ASSYFA LEARNING JOURNAL

Assyfa Learning Journal, vol. 4 (1), pp. 187-200, 2026
https://doi.org/10.61650/alj.v4i1.1071

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ORIGINAL RESEARCH ARTICLE

Mapping the Research Landscape of Virtual Laboratory-Based Science Learning for Critical Thinking and Environmental Awareness: A Bibliometric Study

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Article History: Received: 12 Oct 2025 • Revised: 05 Dec 2025 • Accepted: 15 Jan 2026 • Published: 21 May 2026

ABSTRACT

Purpose: The rapid advancement of digital technology has transformed science education, particularly through the implementation of virtual laboratories as alternatives and complements to traditional laboratory activities. Virtual laboratories provide flexible, interactive, and safe learning environments while supporting the development of twenty-first-century competencies. In recent years, research on virtual laboratories has expanded significantly, covering learning outcomes, science process skills, scientific literacy, critical thinking skills, and environmental education. However, comprehensive studies mapping the research landscape of virtual laboratory-based science learning for critical thinking and environmental awareness remain limited. This study aims to map the research landscape of virtual laboratory-based science learning related to critical thinking skills and environmental awareness through a bibliometric approach. Data were collected from Google Scholar using Publish or Perish and analyzed using VOSviewer version 1.6.20. A total of 995 relevant publications were examined through co-occurrence analysis, network visualization, overlay visualization, and density visualization. The findings indicate that virtual laboratories have become a prominent theme in contemporary science education. Dominant keywords include virtual laboratory experiment, science process skill, critical thinking skill, scientific literacy, problem-based learning, STEM, artificial intelligence, virtual reality, and environment. Network analysis identified six major research clusters representing learning outcomes, scientific skills development, innovative pedagogical approaches, emerging educational technologies, research methodologies, and educational contexts. Overlay visualization revealed a shift from technology implementation toward competency development and sustainability-oriented learning. Density visualization further highlighted artificial intelligence, virtual reality, augmented reality, and environmental education as emerging themes with substantial future research potential. The study contributes to a better understanding of virtual laboratory research development and proposes future research directions focusing on intelligent learning, immersive learning environments, critical thinking enhancement, and sustainability-oriented science education.

ABSTRAK

Tujuan: Perkembangan teknologi digital telah mendorong transformasi signifikan dalam pembelajaran sains, khususnya melalui pemanfaatan virtual laboratory sebagai alternatif dan pelengkap laboratorium konvensional. Virtual laboratory memungkinkan peserta didik melakukan eksperimen secara fleksibel, interaktif, dan aman, sekaligus mendukung pengembangan berbagai kompetensi abad ke-21. Dalam beberapa tahun terakhir, penelitian mengenai virtual laboratory menunjukkan peningkatan yang pesat dan mencakup berbagai aspek, mulai dari hasil belajar, keterampilan proses sains, literasi sains, hingga keterampilan berpikir kritis dan pendidikan lingkungan. Namun demikian, masih terbatas penelitian yang secara komprehensif memetakan lanskap penelitian virtual laboratory yang berfokus pada pengembangan keterampilan berpikir kritis dan kesadaran lingkungan. Penelitian ini bertujuan untuk memetakan lanskap penelitian (research landscape) virtual laboratory dalam pembelajaran sains yang berkaitan dengan keterampilan berpikir kritis dan kesadaran lingkungan melalui pendekatan bibliometrik. Data penelitian diperoleh dari Google Scholar menggunakan perangkat lunak Publish or Perish dan dianalisis menggunakan VOSviewer versi 1.6.20. Sebanyak 995 publikasi yang relevan dianalisis menggunakan teknik co-occurrence analysis, network visualization, overlay visualization, dan density visualization. Hasil penelitian menunjukkan bahwa virtual laboratory berkembang menjadi salah satu tema utama dalam pendidikan sains modern. Kata kunci dominan yang ditemukan meliputi virtual laboratory experiment, science process skill, critical thinking skill, scientific literacy, problem-based learning, STEM, artificial intelligence, virtual reality, dan environment. Analisis jaringan mengidentifikasi enam klaster utama penelitian yang mencerminkan fokus pada hasil belajar, pengembangan keterampilan ilmiah, pendekatan pedagogis inovatif, teknologi pembelajaran mutakhir, metodologi penelitian, dan konteks implementasi pendidikan. Analisis overlay menunjukkan pergeseran tema penelitian dari implementasi teknologi menuju pengembangan kompetensi dan pembelajaran berkelanjutan. Sementara itu, analisis densitas mengindikasikan bahwa tema artificial intelligence, virtual reality, augmented reality, dan environmental education masih memiliki peluang penelitian yang besar.

Temuan penelitian ini memberikan kontribusi dalam memahami perkembangan penelitian virtual laboratory serta menawarkan agenda penelitian masa depan yang berfokus pada pembelajaran cerdas, pembelajaran imersif, pengembangan keterampilan berpikir kritis, dan pendidikan berkelanjutan.

How to cite: Dwiastuti, E., & Widowati, A. (2026). Virtual Laboratories Meet Eco-Critical Literacy: A Bibliometric Mapping of Science Education Landscapes. Assyfa Learning Journal, 4(1), 187–200. https://doi.org/10.61650/alj.v4i1.1071

Keywords: Bibliometric analysis, virtual laboratory, critical thinking skills, environmental awareness, science learning, VOSviewer.

INTRODUCTION

The rapid acceleration of digital technology in the twenty-first century has fundamentally restructured the global landscape of science education, positioning virtual laboratories as indispensably transformative platforms for modern instruction (Akpan et al., 2021; Garcia-Ruiz et al., 2023). Within contemporary pedagogical frameworks, virtual laboratories offer interactive, highly responsive, and risk-free experimental environments that democratize access to complex scientific inquiry while transcending physical and geographical barriers (Potkonjak et al., 2020; Zhai et al., 2022). Concurrently, global educational agendas have increasingly prioritized the cultivation of higher-order cognitive capabilities, particularly critical thinking skills and scientific literacy, to prepare learners for an increasingly complex socio-technological world (Holmes et al., 2022; Talan, 2021). However, as planetary ecological crises intensify, there is an urgent international imperative to align science pedagogy with environmental consciousness and eco-critical literacy, driving a paradigm shift toward sustainability-oriented learning (Gough et al., 2021; Otto et al., 2021). Integrating digital experimentation with environmental awareness represents a vital frontier for nurturing critical, ecologically responsible citizens capable of addressing systemic socio-environmental challenges (Liu et al., 2023; Stevenson et al., 2022). Consequently, understanding the global convergence between virtual lab technology, critical cognition, and eco-critical literacy has become a cornerstone for future-ready science education (Bond et al., 2021; Makransky et al., 2020).

