* and *engagement* are prominent, representing studies that examine the effects of VR applications on learning processes.

***Blue cluster:*** This cluster covers themes of instructional design and technology integration. It includes concepts such as *STEM education, augmented reality, higher education,* and *instructional design,* reflecting the instructional contexts in which VR is employed.

These findings demonstrate that VR research in science education is concentrated along two main axes: (i) students' cognitive and motivational processes, and (ii) instructional design and technology integration. Thus, it is revealed that the field has been developing both on learner-centered outcomes and on pedagogical designs.

## 3.2. Methodological Approaches, Samples, and Data Collection Instruments (2008–2024)

This section presents the findings related to the second research question—"What distribution do the methodological approaches, sample types, sample sizes, and data collection instruments of these studies exhibit?" The data obtained through content analysis are reported across the dimensions of methodological approaches, sample types, sample sizes, and data collection instruments.

### *3.2.1. Methodological Approaches*

The methodological approaches employed in VR research in science education were examined. This analysis reveals how the studies are distributed across quantitative, qualitative, and mixed-methods designs. The findings are presented in Figure 6.

**Figure 6**

*Distribution of research methods*

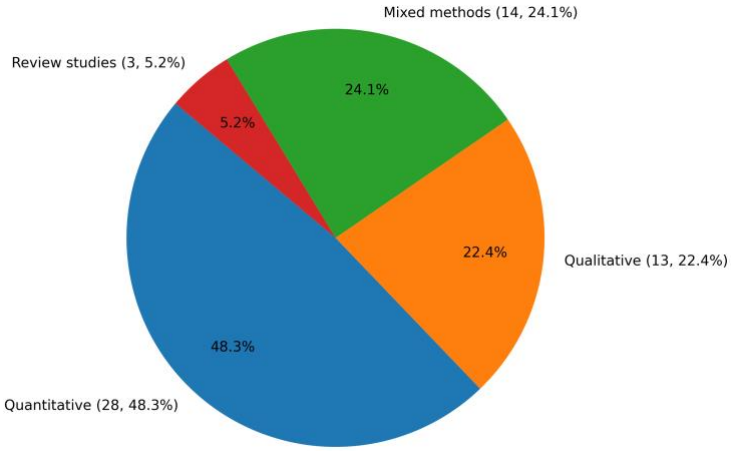



Figure 6 presents the distribution of research methods across the 58 studies. Quantitative research was the most frequently employed approach (48.3%, n = 28), followed by mixed-methods research (24.1%, n = 14), qualitative research (22.4%, n = 13), and review studies (5.2%, n = 3). Review studies were classified separately from empirical qualitative research to ensure methodological consistency. Qualitative studies included case study designs and self-study research, whereas quantitative studies predominantly employed experimental and quasi-experimental designs. Overall, the findings indicate that quantitative approaches remain dominant in VR research in science education.

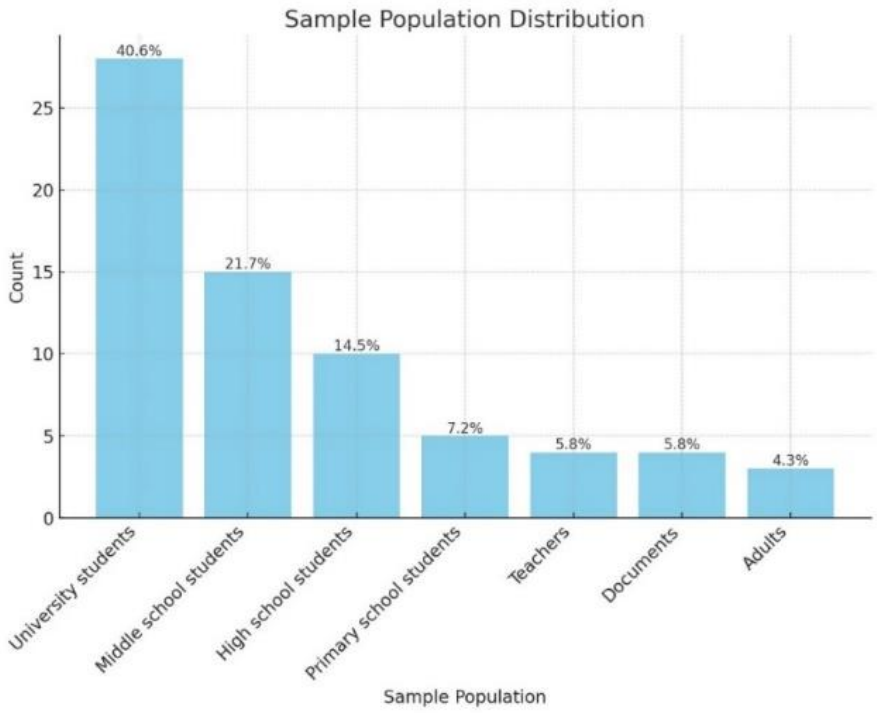
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### 3.2.2. Sample Types

The sample groups preferred in the studies (middle school, high school, university students, teachers, etc.) were examined. The findings are presented in Figure 7.

**Figure 7**

*Distribution of sample populations (2008–2024)*




When Figure 7 is examined, it is observed that university students constitute the largest sample group in VR studies in science education, with 40.6%. Middle school students follow with 21.7%, and high school students rank third with 14.5%. In contrast, elementary school students are represented to a more limited extent at 7.2%. Teachers (5.8%), documents (5.8%), and adults (4.3%) are among the least frequently chosen groups. This distribution indicates that VR research in science education has been conducted predominantly with student-centered samples, with comparatively less focus on teacher education and adult learning.

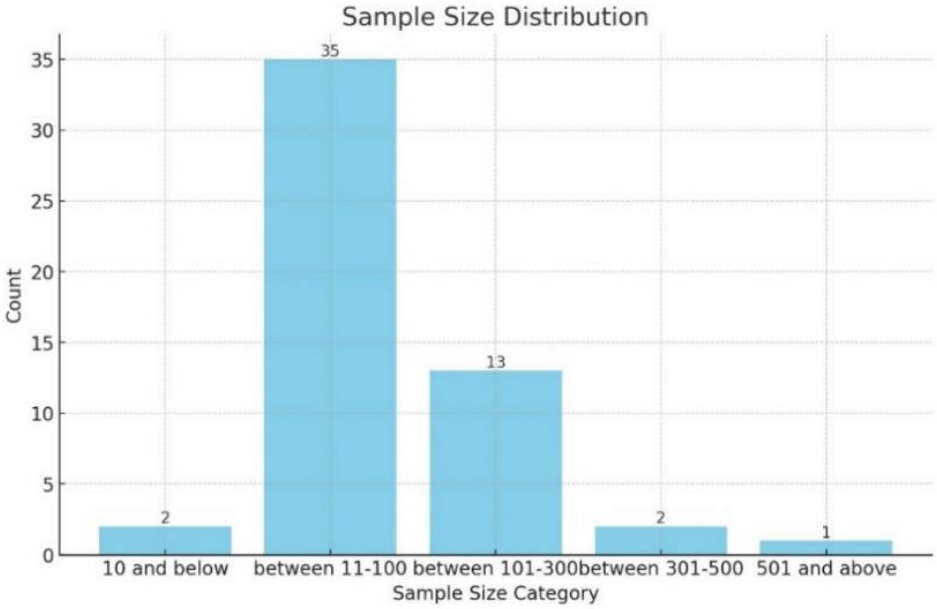
### 3.2.3. Sample Sizes

Figure 8 presents the distribution of sample sizes across the reviewed studies. Of the 58 studies included in the analysis, three were literature reviews and two did not report a specific sample size. Therefore, the sample-size distribution was calculated based on 53 studies for which sample-size information was available. Most of these studies involved small- and medium-sized samples, particularly between 11 and 100 participants. Studies with sample sizes ranging from 101 to 300 were also represented, whereas only two studies included between 301 and 500 participants, and one study involved more than 500 participants. Overall, the findings indicate that VR research in science education has predominantly relied on relatively small and accessible samples.