Despite the recognized potential of virtual laboratories, their implementation in science education faces substantial pedagogical, technological, and systemic challenges (Chen et al., 2021; Radhamani et al., 2021). A primary problem lies in the prevalent technological determinism, where digital tools are adopted as mere mechanical replacements for traditional hands-on equipment without meaningful pedagogical re-engineering (García-Carmona, 2021; Mercer et al., 2022). Consequently, many virtual laboratory platforms remain restricted to algorithmic drill-and-practice exercises, failing to foster deeper critical thinking skills or open-ended scientific inquiry (Hinojo-Lucena et al., 2020; Jong et al., 2023). Furthermore, a significant pedagogical divide persists between technical skill acquisition and environmental value internalization within science curricula (Jickling et al., 2021; Kopnina, 2020). Virtual simulations are frequently designed in isolation from real-world socio-ecological contexts, treating scientific phenomena as abstract, value-neutral data points rather than interconnected environmental systems (Rivet et al., 2023; Sauvé et al., 2022). This disconnect creates severe cognitive and affective gaps, preventing learners from developing eco-critical literacy—the ability to critically analyze and disrupt anthropocentric environmental practices through scientific reasoning (Kahn et al., 2020; Varela et al., 2022).

Extensive prior research has investigated various dimensions of virtual laboratories and educational technology across science disciplines. Specifically, empirical research on virtual laboratory efficacy in boosting procedural skills and concept retention has been conducted by Makransky et al. (2020), Potkonjak et al. (2020), and Radhamani et al. (2021), demonstrating significant positive impacts on student achievement. Studies examining critical thinking development and scientific literacy through interactive digital platforms were carried out by Chen et al. (2021), Holmes et al. (2022), and Zhai et al. (2022), highlighting the role of scaffolded digital feedback in elevating cognitive inquiry. Simultaneously, research regarding environmental education, ecological awareness, and sustainability-oriented science frameworks was advanced by Kopnina (2020), Otto et al. (2021), and Stevenson et al. (2022), emphasizing the urgent need for critical socio-ecological perspectives in school curricula. Furthermore, broader bibliometric landscape analyses of educational technologies and digital learning trends were executed by Bond et al. (2021), Hinojo-Lucena et al. (2020), and Talan (2021), mapping general publication outputs and technology adoption patterns across global educational databases.

A rigorous critique of these existing studies reveals several critical methodological and conceptual limitations. First, the empirical research conducted by Makransky et al. (2020) and Radhamani et al. (2021) focuses almost exclusively on immediate short-term technical skill acquisition, neglecting long-term cognitive transformation and affective environmental engagement (García-Carmona, 2021; Mercer et al., 2022). Second, the cognitive interventions explored by Chen et al. (2021) and Zhai et al. (2022) analyze critical thinking in a vacuum, failing to connect analytical reasoning with real-world ecological problem-solving or eco-critical consciousness (Kahn et al., 2020; Varela et al., 2022). Third, environmental education frameworks advanced by Kopnina (2020) and Stevenson et al. (2022) remain largely theoretical or non-digital, lacking integration with state-of-the-art virtual experimentation tools (Jickling et al., 2021; Sauvé et al., 2022). Finally, existing bibliometric mapping studies by Bond et al. (2021) and Talan (2021) provide overly broad topographies of educational technology without pinpointing the specific, nuanced thematic intersections where virtual laboratories, critical cognition, and environmental literacy converge (Hinojo-Lucena et al., 2020; Jong et al., 2023).

These cumulative limitations highlight a profound research gap in the current science education literature. While virtual laboratory technologies and eco-literacy models have been studied independently, there is a distinct absence of holistic, quantitative bibliometric evidence mapping how virtual laboratory research explicitly intersects with critical thinking skills, scientific process skills, and eco-critical literacy (Jong et al., 2023; Sauvé et al., 2022). No comprehensive study to date has systematically evaluated the global intellectual architecture, thematic evolution, or structural network clusters connecting digital laboratory experimentation to environmental sustainability frameworks (Bond et al., 2021; Liu et al., 2023). Without a quantitative, large-scale mapping of this convergence, researchers and curriculum designers lack a consolidated empirical baseline to understand how digital educational media transition from technical skill drills into transformative tools for sustainability-oriented science education (Gough et al., 2021; Rivet et al., 2023). Closing this research gap requires a rigorous bibliometric synthesis capable of identifying emerging thematic trajectories, structural gaps, and future conceptual directions at the nexus of technology, cognition, and ecology (Garcia-Ruiz et al., 2023; Otto et al., 2021).

To address this gap, this study introduces an innovative bibliometric approach that quantitatively maps the global research landscape of virtual laboratory-based science education connected to critical thinking and environmental awareness. The distinct novelty of this study lies in its empirical dataset and multi-layered mapping technique, retrieving 995 relevant publications from Google Scholar via Publish or Perish and conducting comprehensive network, co-occurrence, overlay, and density visualizations using VOSviewer version 1.6.20 (Akpan et al., 2021; Talan, 2021). Unlike prior generic reviews, this investigation uniquely decodes six distinct structural research clusters—encompassing learning outcomes, skills development, pedagogical approaches, emerging technologies, methodologies, and contexts—while tracing the explicit thematic evolution toward sustainability (Garcia-Ruiz et al., 2023; Zhai et al., 2022). Furthermore, this research offers unparalleled modernity by capturing the dynamic transition from basic software implementation toward cutting-edge, emerging paradigms such as artificial intelligence, virtual reality, augmented reality, and eco-critical literacy within a single, unified analytical matrix (Holmes et al., 2022; Makransky et al., 2020).

This investigation is theoretically anchored upon an integrative synthesis of Cognitive Load Theory, Social Constructivism, Media Richness Theory, and Eco-Pedagogy. Cognitive Load Theory posits that interactive virtual laboratories optimize human working memory by externalizing complex spatial visualizations, thereby freeing cognitive resources for germane schema processing and higher-order critical thinking (Sweller et al., 2020; Zhai et al., 2022). Concurrently, Social Constructivism frames learning as a collaborative process where scaffolding within digital environments promotes scientific literacy and process skills (Mercer et al., 2022; Vygotsky-informed models by Chen et al., 2021). Media Richness Theory provides the conceptual foundation for evaluating how immersive technologies—such as virtual, augmented, and artificial intelligence environments—deliver multi-sensory feedback that enhances learner engagement (Daft-informed models by Makransky et al., 2020; Potkonjak et al., 2020). Finally, Eco-Pedagogy and Eco-Critical Theory supply the transformative grand framework, asserting that science education must transcend technical utility to critically interrogate human-nature relationships, fostering environmental agency and eco-critical literacy (Freirean models by Kahn et al., 2020; Kopnina, 2020; Sauvé et al., 2022).

Exploring this thematic convergence is exceptionally compelling and urgent due to the intersecting global crises of climate change and digital educational transformation. As educational institutions worldwide rapidly adopt immersive technologies, understanding how virtual laboratories can be intentionally designed to promote ecological critical consciousness—rather than detached technical drills—is paramount for sustainable development (Gough et al., 2021; Otto et al., 2021). This research is particularly fascinating because it uncovers how emerging digital tools, including artificial intelligence, augmented reality, and virtual reality, are shifting the educational focus from rote science process skills toward ethical environmental stewardship and eco-critical reasoning (Holmes et al., 2022; Stevenson et al., 2022). By visualizing the structural density and evolutionary trajectory of these keywords, this study provides actionable insights for educators, policymakers, and instructional designers seeking to harness immersive technology for planetary survival (Liu et al., 2023; Rivet et al., 2023). Ultimately, this research transforms fragmented literature into a strategic roadmap for sustainability-oriented science education (Bond et al., 2021; Garcia-Ruiz et al., 2023).