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**Figure 8**

*Distribution of sample sizes (2008–2024)*




**Note.** Sample-size data were available for 53 of the 58 included studies. Three literature reviews and two studies without a reported sample size were excluded from this distribution.

When Figure 8 is examined, it is seen that most studies on virtual reality in science education (excluding four literature reviews) were conducted with small- and medium-scale sample groups consisting of 11–100 participants. Studies with sample sizes in the range of 101–300 also stand out. In contrast, only two studies had sample sizes between 301 and 500, while the single study with more than 501 participants was a survey based on structural equation modeling and did not constitute an applied research study. These findings reveal a tendency in VR research in science education to focus primarily on small and accessible sample groups.

### *3.2.4. Data Collection Instruments*

The data collection instruments used in the studies were examined. This analysis shows which measurement tools were preferred to assess learning outcomes, attitudes, motivation, and experiential dimensions of virtual reality applications. The findings are presented in Table 1.

**Table 1**

*The Distribution of the Articles by Data Collection Tools (2008–2024)*

| Data Collection Tool | Frequency (n) | Percentage (%) |
|---|---|---|
| Questionnaires/Scales | 41 | 36.94 |
| Tests | 26 | 23.42 |
| Interviews | 20 | 18.02 |
| Observations | 10 | 9.01 |
| Documents | 4 | 3.60 |
| Rubric | 4 | 3.60 |
| Participant products | 4 | 3.60 |
| Physiological and Biometric Measurements | 2 | 1.80 |

When Table 1 is examined, it is seen that the most commonly used data collection instruments in VR research in science education are questionnaires and scales (36.94%). Tests (23.42%) were preferred to assess academic

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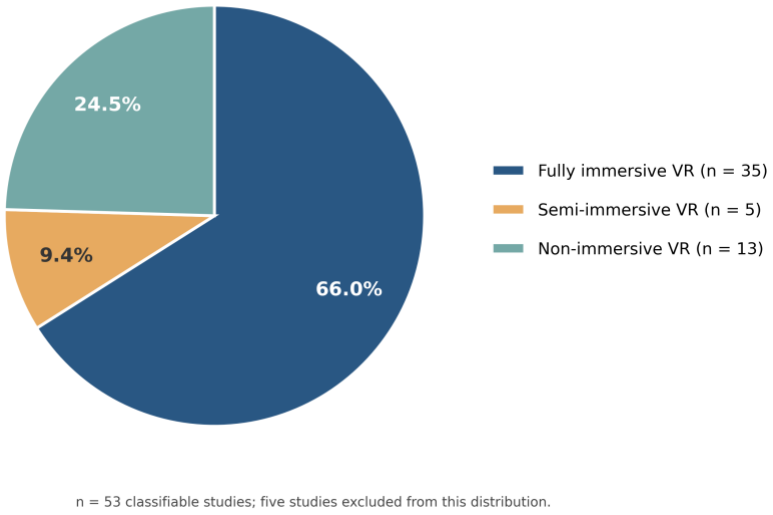
achievement. Interviews (18.02%) and observations (9.01%) were employed to examine participants' experiences in greater depth. To a lesser extent, documents, rubrics, and student products (3.60%) as well as physiological and biometric measurements (1.80%) were used as data collection tools. This distribution reveals that VR research in science education has largely relied on quantitative data collection instruments, though these have been complemented by qualitative methods.

### 3.3. Distribution of VR Types and Science Disciplines (2008–2024)

This section presents the findings related to the third research question, which examines the distributions of VR types and science disciplines in VR research in science education. Two dimensions were examined separately: the distribution of VR types employed in the reviewed studies and the distribution of studies across science disciplines. Figure 9 presents the distribution of VR types, Appendix Figure A5 illustrates the distribution of science disciplines, and Appendix Table A1 provides detailed content categories and subthemes within these disciplines.

**Figure 9**

*Distribution of virtual reality types (2008–2024)*




**Note.** The distribution is based on 53 studies. Three literature reviews and two studies without a clearly specified VR immersion category were excluded.

Figure 9 presents the distribution of VR types across the reviewed studies. Of the 58 studies, three were literature reviews, while two additional studies could not be clearly classified according to their level of immersion. Therefore, the distribution was calculated based on 53 studies. Fully immersive VR was the most frequently reported type (66.0%, n = 35), followed by non-immersive VR (24.5%, n = 13) and semi-immersive VR (9.4%, n = 5). These findings indicate that fully immersive VR predominated among the classifiable studies.

When Appendix Figure A5 is examined, it is seen that VR studies in science education were most frequently conducted in the fields of Biology (40.7%) and Physics (25.9%), while they remained more limited in areas such as Chemistry, STEM, scientific inquiry, concept teaching, and educational technology. This distribution reveals the subject areas around which VR applications in science education are concentrated and shows that VR is effectively used to concretize biological structures and physical phenomena.

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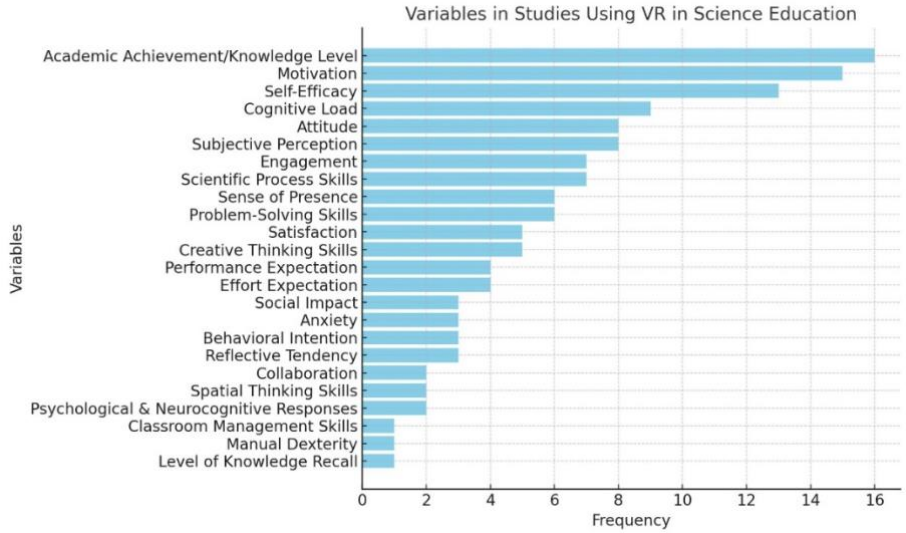
This general distribution is supported by detailed analyses that reveal the specific subtopics around which the contents are shaped. Indeed, as presented in Appendix Table A1, the detailed content categories and subthemes are grouped under the main categories of Biology, Physics, Chemistry, STEM, Scientific Inquiry, Conceptual Teaching, and Educational Technology, each elaborated according to the unique structure of the respective discipline. In this regard, anatomy and physiology as well as ecology and environmental science stand out in Biology, astronomy, electricity, and mechanics in Physics, and molecular structures in Chemistry. Overall, the figure illustrates how VR is distributed across different areas of science education and highlights the topics that are more frequently addressed.

### 3.4. Dimensions Examined in Measurement Instruments (2008–2024)

This section presents the findings related to the fourth research question—"Which dimensions (e.g., cognitive achievement, motivation, self-efficacy, presence) are covered by the measurement instruments used in VR research in science education, and how do these reflect the research trends in the field?" Within the scope of the analysis, the learning outcomes and psychological dimensions targeted by the measurement instruments used in VR research were identified. In this way, it was revealed which aspects of VR were more frequently addressed and which topics received particular focus. The findings are presented in Figure 10.

**Figure 10**

*Distribution of variables (2008–2024)*




When Figure 10 is examined, it is observed that the most frequently investigated dimension in studies involving VR in science education is academic achievement/knowledge level. This indicates that researchers have primarily focused on examining the effects of VR on student performance and knowledge acquisition. The motivation dimension also stands out with high frequency; this finding reveals that researchers have often evaluated whether VR increases students' interest and participation in the learning process. In addition, the clear attention given to self-efficacy and cognitive load demonstrates that individual confidence and mental effort have also been important focal points when examining the effects of VR on students. Variables such as attitudes and subjective perceptions, which were investigated at lower frequencies, shed light on studies aimed at understanding the impact of VR on individual experiences. Overall, the figure shows that VR has been addressed in science education from multiple dimensions and highlights the areas on which researchers have concentrated.

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## 4. Discussion

This study examined virtual reality (VR) research in science education between 2008 and 2024 through the combined use of bibliometric analysis and descriptive content analysis. Although the literature includes a limited number of reviews based solely on bibliometric or content analysis, comprehensive evaluations covering an extended period specifically within the context of science education have remained limited. This study addresses this gap by presenting annual trends in VR research, methodological characteristics, the distributions of VR types and science disciplines, and the dimensions examined through measurement instruments.

Taken together, the results suggest that the central issue in VR-supported science education is not simply whether VR is effective. A more comprehensive and forward-looking research agenda should be structured around the question: "Which type of VR, combined with which science topic and pedagogical design, is most effective, and for whom?" This overarching framework assumes that the educational value of VR does not arise solely from its technological features. Rather, it depends on the alignment among the type of VR, the representational demands of the science content, the quality of the pedagogical design, and the characteristics of the learners. Accordingly, the results are discussed not merely as a restatement of existing trends but in terms of their underlying reasons, position within the literature, expected or noteworthy aspects, and broader implications for science education research and practice. This framework also requires the educational implications of VR to be interpreted through relevant learning perspectives. From a constructivist perspective, VR may allow learners to examine virtual objects, manipulate variables, and construct meaning through active interaction rather than passively receiving information. From an experiential learning perspective, it can provide access to phenomena that are difficult, dangerous, expensive, or impossible to experience directly. Embodied cognition further suggests that movement, orientation, and object manipulation in immersive environments may support the connection of scientific concepts with bodily and spatial experiences (Lindgren & Johnson-Glenberg, 2013). However, the cognitive and affective outcomes of immersive learning depend on interrelated processes such as presence, learner control, cognitive load, and pedagogical guidance (Makransky & Petersen, 2021). Multimedia learning perspectives similarly indicate that visual, auditory, and interactive features are beneficial only when they are aligned with learning objectives; unnecessary stimuli may divert learners' limited cognitive resources away from the target content (Makransky & Mayer, 2022; Parong & Mayer, 2018). Thus, the educational impact of VR depends less on the mere presence of the technology than on the theoretical and pedagogical principles guiding its use.

### 4.1. Publication Growth, Thematic Development, and Disciplinary Concentration

The first research question examined annual publication trends, thematic focuses, and conceptual network structures in VR research in science education between 2008 and 2024. The results indicate a marked increase in the number of publications, particularly after 2016. This increase may be associated with improved access to VR hardware, the wider use of VR-based learning environments, and the momentum created by remote and blended teaching practices. This pattern is consistent with previous research (Jensen & Konradsen, 2018; Radianti et al., 2020).

Regarding disciplinary distribution, the studies were concentrated mainly in biology and physics. Topics such as cellular structures, anatomy, astronomy, electricity, and mechanics were frequently represented through VR in more concrete and experiential forms. Previous research also supports the cognitive advantages of VR for learning

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microscopic structures and content requiring three-dimensional spatial reasoning (Gittinger & Wiesche, 2024; Lindgren & Johnson-Glenberg, 2013; Wu et al., 2020).

However, this concentration should not be interpreted merely as a numerical pattern confirming earlier studies. It also reflects the representational and pedagogical characteristics of biology and physics. Cellular structures, organ systems, astronomical scales, electrical phenomena, and mechanical processes are often difficult to observe directly, occur at substantially different scales, or involve dynamic and three-dimensional spatial relationships. VR can enable learners to move between micro- and macro-level representations, examine structures from different perspectives, and experience phenomena that are inaccessible in conventional classrooms. Its capacity to represent abstract and complex scientific concepts through three-dimensional interaction therefore provides a pedagogical explanation for the prominence of biology and physics (Merchant et al., 2014; Radianti et al., 2020). This interpretation is compatible with constructivist, experiential, and embodied approaches to learning. In virtual environments, learners may do more than observe scientific structures and processes; they may manipulate them and develop their own mental models. Experiences such as moving inside a cell, examining an anatomical structure from multiple perspectives, or exploring scale relationships among astronomical objects are difficult to reproduce through conventional two-dimensional materials. Moving around, rotating, or changing one's position relative to a virtual object may help connect abstract spatial relationships with embodied experience (Lindgren & Johnson-Glenberg, 2013; Makransky & Mayer, 2022).

Nevertheless, the prominence of biology and physics should not be taken to mean that VR is pedagogically suitable only for these disciplines. The limited representation of chemistry and earth sciences may reflect insufficient development of relevant content, software, and pedagogical designs rather than a lack of educational potential. Molecular bonding, reaction mechanisms, crystal structures, plate movements, and geological processes may also benefit from dynamic and three-dimensional representation. The limited number of VR applications and assessment designs in chemistry and earth sciences has also been noted in the literature (Sviridova et al., 2023). Therefore, the results confirm the established disciplinary concentration while also suggesting that the existing distribution does not fully represent the pedagogical potential of VR across science education. Conceptual network analyses showed that the studies were still organized around several core themes, although diversification had begun within integrated STEM research. The keyword clusters identified in the present study reflect two main thematic dimensions: cognitive and motivational processes related to learning, and instructional design and technology integration.