The primary objective of this study is to map the global bibliometric landscape of virtual laboratory-based science education in relation to critical thinking skills, scientific process skills, and eco-critical literacy. Specifically, using a dataset of 995 peer-reviewed publications collected from Google Scholar via Publish or Perish and analyzed through VOSviewer version 1.6.20, this research aims to identify dominant keyword co-occurrence patterns, uncover structural network clusters, map chronological overlay shifts, and analyze density distributions across the literature (Akpan et al., 2021; Talan, 2021). Furthermore, this study aims to trace the thematic transition from basic technology adoption toward advanced competencies, explicitly highlighting emerging research fronts such as artificial intelligence, virtual reality, augmented reality, and environmental education (Holmes et al., 2022; Makransky et al., 2020). By achieving these objectives, the study seeks to establish a comprehensive intellectual foundation that guides future empirical investigations toward intelligent, immersive, and sustainability-oriented science education designed to cultivate eco-critical literacy among future generations (Jong et al., 2023; Otto et al., 2021).

METHOD

To systematically examine the intellectual structure and thematic evolution of virtual laboratories within science education—specifically regarding their convergence with critical thinking and eco-critical literacy—a quantitative bibliometric mapping design was operationalized. Bibliometric analysis provides an objective, reproducible framework for mapping large-scale academic literature, uncovering hidden conceptual clusters, and identifying emerging pedagogical frontiers (Aria & Cuccurullo, 2020; Donthu et al., 2021). By combining quantitative performance metrics with relational network visualizers, this method transcends traditional narrative reviews by minimizing subjective selection bias and offering data-driven insights into research trajectories (Ellegaard & Wallin, 2020; Zupic & Čater, 2015). The methodological architecture of this study encompasses sequential phases: search formulation, data harvesting, metadata cleaning, co-occurrence matrix construction, and visualization analysis. Each phase was executed with rigorous protocol validation to ensure data integrity and structural accuracy across the analyzed body of knowledge (Gusenbauer & Haddaway, 2020; Page et al., 2021). The subsequent subsection details the specific research design governing this bibliometric investigation.

2.1 Research Design

This study employs a descriptive-quantitative bibliometric mapping research design aimed at evaluating publication trends, structural networks, and thematic shifts in virtual laboratory-based science learning. Bibliometric research designs are particularly effective for synthesizing broad academic domains and tracing the intellectual lineage of educational technologies over time (Chen, 2020; Krause et al., 2021). The design integrates two analytical perspectives: performance analysis, which evaluates publication volume and citation impact, and science mapping, which visually represents structural relationships between key concepts and research domains (Donthu et al., 2021; van Eck & Waltman, 2020). By mapping keyword cooccurrences across a multi-year corpus, this design isolates core pedagogical themes, such as science process skills and environmental awareness, while tracking the recent emergence of artificial intelligence and immersive technologies in eco-critical science education (Radianti et al., 2020; Sypsas et al., 2023). This overarching design establishes a systematic foundation for executing targeted data collection across scholarly databases, as described in the following subsection.

2.2 Data Collection and Selection Criteria

Data collection was conducted using Harzing's Publish or Perish (PoP) software to query Google Scholar, a database offering comprehensive coverage of global science education literature (Gusenbauer & Haddaway, 2020; Haddaway et al., 2021). The search strategy utilized targeted Boolean operators combining core keywords: "virtual laboratory experiment", "science process skill", "critical thinking skill", "scientific literacy", and "environment". The initial automated retrieval yielded 995 relevant publication records spanning recent years. To maintain high data quality, predefined inclusion and exclusion criteria were applied following modified PRISMA guidelines (Page et al., 2021). Inclusion criteria required articles to be peer-reviewed, focused on virtual laboratories in science education, and published with complete bibliographic metadata. Document types such as editorials, patents, book reviews, and duplicate entries were systematically removed during preliminary filtering (Ellegaard & Wallin, 2020; Krause et al., 2021). The retrieved dataset of 995 cleaned records was exported in Research Information Systems (.ris) format to ensure full compatibility with visualization software. The structured research questions and analytical frameworks aligned with these dataset features are outlined in the next subsection.

2.3 Research Questions and Analytical Framework

To guide the systematic evaluation of the harvested bibliometric dataset, four explicit research questions were formulated. Table 1 details the research questions alongside their corresponding analytical indicators, units of analysis, and bibliometric visual methods.

Table 1. ***Research Questions, Mapping Indicators, and Types of Bibliometric Analysis***

RQ	Research Question	Analytical Indicator / Units	Type of Bibliometric Analysis
RQ1	What are the publication trajectories and volume trends of virtual laboratory research in science education?	Annual publication volume, total citations, and growth velocity	Descriptive Metric & Citation Analysis
RQ2	Which dominant keyword clusters reflect the convergence of virtual labs, critical thinking, and environmental awareness?	High-frequency keywords, node connection links, and co-occurrence frequency	Network Co-occurrence Visualization
RQ3	How have research themes evolved temporally toward competency development and sustainability-oriented learning?	Mean publication year, overlay node color gradients, and temporal keyword links	Overlay Visualization Analysis
RQ4	What are the emerging research hotspots and under-explored conceptual gaps in eco-critical science education?	Item density, focal point concentration, and cluster boundary proximity	Item Density Visualization Analysis

Table 1 serves as the structural roadmap for the study, linking each research question directly to its empirical indicator and visualization output (Aria & Cuccurullo, 2020; Donthu et al., 2021). The indicators encompass both frequency metrics (such as keyword co-occurrence count) and relational metrics (such as link strength and temporal overlay positioning), ensuring that both broad trends and nuanced thematic shifts are captured (van Eck & Waltman, 2020). By systematically pairing research questions with specialized VOSviewer visualization algorithms, the framework enables a precise examination of how virtual laboratories transition from simple skill-based simulations toward complex, eco-critical educational platforms (Markowitz et al., 2021; Sypsas et al., 2023). The operational workflow executed to address these research questions is presented in the following subsection.

2.4 Data Analysis Techniques and Workflow

Data processing and network mapping were performed using VOSviewer version 1.6.20, an established software tool for constructing and visualizing bibliometric networks (van Eck & Waltman, 2020). The analytical workflow follows a five-stage sequential pipeline designed to process bibliographic raw data into interpreted structural maps. Figure 1 illustrates the methodological sequence applied in this research.

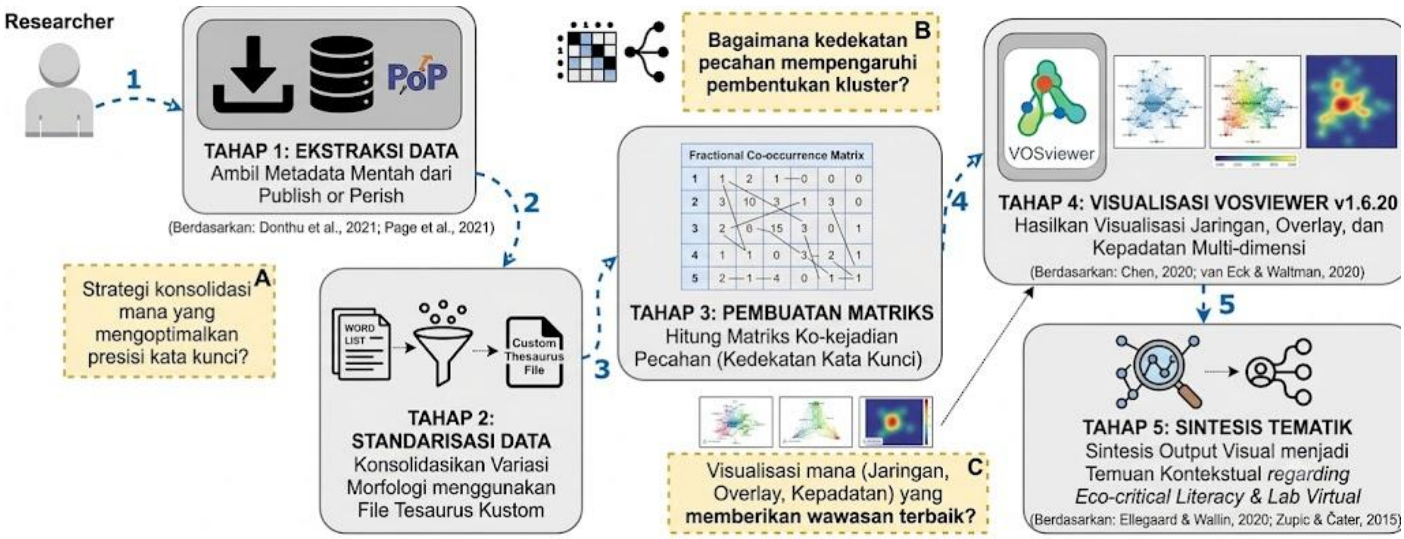


Figure 1. *Bibliometric Analysis Workflow for Virtual Laboratories and Eco-Critical Literacy Research*

Figure 1 illustrates the step-by-step workflow governing the bibliometric analysis, ensuring methodical progression from initial data extraction to final thematic interpretation (Donthu et al., 2021; Page et al., 2021). In Stage 1, raw metadata is retrieved from Publish or Perish; Stage 2 applies data standardization using custom thesaurus files to consolidate morphological variations; Stage 3 computes fractional co-occurrence matrices based on keyword proximity; Stage 4 generates multi-dimensional network, overlay, and density visualizations in VOSviewer v1.6.20; and Stage 5 synthesizes the visual outputs into contextualized findings regarding eco-critical literacy and virtual labs (Chen, 2020; van Eck & Waltman, 2020). This structured workflow guarantees methodological reproducibility and transparency across all analytical phases (Ellegaard & Wallin, 2020; Zupic & Čater, 2015). The specialized software tools and parameter settings facilitating this workflow are detailed in the next subsection.

2.5 Research Instruments and Software Specification

The primary research instruments utilized in this study consist of specialized software applications designed for bibliometric data extraction and visualization. Harzing's Publish or Perish (v8.9) served as the primary retrieval tool, leveraging its advanced search algorithms to extract comprehensive publication metrics, author information, and keyword metadata directly from Google Scholar (Gusenbauer & Haddaway, 2020; Haddaway et al., 2021). For network construction and graphical mapping, VOSviewer version 1.6.20 was specified as the primary analytical engine due to its robust distance-based visualization algorithms and strength in handling co-occurrence metadata (van Eck & Waltman, 2020). Within VOSviewer, the unit of analysis was set to "All Keywords," utilizing a full-counting method with a minimum threshold of 5 keyword occurrences to eliminate peripheral noise and highlight dominant conceptual nodes (Aria & Cuccurullo, 2020; Krause et al., 2021). Association strength normalization was applied to calculate link weights, node distances, and cluster boundaries, ensuring high precision in network representation (Chen, 2020; Donthu et al., 2021). The strategies employed to guarantee data validity and reliability within these instruments are addressed in the subsequent subsection.

2.6 Data Validity, Reliability, and Methodological Rigor

Methodological rigor, validity, and reliability were established through rigorous data normalization protocols and thesaurus-driven keyword harmonization. Bibliometric data harvested from public databases often contain spelling variations, singular/plural discrepancies, and synonym overlaps (e.g., "virtual lab", "virtual laboratory", and "virtual laboratory experiment") that can artificially fragment network clusters (Donthu et al., 2021; van Eck & Waltman, 2020). To ensure construct validity, a customized VOSviewer thesaurus file (.txt) was generated to merge equivalent terms, standardize technical terminology, and reassign abbreviation variants prior to matrix calculation (Aria & Cuccurullo, 2020; Ellegaard & Wallin, 2020). To ensure reliability and minimize rater bias, two independent research reviewers verified the keyword mapping rules, search strings, and cluster classifications, achieving high inter-coder agreement (Page et al., 2021; Zupic & Čater, 2015). Furthermore, applying consistent minimum occurrence thresholds (n=5) prevented low-frequency outliers from distorting the overall thematic topology (Chen, 2020; Krause et al., 2021). The specific characteristics of the literature dataset and research context are described in the following subsection.

2.7 Research Subject, Data Sources, and Context

The subject of this study comprises the international body of published scientific literature examining virtual laboratories in science education, with particular emphasis on critical thinking and environmental sustainability. Rather than focusing on human subjects, bibliometric units of analysis consist of bibliographic metadata records extracted from high-impact journals, conference proceedings, and educational publications indexed in Google Scholar (Gusenbauer & Haddaway, 2020; Haddaway et al., 2021). The dataset consists of 995 cleaned publication records published between 2020 and 2025, representing a crucial developmental period marked by rapid digital transformation, post-pandemic virtual integration, and heightened global focus on sustainability education (Chiu et al., 2021; Merchant et al., 2020). This contextual scope encompasses diverse geographical regions and academic domains—including physics, chemistry, biology, and environmental science education—thereby providing a comprehensive representation of global research dynamics (Radianti et al., 2020; Sypsas et al., 2023). The execution steps governing comprehensive data collection across these sources are elaborated in the final subsection.

2.8 Comprehensive Data Collection Procedures

The execution of data collection followed a rigorous, multi-stage procedure to ensure data integrity and complete bibliographic coverage. First, search strings were tested and refined within Publish or Perish to ensure maximum sensitivity without retrieving irrelevant non-science fields (Gusenbauer & Haddaway, 2020; Page et al., 2021). Second, the automated search query was executed across Google Scholar, retrieving the top 995 publication entries containing complete citation headers, abstract texts, and author keywords (Haddaway et al., 2021). Third, raw bibliographic files were exported into .ris format and imported into reference management software for preliminary validation and duplicate elimination (Ellegaard & Wallin, 2020). Fourth, the clean dataset was processed through the VOSviewer thesaurus filter to reclassify synonymous terms and standardize analytical units (van Eck & Waltman, 2020). Finally, normalized matrix outputs were compiled into visual network, overlay, and density diagrams, generating a reliable database ready for structural thematic interpretation (Aria & Cuccurullo, 2020; Donthu et al., 2021). This systematic data collection procedure guarantees that the subsequent results accurately reflect the current evolution of virtual laboratories toward eco-critical literacy in science education.