The prominence of cognitive processes and technology integration is an expected result in an emerging technology-related research field because researchers initially tend to focus on whether a new technology is effective and practically applicable. In contrast, the more limited development of themes such as teacher education, instructional design, and earth sciences is noteworthy and may indicate that the technological growth of the field has progressed more rapidly than its pedagogical maturation. The next stage of research should therefore involve not only developing additional VR applications but also identifying which technological features correspond to specific pedagogical needs in different science domains. Future studies should extend VR research to less-represented areas, including the modelling of molecular structures and reactions in chemistry, virtual field experiences in ecology and environmental science, and three-dimensional representations of geological processes in earth sciences. These studies should evaluate not only fully immersive systems but also the pedagogical adequacy of lower-cost mobile and

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desktop solutions. Overall, the results demonstrate that VR research in science education remains an emerging but rapidly developing field, shaped by both technological advances and the pedagogical needs of science disciplines. The high inter-coder reliability coefficient obtained in the descriptive content analysis (κ = 0.82) also supports the reliability of the content-analysis results.

### 4.2. Methodological Orientations, Samples, and Data Collection

The second research question examined the methodological approaches, sample types and sizes, and data collection instruments used in VR research in science education. The results demonstrate that quantitative research designs were dominant, while qualitative and mixed-methods approaches were less frequently represented. This quantitative dominance indicates that the field continues to be shaped by an effect-testing orientation, a tendency also reported in recent studies (Huang & Tseng, 2025; Jensen & Konradsen, 2018; Zhang et al., 2024).

Although such an orientation is understandable in a developing technology field, achievement scores and scale results alone may be insufficient to explain how, why, and under what conditions VR is effective. An achievement test may demonstrate the outcome of an intervention, but it cannot independently reveal which design features supported learning, where learners encountered difficulties, or how teacher guidance influenced the process. The limited representation of qualitative and mixed-methods research therefore restricts the field's capacity to explain learning processes and the mechanisms underlying the observed outcomes.

Most studies were conducted with university students, whereas teachers, high school students, and younger learners were underrepresented. This result shows that VR applications in science education have predominantly been examined within higher education contexts, while studies focusing on younger learners and teacher education have remained limited (Han et al., 2025; Luo et al., 2021; Merchant et al., 2014; Wu et al., 2020).

The dominance of university student samples means that the current knowledge base largely reflects the experiences of adult learners who may be relatively prepared to use technology and who often participate in controlled learning environments. However, age, developmental level, prior technology experience, spatial ability, academic readiness, and special educational needs may cause the same VR application to produce different outcomes across learner groups. The results therefore do not confirm that VR is generally effective for all learners. Rather, they show that the conditions under which it may be effective for different learner groups have not yet been sufficiently clarified. High levels of immersion and interaction may support the motivation of younger learners, but complex interfaces, cognitive load, and the need for guidance may also become more pronounced. University students may use technological systems more independently, but results obtained from this group cannot be directly generalized to elementary or middle school students. Similarly, learners' prior technology experience and spatial abilities may affect the extent to which they benefit from three-dimensional environments. Future studies should consequently examine interactions between learner characteristics, VR type, and pedagogical design rather than focusing only on age or grade level.

The limited representation of teachers is particularly important from a pedagogical perspective. The classroom impact of VR is not determined solely by the interaction between the learner and the technology. It may also depend on the teacher's ability to align the application with the curriculum, guide learners, manage technical problems, and connect the virtual experience with classroom explanation, discussion, and assessment. In learner-centred

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environments, the teacher's role is not merely to transmit information but to provide the pedagogical support needed to transform experience into scientific understanding. The limited attention paid to teacher education may therefore suggest that technical developments in VR have progressed more rapidly than research on pedagogical integration and teacher competence.

Achievement tests and questionnaires or scales were the most frequently used data collection instruments, whereas observations, interviews, and performance assessments were used less often. This result indicates that VR research in science education has placed greater emphasis on cognitive outcomes, while affective, behavioural, and process-oriented dimensions have received comparatively less attention. Previous reviews similarly identify achievement tests and questionnaires as the most frequently employed tools (Llanos-Ruiz et al., 2025; Strojny & Dużmańska-Misiarczyk, 2023; Tusher et al., 2024).

Overall, VR research in science education has continued to operate within a relatively narrow methodological framework. There is a need for greater representation of teachers, younger learners, and groups with diverse learning characteristics, as well as for the integration of quantitative results with interviews, observations, learner products, performance assessments, and system interaction records. Future studies may design VR-supported laboratory scenarios to examine the pedagogical development of pre-service teachers, investigate middle school learners' VR experiences through observations and interviews, and employ mixed-methods designs that assess academic achievement and classroom interaction simultaneously. Such methodological diversity would contribute to explaining not only whether VR works but also how, why, and for whom it works.

### 4.3. Distribution of VR Types and Science Disciplines

The third research question examined the distributions of VR types and science disciplines separately, providing an overview of the technological approaches and subject areas represented in science education research. The results indicate that fully immersive VR applications were preferred in the majority of the reviewed studies, whereas desktop-based and mobile solutions were used less frequently. This distribution suggests that researchers have been attracted to fully immersive technologies because of their potential to create stronger interaction, presence, and perceived realism.

However, the widespread use of fully immersive VR does not demonstrate that it is the most effective solution for every learning objective and learner group. The literature also highlights the need to balance pedagogical impact with cost and accessibility, noting that fully immersive VR can offer powerful experiences, while mobile and desktop-based solutions may provide more scalable and accessible alternatives (Conrad et al., 2024; Makransky & Petersen, 2021; Parong & Mayer, 2018). The dominance of fully immersive VR may be explained by its potential to provide presence, embodied interaction, and spatial experience. According to embodied cognition, learners' movements, their examination of objects from different perspectives, and their bodily interaction with scientific representations may support conceptual learning (Lindgren & Johnson-Glenberg, 2013). The Cognitive Affective Model of Immersive Learning also proposes that immersive environments may influence learning through presence, learner control, interest, and self-efficacy (Makransky & Petersen, 2021). Nevertheless, greater immersion may also involve more sensory stimuli and more complex interaction. Complicated controls, unnecessary visual elements, or interactions unrelated to the learning objectives may divert learners' cognitive resources away from the target content. Learners may focus more on the novelty of the technology than on the scientific concept, and high immersion may increase

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cognitive load in some contexts. Although immersive VR may support motivation and presence, previous research has reported mixed learning outcomes because of short-term effects and implementation-related constraints (Makransky et al., 2019; Radianti et al., 2020). Therefore, the assumption that stronger immersion necessarily produces higher academic achievement should be evaluated critically.

At the disciplinary level, VR was most frequently used in biology and physics. In biology, abstract and three-dimensional concepts such as cellular structures, anatomy, and ecology were made more concrete; in physics, astronomy, electricity, and mechanics were prominent. This result demonstrates that VR is frequently preferred in areas where visualization and experiential learning are particularly valuable. Previous studies similarly indicate that VR may support the understanding of abstract concepts and the simulation of complex processes (Chang et al., 2023; Wu et al., 2020; Yang et al., 2024). Although less frequently represented, chemistry applications focused on molecular structures and abstract concepts, while STEM and educational technology studies incorporated VR into engineering design and problem-solving scenarios. Thus, VR is not limited to concept teaching but is also being used in interdisciplinary and applied learning contexts.