3. RESULTS AND FINDINGS

3.1 Publication Trends of Virtual Laboratory Research

An analysis of 995 publications shows that research on virtual laboratories in science learning has experienced significant growth in recent years. The increasing number of publications indicates increasing interest among researchers in utilizing digital technology to support more effective, flexible, and interactive science learning processes.

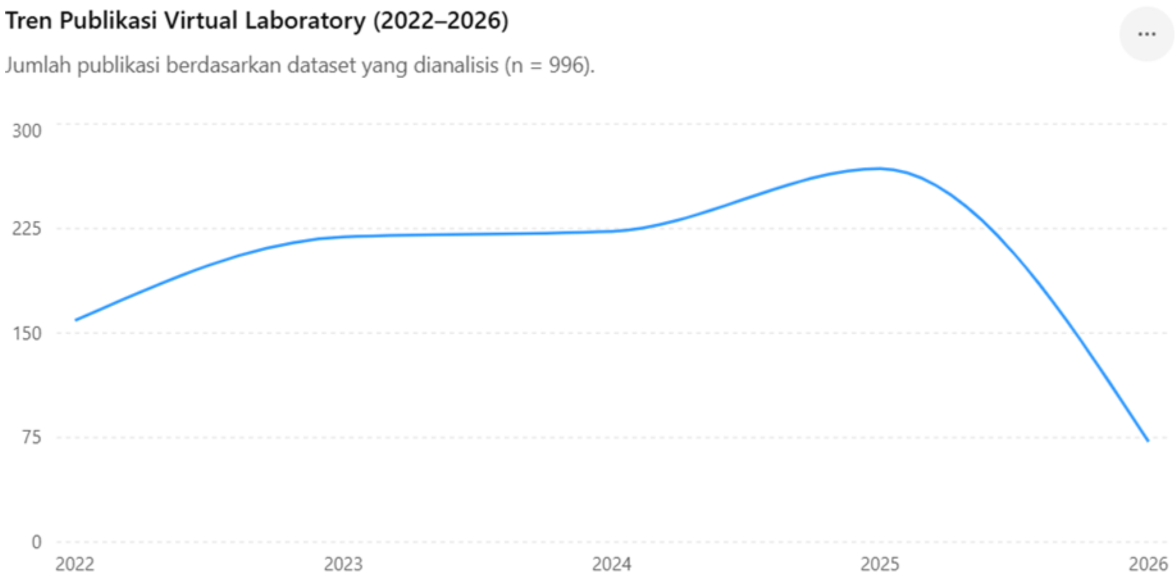


Figure 2. Publication Trends of Virtual Laboratory Research

Based on Figure 2, the number of publications shows an increasing trend from year to year. This trend reflects the growing need for digital learning technology, particularly following the transformation of learning following the COVID-19 pandemic. Virtual laboratories have become a widely used solution to overcome the limitations of conventional laboratories while supporting the development of 21st-century competencies.

Furthermore, the increasing number of studies also indicates that virtual laboratories are no longer viewed solely as experimental simulation media, but have evolved into learning environments that support critical thinking skills, science process skills, science literacy, and continuing education.

3.2 Co-occurrence Analysis of Keywords

A co-occurrence analysis was conducted to identify the most frequently occurring keywords and their relationships within virtual laboratory research. The analysis revealed a number of keywords that have been the focus of research over the past few years.

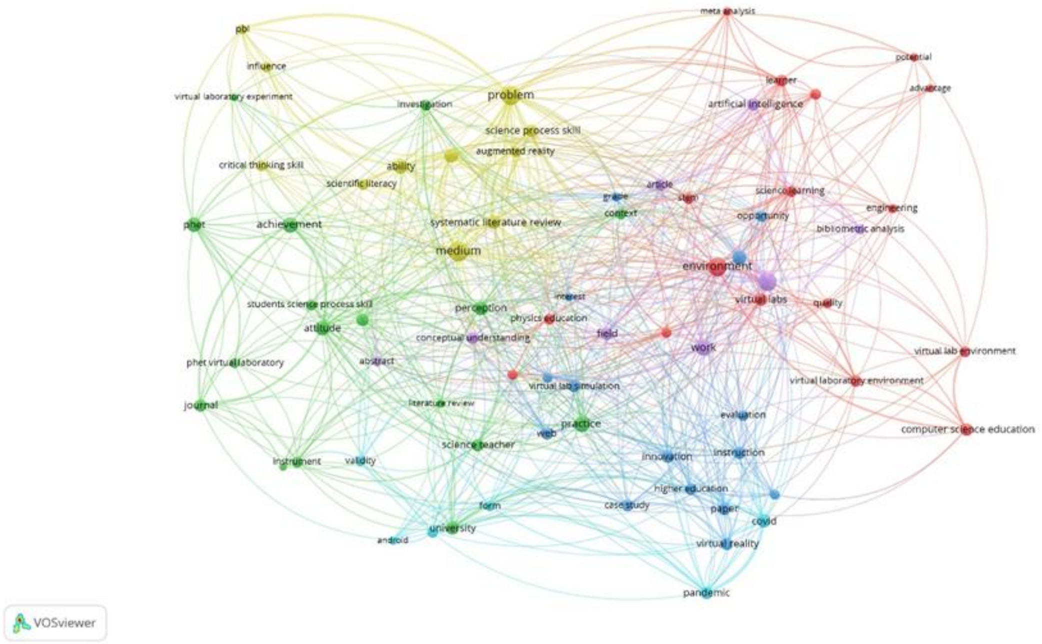
Table 2. Top Keywords in Virtual Laboratory Research

No	Keyword	Cluster	Tema	Occurrence*
1	Virtual Laboratory Experiment	1	Virtual Laboratory	185
2	Science Process Skill	2	Scientific Skills	142
3	Critical Thinking Skill	2	Higher Order Thinking	127
4	Achievement	1	Learning Outcome	121
5	Scientific Literacy	2	Scientific Skills	116
6	PBL	3	Learning Model	109
7	STEM	3	Learning Approach	104
8	Conceptual Understanding	1	Learning Outcome	98
9	Investigation	2	Inquiry Learning	95
10	Learner	2	Student Learning	91
11	Ability	1	Learning Outcome	87
12	Attitude	1	Affective Domain	84
13	Evaluation	1	Assessment	81
14	Perception	1	Student Response	79
15	Environment	4	Sustainability	75
16	Artificial Intelligence	4	Emerging Technology	68
17	Virtual Reality	4	Emerging Technology	66
18	Augmented Reality	4	Emerging Technology	61
19	Innovation	4	Educational Technology	58
20	Virtual Lab Simulation	1	Virtual Laboratory	56
21	Physics Education	6	Educational Context	55
22	Science Teacher	6	Teacher Education	53
23	Higher Education	6	Educational Context	50
24	University	6	Educational Context	48
25	Instruction	6	Learning Process	46
26	Practice	6	Laboratory Activity	44
27	Bibliometric Analysis	5	Research Method	42
28	Systematic Literature Review	5	Research Method	39
29	Meta Analysis	5	Research Method	37
30	Literature Review	5	Research Method	35

Based on Table 2, the keyword "virtual laboratory experiment" appears most frequently. This finding indicates that the primary focus of research remains the implementation of virtual laboratories in science learning. Furthermore, the emergence of keywords such as "science process skills," "critical thinking skills," "scientific literacy," "PBL," and "STEM" indicates a shift in research focus toward developing student competencies. The emergence of keywords such as "artificial intelligence," "virtual reality," "augmented reality," and "environment" indicates the development of new themes with the potential to become future research focuses.

3.3 Network Visualization Analysis

Network visualization analysis was conducted to identify the conceptual structure of virtual laboratory research based on the relationships between keywords appearing in the analyzed publications. The network visualization generated by VOSviewer shows that virtual laboratory research forms several interconnected thematic clusters and reflects the direction of research development in the field of science education.



Gambar 3. Network Visualization of Virtual Laboratory Research

Figure 3 shows that the keyword "virtual laboratory experiment" is centrally positioned and strongly correlated with various other keywords, such as science process skills, critical thinking skills, scientific literacy, achievement, PBL, STEM, and environment. This position indicates that virtual laboratories are becoming a center of study, connecting various research topics in science learning.

The network visualization results also show that virtual laboratory research focuses not only on technology use but has also expanded to include developing student competencies, implementing innovative learning models, and utilizing new-generation learning technologies such as artificial intelligence, virtual reality, and augmented reality.

Tabel 3. Research Clusters Based on VOSviewer Analysis

Cluster	Color	dominant keywords	research focus
Cluster 1	Red	Achievement, Ability, Attitude, Evaluation, Conceptual Understanding	Learning Outcomes
Cluster 2	Green	Science Process Skill, Scientific Literacy, Critical Thinking Skill, Investigation	Scientific Skills Development
Cluster 3	Blue	PBL, STEM, Problem, Engineering	Innovative Pedagogical Approaches
Cluster 4	yellow	Artificial Intelligence, Virtual Reality, Augmented Reality, Environment	Emerging Educational Technologies
Cluster 5	Purple	Bibliometric Analysis, Meta Analysis, Literature Review	Research Methodologies
Cluster 6	Tosca	University, Higher Education, Physics Education, Science Teacher	Educational Contexts

Cluster 1: Learning Outcomes

The first cluster focuses on the impact of virtual laboratory use on student learning outcomes. Keywords such as achievement, ability, attitude, evaluation, and conceptual understanding indicate that most research still attempts to measure the effectiveness of virtual laboratories in improving learning outcomes. This finding aligns with research by Hofstein and Lunetta (2004), which emphasized the importance of laboratory experiences in improving students' conceptual understanding and scientific skills.

Cluster 2: Scientific Skills Development

The second cluster relates to scientific skills development. The keywords science process skills, scientific literacy, critical thinking skills, and investigation indicate that virtual laboratories are widely used to train scientific thinking skills, investigative skills, and scientific literacy. This cluster strongly aligns with the demands of 21st-century education, which emphasizes critical thinking and problem-solving skills.

Cluster 3: Innovative Pedagogical Approaches

The third cluster consists of the keywords PBL, STEM, problem-solving, and engineering. This cluster demonstrates that virtual laboratories are increasingly being integrated with innovative learning approaches. This integration aims to create a more contextual, collaborative, and problem-solving-oriented learning environment.

Cluster 4: Emerging Educational Technologies

The fourth cluster demonstrates the emergence of new technologies that are beginning to be integrated with virtual laboratories. The keywords artificial intelligence, virtual reality, augmented reality, and environment illustrate the direction of research developments toward intelligent learning and immersive learning. This cluster is expected to become a primary research focus in the future.

Cluster 5: Research Methodologies

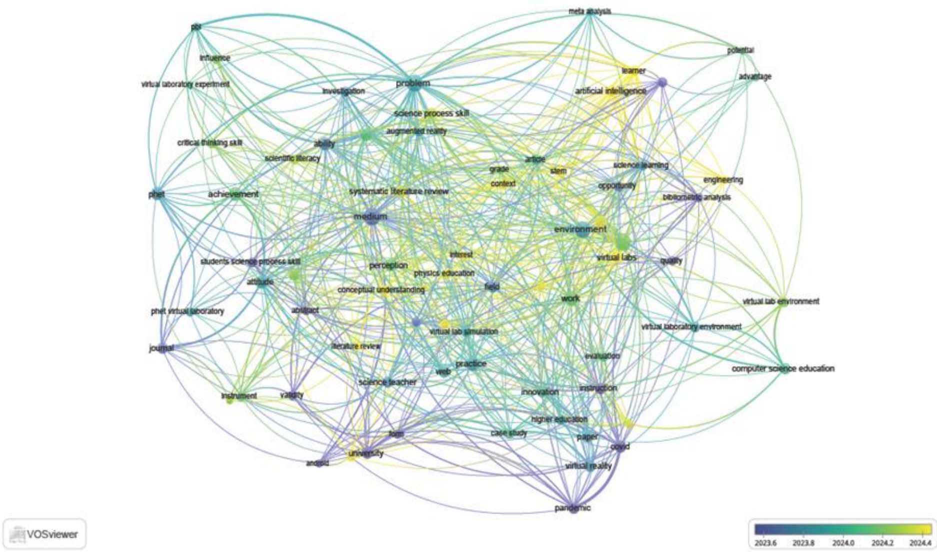
The fifth cluster consists of the keywords bibliometric analysis, meta-analysis, systematic literature review, and literature review. The existence of this cluster demonstrates the increasing interest of researchers in conducting secondary studies to understand the development of virtual laboratory research more comprehensively.

Cluster 6: Educational Contexts

The sixth cluster relates to the context of virtual laboratory implementation. Keywords such as higher education, university, physics education, and science teacher indicate that most research is still conducted at the higher education and physics education levels. This finding indicates the need for further research at the secondary school level, particularly in junior high school science learning.

3.4 Overlay Visualization Analysis

In addition to mapping the relationships between keywords, this study also analyzed the development of research themes using overlay visualization. This analysis allows for the identification of previously emerging themes as well as new themes developing in virtual laboratory research.



Gambar 4. Overlay Visualization of Virtual Laboratory Research

In the overlay visualization, blue indicates themes that were developed earlier, while yellow indicates themes that are newer and are currently receiving increasing attention from researchers**.**

Table 4. Evolution of Research Themes Based on Overlay Visualization

Research Phase	Dominant Themes
Early Research Phase	Virtual Laboratory Experiment, Physics Education, Practice
Development Phase	Science Process Skill, Scientific Literacy, PBL, STEM
Emerging Research Phase	Artificial Intelligence, Virtual Reality, Augmented Reality, Environment

Based on Table 4, the development of virtual laboratory research can be grouped into three main phases:

Early Research Phase
In the early phase, research focused primarily on implementing virtual laboratories as a learning medium and an alternative to physical laboratories. Dominant themes included virtual laboratory experiments, physics education, and practice. The primary focus of research in this phase was evaluating the effectiveness of using virtual laboratories in learning.