The pedagogical value of a VR type cannot be evaluated independently of the characteristics of the science content. A fully immersive system may not be necessary for rotating a molecular model, changing selected variables, or repeatedly observing a scientific process. In such cases, desktop or mobile solutions may offer less costly and more practical alternatives. In contrast, fully immersive systems may be more appropriate when learners need to move inside an anatomical structure, experience scale relationships between astronomical objects, or perform embodied actions in a complex laboratory environment. The selection of a VR type should therefore be based not on technological sophistication alone but on the level of visualization, interaction, and immersion required by the learning objective. Future studies should compare fully immersive, desktop, and mobile VR applications for the same science topic under similar pedagogical conditions. These comparisons should assess not only academic achievement but also cognitive load, presence, accessibility, and cost-effectiveness. Such designs would provide clearer evidence regarding which technological solution is pedagogically necessary and sustainable for particular science content.

### 4.4. Measurement Priorities and Pedagogical Design

The fourth research question examined the dimensions covered by the measurement instruments used in VR research in science education, including cognitive achievement, motivation, self-efficacy, and presence. The results indicate that academic achievement and knowledge level were the most frequently measured variables. This suggests that researchers have prioritized the cognitive effects of VR. Previous studies similarly report that achievement tests are widely used in VR research in science education (Merchant et al., 2014; Radianti et al., 2020). Chang et al. (2023) also note that VR studies have focused heavily on cognitive outcomes, while affective and pedagogical outcomes have received less attention.

However, the educational effectiveness of a VR application cannot be reduced to an increase in test scores. The same application may support academic achievement while producing high cognitive load, create short-term motivation without contributing to long-term retention, or support individual performance while limiting collaboration and communication. Consequently, the meaning of “effective” should be explicitly defined in relation to cognitive, affective, social, behavioural, or experiential outcomes. Motivation was also frequently examined, which is expected given the visually engaging and innovative nature of VR. Previous research suggests that immersive VR may support

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students' interest and career aspirations (Makransky et al., 2020), while the CAMIL framework explains how immersion may influence interest and intrinsic motivation (Makransky & Petersen, 2021). However, short-term studies cannot always determine whether increased motivation reflects sustainable interest in learning or an initial novelty effect. Future research should therefore distinguish initial interest generated by first exposure to VR from long-term motivation by using extended interventions and delayed measurements.

Self-efficacy and cognitive load were investigated less frequently.

The limited attention given to cognitive load is noteworthy because multimedia learning theory suggests that VR may support learning through the integration of visual and auditory information, while poorly designed environments may impose unnecessary cognitive demands. Presence, immersion, and motivation should therefore be evaluated together with achievement and cognitive load (Makransky & Mayer, 2022; Makransky & Petersen, 2021). A strong sense of presence may increase engagement with the virtual environment, but it cannot be regarded as evidence of pedagogical effectiveness unless the interaction supports scientific understanding. The limited measurement of affective, social, and pedagogical outcomes also suggests that VR has largely been conceptualized as an individual and cognitive learning tool. Science education, however, also involves scientific communication, collaboration, evidence-based explanation, problem solving, and shared decision-making. Research showing that collaborative immersive environments can influence students' scientific explanations indicates that the social and discursive dimensions of VR deserve greater attention (Matovu et al., 2023). Achievement tests should therefore be supplemented with observations, interviews, performance assessments, learner products, system logs, interaction records, and delayed retention measurements.

The results also suggest that pedagogical design has been less visible in existing research than technological characteristics. The effectiveness of VR depends not only on transferring science content into a virtual environment but also on the tasks learners complete, the guidance and feedback they receive, and the way the virtual experience is integrated with classroom discussion, explanation, assessment, and real-world experimentation. The same VR technology may support meaningful learning when it includes explicit learning objectives and structured guidance, but it may result in superficial exploration or distraction when pedagogical direction is absent. Learner activity should not be understood solely as physical movement or unrestricted exploration. Learning tasks should encourage learners to make scientific comparisons, collect evidence, test predictions, and explain their experiences. From an experiential learning perspective, virtual experience should be followed by reflection, conceptualization, and application to new situations. Otherwise, VR may remain a memorable experience without developing into scientific understanding. Future studies should therefore report not only hardware type and immersion level but also learner tasks, instructional strategies, guidance, feedback, individual or collaborative use, duration, teacher role, and post-VR meaning-making activities (Matovu et al., 2023; Oje et al., 2025).

When the results of the four research questions are considered together, a four-component alignment framework emerges: VR type, science topic, pedagogical design, and learner characteristics. None of these components can be regarded as independently superior. A fully immersive system may be appropriate for three-dimensional experiential content but may create excessive cognitive load for younger learners when guidance is insufficient. A mobile application may provide less immersion but may be more suitable in terms of accessibility, repeated use, and cost. The same science topic may require different VR types, learner tasks, and measurement strategies when it is taught

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for different pedagogical purposes. Future research should therefore move beyond repeatedly testing the overall effect of VR and focus on identifying effective alignments among these four components.

### 4.5. General Contributions and Limitations

This study makes an important contribution as one of the first comprehensive examinations of VR research in science education between 2008 and 2024. Combining bibliometric analysis with descriptive content analysis revealed not only publication trends and conceptual structures but also methodological characteristics, the distributions of VR types and science disciplines, and measurement dimensions within an integrated framework. Consequently, research trends were evaluated not only through numerical indicators but also within a pedagogical context. The direct alignment of the research questions with the findings also moves the study beyond previous limited bibliometric reviews. Prior research similarly emphasizes that combining bibliometric and descriptive content analyses can provide original contributions to a field (Aktoprak & Hursen, 2022; Guo et al., 2024; Zhao et al., 2023).

The principal contribution of this study is to provide a comprehensive overview of research trends in VR-supported science education by identifying publication patterns, methodological characteristics, disciplinary distributions, VR types, and measurement priorities. The results indicate that no specific VR type can be considered universally superior across all science topics, learner groups, and instructional purposes. The educational potential of VR depends on the alignment among technological features, the representational requirements of the science content, pedagogical design, and learner characteristics. This framework implies that future research should not treat VR use as a single independent variable but should investigate which form of VR produces meaningful outcomes for which content, under which instructional arrangements, and for which learners. The results also challenge technology-centred assumptions that more advanced technology directly leads to better learning. The frequent use of fully immersive systems does not demonstrate that they are the most appropriate option for all learning objectives. Pedagogical appropriateness depends more on alignment with learning objectives, content characteristics, teacher support, and learner needs than on technological sophistication. Accordingly, VR research should move from general comparisons of technologies toward studies of conditional effectiveness and pedagogical alignment.

Several limitations should be considered. First, the review was limited to the Web of Science database. Studies indexed in Scopus, ERIC, Google Scholar, or other databases may therefore have been excluded. Chang et al. (2023) similarly note that evaluating VR and augmented reality research through a single database may restrict the global perspective. Second, because the analysis was limited to English-language publications, relevant studies published in local languages may have been overlooked. Third, although high reliability was achieved in the content coding ($\kappa$ = 0.82), interpretations made by different researchers may produce minor variations. Finally, because data collection covered publications only up to September 2024, studies published during the remaining months of 2024 were not included.

Differences in reporting practices among the reviewed studies may also have limited detailed comparison of VR type, science topic, pedagogical design, and learner characteristics. Some studies described their hardware and software in detail but provided less information about learner tasks, teacher guidance, feedback, intervention duration, and post-VR meaning-making activities. Consequently, all components of the overarching framework could not be evaluated with equal depth. This limitation highlights the need for more standardized and detailed reporting of pedagogical design in future VR studies.

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## 5. Conclusions and Recommendations

The results demonstrate that VR research in science education is growing rapidly but remains in transition from general effect-testing studies toward context-sensitive, theoretically grounded, and pedagogically informed explanations. The next stage of development should not focus solely on demonstrating that VR is effective. Instead, it should explain the technological, disciplinary, pedagogical, and individual conditions under which its educational potential and reported effectiveness emerge. Accordingly, the question "Which type of VR, combined with which science topic and pedagogical design, is most effective, and for whom?" provides not only an integrative framework for interpreting the results of the present study but also a comprehensive research agenda capable of guiding the future development of VR research in science education.

Future research should use broader databases and multilingual reviews to provide a more inclusive global perspective. Sample diversity should be increased, particularly through greater representation of teachers and younger learners. Previous research has similarly identified the underrepresentation of teachers and early-age groups in VR and augmented reality studies (Han et al., 2025; Stavroulia et al., 2025; Walstra et al., 2024). The dimensions measured should also be expanded beyond cognitive outcomes to include motivation, self-efficacy, presence, socio-emotional processes, and cognitive load. Makransky and Mayer (2022), for example, suggest that examining cognitive load and learning satisfaction together can provide more holistic evaluations. The assessment of low-cost and accessible VR solutions is also essential for extending these technologies to broader populations in science education.

Future studies should directly test the overarching framework concerning which VR type, combined with which science topic and pedagogical design, may be most appropriate for particular learners. Fully immersive, semi-immersive, desktop, and mobile VR applications should be compared for the same science topic under similar instructional conditions, while also examining learners with different ages, achievement levels, spatial abilities, technology experience, and special educational needs. Such studies should assess academic achievement, cognitive load, motivation, presence, retention, collaboration, accessibility, and cost-effectiveness. Research involving teachers and pre-service teachers could provide stronger evidence regarding curriculum integration, classroom management, pedagogical decision-making, and the management of technical challenges. Guided and open exploration, individual and collaborative use, different feedback types, and varying levels of teacher guidance should also be compared. Researchers may further compare real laboratories, VR laboratories, and blended models integrating both environments to clarify whether VR is most appropriate as a substitute for real experience or as a tool that prepares, complements, and extends authentic experimentation.

Longitudinal studies are needed to distinguish the short-term novelty effect of VR from sustained motivation and learning. In addition to immediate post-intervention measurements, delayed achievement and retention assessments could provide stronger evidence regarding sustainability. Large-scale and multi-site studies would also allow differences among school types, socioeconomic contexts, and technological infrastructures to be evaluated.

**Declaration of Conflicts of Interest**

The authors declare that they have no conflicts of interest regarding the research, authorship, and publication of this article.

**Declaration of Generative AI Use**

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The authors used ChatGPT (OpenAI) to assist with language editing, improving clarity, and refining the academic writing of the manuscript. All AI-assisted content was critically reviewed and verified by the authors, who take full responsibility for the final content of the manuscript.

**Ethical Statement**

This study was conducted using bibliometric analysis and descriptive content analysis of previously published scientific articles retrieved from the Web of Science Core Collection database. As the study relied exclusively on publicly available secondary data and did not involve direct interaction with human participants or the collection of personal data, ethics committee approval was not required, subject to applicable institutional and journal policies. Throughout the research process, the principles of research and publication ethics were observed.

**Author Contributions**

Güler Göçen Kabaran: Conceptualization, methodology, data analysis, visualization, writing – original draft, writing – review and editing. Gökhan Güven: Conceptualization, methodology, data analysis, writing – review and editing. Both authors reviewed and approved the final version of the manuscript.

## References

Akbay, E., & Deniş Çeliker, H. (2023). The effect of immersive reality on science learning: A meta-analysis. *Malaysian Online Journal of Educational Technology*, *11*(3), 158-172. https://doi.org/10.52380/mojet.2023.11.3.304

Aktoprak, A., & Hursen, C. (2022). A bibliometric and content analysis of critical thinking in primary education. *Thinking Skills and Creativity*, *44*, 101029. https://doi.org/10.1016/j.tsc.2022.101029

Araiza-Alba, P., Keane, T., Matthews, B., Simpson, K., Strugnell, G., Chen, W.S., & Kaufman, J. (2021). The potential of 360-degree virtual reality videos to teach water-safety skills to children. Computers & Education, 163, 104096. https://doi.org/10.1016/j.compedu.2020.104096

Babatunde, E.O. (2025). Teachers' characteristics, school factors as correlates of students achievement in basic science in secondary school in Oyo State. *Sociology Study*, *15*(2), 78-86. https://doi.org/10.17265/2159-5526/2025.02.002

Bailenson, J. (2018). *Experience on demand: What virtual reality is, how it works, and what it can do*. WW Norton & Company.

Balbağ, M.Z., Leblebicier, K., Karaer, G., Sarıkahya, E., & Erkan, Ö. (2016). Science education and teaching problems in Turkey. *Journal of Research in Education and Teaching, 5*(3), 12–23.

Battipede, E., Giangualano, A., Boffi, P., Clerici, M., Calvi, A., Cassenti, L., ... & Gallace, A. (2024, November). Physics Playground: Insights from a Qualitative-Quantitative Study About VR-Based Learning. In *International Conference on Intelligent Human Computer Interaction* (pp. 97-108). Cham: Springer Nature Switzerland.

Bybee, R. (1997). Achieving scientific literacy: From purposes to practices. Heinemann

Chang, C.Y., Kuo, H.C., & Du, Z. (2023). The role of digital literacy in augmented, virtual, and mixed reality in popular science education: A review study and an educational framework development. *Virtual Reality*, *27*, 2461-2479. https://doi.org/10.1007/s10055-023-00817-9

Chen, J. (2018). *Virtual reality technology and applications*. Springer.

Cheng, C., Wang, L., Xie, H., & Yan, L. (2023). Mapping digital innovation: A bibliometric analysis and systematic literature review. *Technological Forecasting and Social Change*, *194*, 122706. https://doi.org/10.1016/j.techfore.2023.122706

Cheng, K.H., & Tsai, C.C. (2019). A case study of immersive virtual field trips in an elementary classroom: Students' learning experience and teacher-student interaction behaviors. *Computers & Education, 140*, 103600. https://doi.org/10.1016/j.compedu.2019.103600

Coban, M., Bolat, Y.I., & Goksu, I. (2022). The potential of immersive virtual reality to enhance learning: A meta-analysis. *Educational Research Review*, *36*, 100452. https://doi.org/10.1016/j.edurev.2022.100452

Conrad, M., Kablitz, D., & Schumann, S. (2024). Learning effectiveness of immersive virtual reality in education and training: A systematic review of findings. *Computers & Education: X Reality*, *4*, 100053. https://doi.org/10.1016/j.cexr.2024.100053

Cooper, G., Park, H., Nasr, Z., Thong, L. P., & Johnson, R. (2019). Using virtual reality in the classroom: preservice teachers' perceptions of its use as a teaching and learning tool. *Educational Media International*, *56*(1), 1-13. https://doi.org/10.1080/09523987.2019.1583461

Durukan, A., Artun, H. & Temur, A. (2020). Virtual reality in science education: a descriptive review. *Journal of Science Learning, 3*(3), 132-142.