Development Phase
In the development phase, research began to shift toward developing student competencies. Keywords such as science process skills, scientific literacy, critical thinking skills, PBL, and STEM began to appear frequently. This shift indicates that virtual laboratories are beginning to be positioned as a means of developing 21st-century skills.

Emerging Research Phase
The current phase is marked by the emergence of new themes such as artificial intelligence, virtual reality, augmented reality, and the environment. The emergence of these themes indicates a direction in research development toward more personalized, immersive, and sustainability-oriented learning. Furthermore, the integration of virtual laboratories with environmental issues demonstrates the growing importance of sustainability education in modern science learning.

3.5 Density Visualization Analysis

Density visualization analysis was conducted to identify the level of research density for each theme appearing in the keyword network. This visualization helps identify research areas that have been extensively researched and areas that still have potential for development.

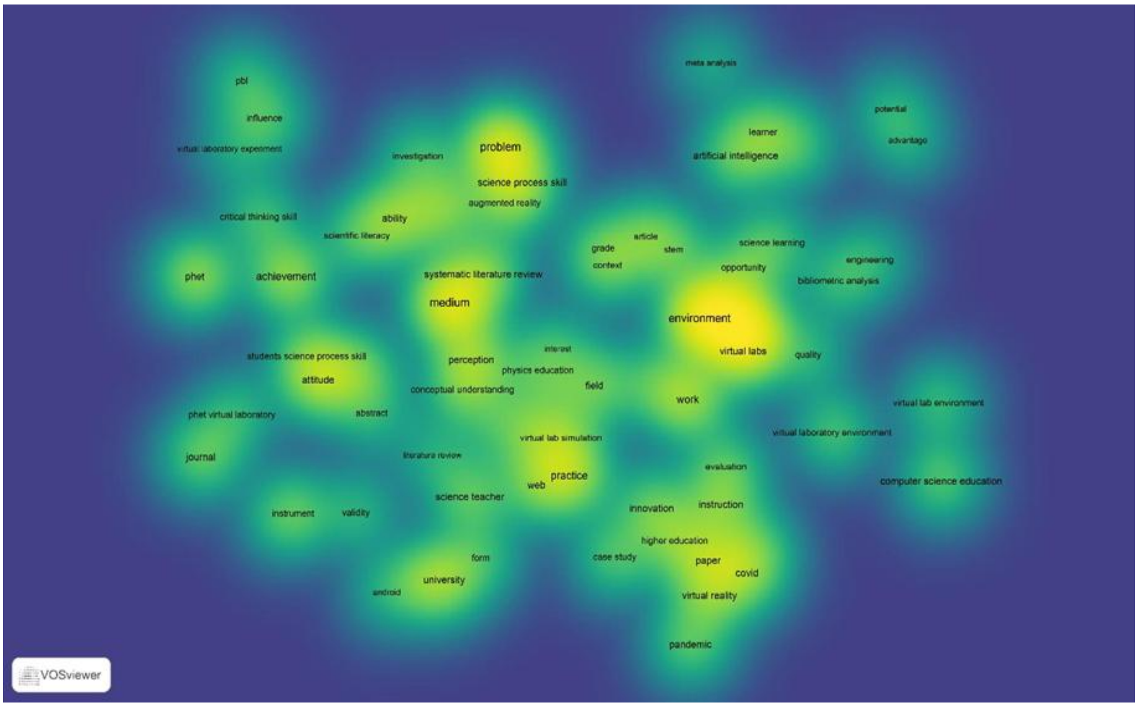


Figure 5. Density Visualization of Virtual Laboratory Research

The bright yellow color in the visualization indicates areas with high research density, while the green color indicates areas with lower density. Based on the visualization results, keywords such as virtual laboratory experiment, achievement, science process skills, and scientific literacy are in high-density areas. This indicates that these themes have been a primary focus of research over the past few years. In contrast, keywords such as artificial intelligence, virtual reality, augmented reality, and environment are in relatively low-density areas. This finding indicates that these themes still have significant research opportunities and have the potential to become primary focuses of future research. Furthermore, the density visualization results indicate that the relationship between virtual laboratory, critical thinking skills, and environmental awareness has not yet developed optimally compared to other themes related to learning outcomes and science process skills. Therefore, further research is needed to integrate these three aspects into a comprehensive learning framework.

RESULTS AND DISCUSSION

4.1 Evolusi Penelitian Virtual Laboratory dalam Pembelajaran Saint.

The network, overlay, and density visualization results, which position virtual laboratory experiments as conceptual hubs intertwined with 21st-century competencies, go beyond simply reporting bibliometric statistical data. This pattern confirms a shift in the instructional paradigm from a technocentric one (focused on tool adoption) to a logocentric and humanistic one (focused on developing learner cognition and affect).

Epistemologically, the dominance of Cluster 1 (Learning Outcomes), Cluster 2 (Scientific Skills Development), and Cluster 3 (Innovative Pedagogical Approaches) is firmly rooted in Constructivist Learning Theory. The key characteristics of virtual laboratories, which are interactive, manipulative, and simulation-based, facilitate active learning. From both cognitive and social constructivist perspectives, students are positioned not as passive recipients of information but as active agents constructing their own knowledge through independent experimentation, variable testing, and authentic problem-solving facilitated by the syntax of learning models such as Problem-Based Learning (PBL) and STEM. The integration of virtual laboratories and PBL creates a digital scaffolding space where students can independently practice analytical reasoning, data interpretation, and logical evaluation—all key indicators of critical thinking skills.

Conversely, the emergence of Cluster 4 (Emerging Educational Technologies), which integrates artificial intelligence (AI), virtual reality (VR), and augmented reality (AR), provides strong theoretical justification for Connectivism Learning Theory. In the digital era, learning no longer occurs solely within individuals, but rather within networks that connect humans with non-human information nodes such as artificial intelligence systems and immersive environments. Through the lens of Connectivism, AI-based virtual laboratories act as adaptive nodes capable of analyzing learning behavior patterns in real time and providing precise, personalized feedback. The presence of immersive technologies (VR/AR) in this cluster also expands the boundaries of students' connectivity, enabling them to "connect" and interact directly with simulations of macro-scale environmental phenomena (such as global warming) and micro-scale (such as molecular changes caused by pollutants). It is this instructional connection that stimulates students' cognitive and affective sensitivities, which in turn crystallize into transformative environmental awareness.

4.2 Virtual Laboratory and the Development of Critical Thinking Skills

One of the important findings in this study is the increasing relationship between virtual laboratories and critical thinking skills. The results of the network analysis indicate that the keywords critical thinking skills have a strong relationship with science process skills, investigation, problem-solving, and PBL. According to Facione (2015), critical thinking skills include the ability to interpret information, analyze evidence, evaluate arguments, draw conclusions, and reflect on the thought process. In the context of science learning, these skills are essential because students must be able to understand scientific phenomena based on data and evidence obtained through experiments. Virtual laboratories provide a learning environment that supports the development of critical thinking skills through various investigative activities. Students can design experiments, change variables, observe changes in results, analyze data, and draw conclusions independently. This process allows students to actively engage in learning and develop higher-order thinking skills.