Elme, L., Jørgensen, M. L., Dandanell, G., Mottelson, A., & Makransky, G. (2022). Immersive virtual reality in STEM: is IVR an effective learning medium and does adding self-explanation after a lesson improve learning outcomes?. *Educational Technology Research and Development*, *70*(5), 1601-1626. https://doi.org/10.1007/s11423-022-10139-3

Eutsler, L., & Long, C. S. (2021). Preservice teachers' acceptance of virtual reality to plan science instruction. *Educational Technology & Society*, *24*(2), 28-43.

Gittinger, M., & Wiesche, D. (2024). Systematic review of spatial abilities and virtual reality: The role of interaction. *Journal of Engineering Education*, *113*(4), 919-938. https://doi.org/10.1002/jee.20568

Guo, X., Chen, S. & Guo, Y. (2024). Advancing multimodal teaching: a bibliometric and content analysis of trends, influences, and future directions. *Humanities and Social Sciences Communications,* 11, 1718. https://doi.org/10.1057/s41599-024-04254-0

Han, I. (2021). Immersive virtual field trips and elementary students' perceptions. *British Journal of Educational Technology, 52*(1), 179-195. https://doi.org/10.1111/bjet.12946

Han, X., Luo, H., Wang, Z., & Zhang, D. (2025). Using virtual reality for teacher education: a systematic review and meta-analysis of literature from 2014 to 2024. *Frontiers in Virtual Reality*, *6*, 1620905. https://doi.org/10.3389/frvir.2025.1620905

Hite, R.L., Jones, M.G., Childers, G.M., Ennes, M., Chesnutt, K., Pereyra, M., & Cayton, E. (2019). Investigating potential relationships between adolescents' cognitive development and perceptions of presence in 3-D, haptic-enabled, virtual reality science instruction. *Journal of Science Education and Technology, 28*, 265-284. https://doi.org/10.1007/s10956-018-9764-y

Huang, T.C., & Tseng, H.P. (2025). Extended reality in applied sciences education: A systematic review. *Applied Sciences*, *15*(7), 4038. https://doi.org/10.3390/app15074038

Huang, W., Roscoe, R. D., Johnson-Glenberg, M. C., & Craig, S. D. (2021). Motivation, engagement, and performance across multiple virtual reality sessions and levels of immersion. *Journal of Computer Assisted Learning*, *37*(3), 745-758. https://doi.org/10.1111/jcal.12520

Jang, S., Vitale, J. M., Jyung, R. W., & Black, J. B. (2017). Direct manipulation is better than passive viewing for learning anatomy in a three-dimensional virtual reality environment. *Computers & Education*, *106*, 150-165. https://doi.org/10.1016/j.compedu.2016.12.009

Jensen, L., & Konradsen, F. (2018). A review of the use of virtual reality head-mounted displays in education and training. *Education and Information Technologies*, *23*(4), 1515-1529. https://doi.org/10.1007/s10639-017-9676-0

Johnson-Glenberg, M. C. (2018). Immersive VR and education: Embodied design principles that include gesture and hand controls. *Frontiers in Robotics and AI*, *5*, 375272. https://doi.org/10.3389/frobt.2018.00081

Johnson-Glenberg, M. C., & Megowan-Romanowicz, C. (2017). Embodied science and mixed reality: How gesture and motion capture affect physics education. *Cognitive Research: Principles and Implications*, *2*(1), 24. https://doi.org/10.1186/s41235-017-0060-9

Johnson-Glenberg, M.C., Bircheld, D., Savvides, P., & Megowan-Romanowicz, C. (2011). *Semi-virtual embodied learning-real world stem assessment* (pp. 241-257). Springer.

Klingenberg, S., Fischer, R., Zettler, I., & Makransky, G. (2023). Facilitating learning in immersive virtual reality: Segmentation, summarizing, both or none?. *Journal of Computer Assisted Learning*, *39*(1), 218-230. https://doi.org/10.1111/jcal.12741

© Author(s) | CC BY 4.0 | e-ISSN 2146-5983

Lampropoulos, G., & Kinshuk, (2024). Virtual reality and gamification in education: A systematic review. *Educational Technology Research and Development*, *72*, 1691-1785. https://doi.org/10.1007/s11423-024-10351-3

Leung, T., Zulkernine, F., & Isah, H. (2018). The use of virtual reality in enhancing interdisciplinary research and education. *Systemics, Cybernetics and Informatics, 16*(6), 4-9. https://doi.org/10.48550/arXiv.1809.08585.

Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by embodiment: Six precepts for research on embodied learning and mixed reality. *Educational researcher*, *42*(8), 445-452. https://doi.org/10.3102/0013189X13511661

Llanos-Ruiz, D., Abella-García, V., & Ausín-Villaverde, V. (2025). Virtual reality in higher education: A systematic review aligned with the sustainable development goals. *Societies*, *15*(9), 251. https://doi.org/10.3390/soc15090251

Luo, H., Li, G., Feng, Q., Yang, Y., & Zuo, M. (2021). Virtual reality in K-12 and higher education: A systematic review of the literature from 2000 to 2019. *Journal of Computer Assisted Learning*, *37*(3), 887-901. https://doi.org/10.1111/jcal.12538

Makransky, G., & Mayer, R. E. (2022). Benefits of taking a virtual field trip in immersive virtual reality: Evidence for the immersion principle in multimedia learning. *Educational Psychology Review*, *34*(3), 1771-1798. https://doi.org/10.1007/s10648-022-09675-4

Makransky, G., & Petersen, G.B. (2021). The cognitive affective model of immersive learning (CAMIL): A theoretical research-based model of learning in immersive virtual reality. *Educational Psychology Review*, *33*, 937-958. https://doi.org/10.1007/s10648-020-09586-2

Makransky, G., Borre-Gude, S., & Mayer, R.E. (2019). Motivational and cognitive benefits of training in immersive virtual reality based on multiple assessments. *Journal of Computer Assisted Learning, 35*(6), 691-707. https://doi.org/10.1111/jcal.12375

Makransky, G., Petersen, G.B., & Klingenberg, S. (2020). Can an immersive virtual reality simulation increase students' interest and career aspirations in science? *British Journal of Educational Technology, 51*(6), 2079-2097. https://doi.org/10.1111/bjet.12954

Matovu, H., Won, M., Treagust, D.F., Ungu, D.A.K., Mocerino, M., Tsai, C.C., & Tasker, R. (2023). Change in students' explanation of the shape of snowflakes after collaborative immersive virtual reality. *Chemistry Education Research and Practice*, *24*(2), 509-525. https://doi.org/10.1039/d2rp00176d

Merchant, Z., Goetz, E.T., Cifuentes, L., Keeney-Kennicutt, W., & Davis, T.J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Computers & Education*, *70*, 29-40. https://doi.org/10.1016/j.compedu.2013.07.033

Meyer, O.A., Omdahl, M.K., & Makransky, G. (2019). Investigating the effect of pre-training when learning through immersive virtual reality and video: A media and methods experiment. *Computers & Education*, 140, 103603. https://doi.org/10.1016/j.compedu.2019.103603

Monahan, T., McArdle, G., & Bertolotto, M. (2008). Virtual reality for collaborative e-learning. *Computers & Education, 50*(4), 1339-1353. https://doi.org/10.1016/j.compedu.2006.12.008

Munafo, J., Diedrick, M., & Stoffregen, T.A. (2017). The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects. *Experimental Brain Research*, *235*, 889-901.