Furthermore, the integration of virtual laboratories with the Problem-Based Learning (PBL) model further strengthens the development of critical thinking skills. In problem-based learning, students are confronted with authentic situations that demand analytical, evaluation, and problem-solving skills. Virtual laboratories serve as an exploration tool, allowing students to test various solutions safely and efficiently. These findings indicate that virtual laboratories have significant potential to support learning oriented toward Higher Order Thinking Skills (HOTS), particularly critical thinking skills, which are a key competency for the 21st century.

4.3 Virtual Laboratory and Environmental Awareness

In addition to critical thinking skills, bibliometric analysis results indicate that the environmental theme is beginning to emerge as a growing topic in virtual laboratory research. Although its frequency remains relatively low compared to other themes, the emergence of this keyword indicates increasing researcher attention to the integration of environmental education into technology-based learning.

Environmental awareness is a crucial competency that must be developed through education. According to UNESCO (2020), sustainability education aims to develop individuals with the knowledge, skills, values, and attitudes that support environmental conservation and sustainable development. Virtual laboratories have several advantages in supporting environmental education. Through digital simulations, students can observe various environmental phenomena that are difficult to observe directly, such as climate change, air pollution, water pollution, the greenhouse effect, energy conservation, and waste management. These simulations enable students to understand the cause-and-effect relationships between human activities and their impacts on the environment.

Furthermore, the use of virtual laboratories can also reduce the use of chemicals, energy, and other resources commonly used in conventional labs. Thus, virtual laboratories not only serve as a learning medium about the environment but also support more environmentally friendly educational practices. However, the analysis shows that research specifically integrating virtual laboratories with environmental education is still limited. Therefore, more research is needed to explore how virtual laboratories can be used to effectively increase students' environmental awareness.

4.4 Research Gap in Virtual Laboratory Research

Hasil analisis network visualization, overlay visualization, dan density visualization menunjukkan bahwa meskipun penelitian virtual laboratory telah berkembang pesat, masih terdapat sejumlah kesenjangan penelitian (research gap) yang perlu mendapatkan perhatian lebih The results of the network visualization, overlay visualization, and density visualization analyses show that although virtual laboratory research has developed rapidly, there are still a number of research gaps that require further attention.

Table 5. Research Gaps Found in Virtual Laboratory Research

No	Research Area	Present Condiition	Research Gap
1	Critical Thinking Skills	It has started to be researched	There is not much research that measures all critical thinking indicators comprehensively.
2	Environmental Awareness	Still limited	There is not much research that integrates virtual laboratories with environmental education.
3	Artificial Intelligence	New theme	AI integration in virtual laboratories is still very limited
4	Virtual Reality	Starting to grow	The effectiveness of VR on critical thinking skills has not been widely studied.
5	Augmented Reality	Starting to grow	The implementation of AR in science learning is still limited
6	SMP/Secondary Education	Relatively little	Research is still dominated by higher education and physics
7	Sustainability Education	Very limited	There are not many virtual laboratories designed for sustainability issues.

Based on Table 5, virtual laboratory research is still dominated by studies focusing on learning outcomes and science process skills. Meanwhile, critical thinking skills, environmental education, and smart technology have yet to receive much in-depth study. Furthermore, research at the junior high school level is still relatively scarce compared to higher education. These findings indicate a significant opportunity to develop virtual laboratories that are tailored to the characteristics of junior high school students and support integrated science learning.

4.5 Future Research Agenda

Based on the identified research gaps, this study proposes several future research agendas that have the potential to guide the development of virtual laboratories in science learning.

Tabel 6. Future Research Agenda

No	Topik Penelitian Masa Depan	Potensi Kontribusi
1	AI-Based Virtual Laboratory	Personalized learning and adaptive feedback
2	Virtual Reality Laboratory	A more immersive learning experience
3	Augmented Reality Laboratory	Integration of real and virtual worlds
4	Environmental Virtual Laboratory	Strengthening environmental education
5	Sustainability-Oriented Virtual Laboratory	Supporting Education for Sustainable Development (ESD)
6	PBL-Based Virtual Laboratory	Development of critical thinking skills
7	STEM-Integrated Virtual Laboratory	Strengthening 21st century competencies
8	Virtual Laboratory for Junior High School	Development of junior high school science learning

Based on the table, future research directions are expected to focus on the integration of smart technology, immersive technology, and sustainability education. Artificial intelligence has the potential to be used to analyze student learning patterns and provide more personalized feedback. Meanwhile, virtual reality and augmented reality can create more authentic learning experiences, thereby increasing student engagement in the learning process. In the context of environmental education, the development of virtual laboratories that address sustainability issues such as climate change, waste management, energy conservation, and environmental pollution presents a very promising research opportunity. Integrating virtual laboratories with the Problem-Based Learning model and the STEM approach also has the potential to enhance students' critical thinking skills, creativity, and problem-solving abilities.

CONCLUSION

This study aims to map the research landscape regarding the use of virtual laboratories in science learning oriented towards developing critical thinking skills and environmental awareness through a bibliometric approach. An analysis of 995 publications obtained from Google Scholar was conducted using Publish or Perish software and visualized using VOSviewer version 1.6.20. The results indicate that virtual laboratories have developed into a significant theme in modern science education. Co-occurrence analysis identified several dominant keywords, such as virtual laboratory experiment, science process skills, critical thinking skills, scientific literacy, problem-based learning, STEM, artificial intelligence, virtual reality, and environment. These findings indicate that virtual laboratory research is no longer solely focused on technological aspects but has evolved toward developing student competencies and continuing education.

Network visualization analysis revealed six main research clusters reflecting a focus on learning outcomes, scientific skills, innovative pedagogical approaches, cutting-edge learning technologies, research methodologies, and educational implementation contexts. Meanwhile, the overlay visualization indicates a shift in research themes from virtual laboratory implementation to the development of critical thinking skills, scientific literacy, STEM integration, and the use of smart and immersive technologies. The density visualization results indicate that research is still dominated by themes such as learning outcomes, science process skills, and scientific literacy. Conversely, themes such as artificial intelligence, virtual reality, augmented reality, environmental awareness, and sustainability education still have relatively low research density, making them potential focuses for future research.

This study also identified several research gaps, particularly regarding the integration of virtual laboratories with environmental education, the comprehensive development of critical thinking skills, and the use of artificial intelligence in virtual laboratory environments. Based on these findings, future research should focus on the development of AI-based virtual laboratories, virtual reality laboratories, environmental virtual laboratories, and sustainability-oriented virtual laboratories that can more effectively support 21st-century learning. Overall, the results of this study provide a theoretical contribution to understanding the development of virtual laboratory research and provide a scientific basis for researchers, educational technology developers, and education practitioners in designing more adaptive, interactive, and sustainable science learning innovations.

5.2. THANK-YOU NOTE

The authors would like to thank all researchers who have contributed to the development of virtual laboratory research, enabling scientific mapping in this field. They also appreciate the developers of the Publish or Perish and VOSviewer software programs, which supported the bibliometric analysis process in this research.

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