National Research Council (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13165.

Oje, A.V., Hunsu, N.J., & Fiorella, L. (2025). A systematic review of evidence-based design and pedagogical principles in educational virtual reality environments. *Educational Research Review*, *47*, 100676. https://doi.org/10.1016/j.edurev.2025.100676

Omowumi, O.E., Michael, F.B., Friday, O.H., Taofeeq, B., Chinenye, E.C., & Samiala, B.B. (2024) Impact of inadequate infrastructure on the effective teaching and learning of physics in senior secondary schools in Bwari area council of Abuja. *International Journal of Humanities Social Science and Management*, 4(4), 1281-1288.

Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., ... & Moher, D. (2021). Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement. *Journal of clinical epidemiology*, *134*, 103-112.

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Pande, P., Thit, A., Sørensen, A. E., Mojsoska, B., Moeller, M. E., & Jepsen, P. M. (2021). Long-Term Effectiveness of Immersive VR Simulations in Undergraduate Science Learning: Lessons from a Media-Comparison Study. *Research in Learning Technology*, *29*. https://doi.org/10.25304/rlt.v29.2482

Parong, J., & Mayer, R. E. (2018). Learning science in immersive virtual reality. *Journal of Educational Psychology, 110*(6), 785–797. https://doi.org/10.1037/edu0000241

Parong, J., & Mayer, R. E. (2021). Cognitive and affective processes for learning science in immersive virtual reality. *Journal of Computer Assisted Learning*, *37*(1), 226-241. https://doi.org/10.1111/jcal.12482

Pellas, N., Kazanidis, I., & Palaigeorgiou, G. (2020). A systematic literature review of mixed reality environments in K-12 education. *Education and Information Technologies*, *25*(4), 2481-2520. https://doi.org/10.1007/s10639-019-10076-4

Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Computers & Education*, *95*, 309-327. https://doi.org/10.1016/j.compedu.2016.02.002

Radianti, J., Majchrzak, T.A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education, 147,* 103778. https://doi.org/10.1016/j.compedu.2019.103778

Sakr, A., & Abdullah, T. (2024). Virtual, augmented reality and learning analytics impact on learners, and educators: A systematic review. *Education and Information Technologies*, *29*, 19913-19962. https://doi.org/10.1007/s10639-024-12602-5

Shah, S.F.A., Mazhar, T., Shahzad, T., Khan, M.A., Ghadi, Y.Y., & Hamam, H. (2024). Integrating educational theories with virtual reality: Enhancing engineering education and VR laboratories. *Social Sciences & Humanities Open*, *10*, 101207. https://doi.org/10.1016/j.ssaho.2024.101207

Slater, M., & Sanchez-Vives, M.V. (2016). Enhancing our lives with immersive virtual reality. *Frontiers in Robotics and AI*, *3*, 74. https://doi.org/10.3389/frobt.2016.00074

Stavroulia, K.E., Baka, E., & Lanitis, A. (2025). VR-based teacher training environments: A systematic approach for defining the optimum appearance of virtual classroom environments. *Virtual Worlds, 4*(1), 6. https://doi.org/10.3390/virtualworlds4010006

Strojny, P., & Dużmańska-Misiarczyk, N. (2023). Measuring the effectiveness of virtual training: A systematic review. *Computers & Education: X Reality*, *2*, 100006. https://doi.org/10.1016/j.cexr.2022.100006

Sviridova, E., Yastrebova, E., Bakirova, G., & Rebrina, F. (2023). Immersive technologies as an innovative tool to increase academic success and motivation in higher education. *Frontiers in Education,* 8, 1192760. https://doi.org/10.3389/feduc.2023.1192760

Tusher, H. M., Mallam, S., & Nazir, S. (2024). A systematic review of virtual reality features for skill training. *Technology, Knowledge and Learning*, *29*(2), 843-878. https://doi.org/10.1007/s10758-023-09713-2

Walstra, K.A., Cronje, J., & Vandeyar, T. (2024). A review of virtual reality from primary school teachers' perspectives. *The Electronic Journal of e-Learning, 22*(3), 1-11. https://doi.org/10.34190/ejel.21.4.3060

Wu, B., Yu, X., & Gu, X. (2020). Effectiveness of immersive virtual reality using head-mounted displays on learning performance: A meta-analysis. *British Journal of Educational Technology*, *51*(6), 1991-2005. https://doi.org/10.1111/bjet.13023

Wu, J., Guo, R., Wang, Z., & Zeng, R. (2021). Integrating spherical video-based virtual reality into elementary school students' scientific inquiry instruction: effects on their problem-solving performance. *Interactive Learning Environments*, *29*(3), 496-509. https://doi.org/10.1080/10494820.2019.1587469

Yang, C., Zhang, J., Hu, Y., Yang, X., Chen, M., Shan, M., & Li, L. (2024). The impact of virtual reality on practical skills for students in science and engineering education: A meta-analysis. *International Journal of STEM Education*, *11*, 28. https://doi.org/10.1186/s40594-024-00487-2

Zhang, Y., Feijoo-Garcia, M.A., Gu, Y., Popescu, V., Benes, B., & Magana, A.J. (2024). Virtual and augmented reality in science, technology, engineering, and mathematics (STEM) education: An umbrella review. *Information, 15*, 515. https://doi.org/10.3390/ info15090515

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Zhao, J., Lin, L., Sun, J., & Liao, Y. (2020). Using the summarizing strategy to engage learners: Empirical evidence in an immersive virtual reality environment. *The Asia-Pacific Education Researcher, 29*, 473-482. https://doi.org/10.1007/s40299-020-00499-w

Zhao, X., Ren, Y., & Cheah, K. S. (2023). Leading virtual reality (VR) and augmented reality (AR) in education: bibliometric and content analysis from the web of science (2018–2022). *Sage Open*, *13*(3), https://doi.org/10.1177/21582440231190821

Zinchenko, Y.P., Khoroshikh, P.P., Sergievich, A.A., Smirnov, A.S., Tumyalis, A.V., Kovalev, A.I., Gutnikov, S.A., Golokhvast, K.S. (2020). Virtual reality is more efficient in learning human heart anatomy especially for subjects with low baseline knowledge. *New Ideas in Psychology, 59*, 100786. https://doi.org/10.1016/j.newideapsych.2020.100786

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