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Problem Based Learning in Digital and Virtual Science Learning Environments

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ABSTRACT

Objective: *This study aims to analyze research trends in Problem-Based Learning (PBL) in digital and virtual science learning environments during the period 2015–2025. The analysis focuses on identifying dominant research themes, mapping the structure of the research field, and examining the evolution of research on the integration of digital technologies in science learning.* ***Method:*** *This study employed a bibliometric analysis of publications indexed in the Scopus database. The article selection process followed the PRISMA guidelines, yielding 101 documents for analysis. The study examined keyword co-occurrence, citation patterns, and thematic structures. Network, overlay, and density visualizations were conducted using VOSviewer to explore relationships between keywords and the temporal development of research topics.* ***Results:*** *The findings indicate that research on PBL in digital and virtual science learning is structured around core themes such as problem-based learning, students, e-learning, and virtual reality, which show strong interconnections. The temporal analysis reveals a shift from general educational contexts toward the integration of digital and immersive technologies, including virtual reality, augmented reality, and artificial intelligence. In addition, density and citation analyses highlight the central role of digital technology in shaping contemporary PBL research. In contrast, emerging topics such as machine learning and digital twins remain less explored.* ***Novelty:*** *This study provides a comprehensive bibliometric mapping of the convergence between PBL and digital–virtual technologies in science learning, revealing a conceptual shift toward intelligent and immersive learning environments and identifying emerging research opportunities.*

INTRODUCTION

The rapid development of digital technology over the past decade has created significant opportunities to improve the quality of learning, including science education (Q. Wang et al, 2021). Digital technologies enable more interactive learning experiences through the integration of multimedia, simulations, and diverse online learning resources (Bond et al, 2021; Peng et al, 2023). Furthermore, the use of digital and virtual technologies allows students to visualize abstract scientific concepts and explore phenomena that are difficult to observe directly in conventional classroom settings (Dede et al, 2017). In addition, the development of educational technology supports the creation of more flexible and adaptive learning environments that can better accommodate students' learning needs. In the context of modern education, science learning is expected to shift from teacher-centered to student-centered approaches that emphasize exploration, collaboration, and problem-solving (Makransky et al., 2019).

However, the implementation of digital technology in science learning has not always led to optimal improvements in the quality of the learning process (Al-Emran et al., 2022). In many cases, technology is used merely to deliver instructional materials, without fundamentally transforming traditional teaching approaches. As a result, educators do

not fully leverage the potential of digital technology to support active, meaningful learning. Several studies have indicated that the integration of technology in learning environments often focuses more on information delivery than on facilitating students' thinking processes (Garzón et al, 2019). This condition may lead to low student engagement in science learning and limited opportunities for students to develop higher-order thinking skills and effective problem-solving abilities (Syawaludin et al, 2019).

These conditions indicate that integrating digital technology into science learning requires appropriate pedagogical strategies to support more meaningful learning experiences (Suprapto et al., 2021). Without an appropriate learning model, digital technology may function only as a tool for delivering information rather than as a medium that supports active knowledge construction. At the same time, research on digital and virtual technologies in science education continues to grow rapidly across diverse educational contexts. The increasing number of publications in this area has produced a large body of research findings that remain scattered and difficult to synthesize systematically. Consequently, it is important to conduct studies that map research developments, identify dominant themes, and reveal emerging research directions in this field (Zhang et al., 2023).

One learning approach with strong potential to support the effective integration of digital technology into science education is Problem-Based Learning. This learning model positions contextual problems as the starting point of the learning process, encouraging students to investigate and analyze information and develop solutions collaboratively. Through these activities, students are expected to develop critical thinking and systematic problem-solving skills. Moreover, Problem-Based Learning enables students to connect scientific concepts with real-world situations, making learning more meaningful. Previous studies have shown that implementing PBL can improve students' higher-order thinking skills and conceptual understanding in science learning (Hmelo-Silver et al., 2020).

Despite the large initial number of identified publications, 49,299 documents from the Scopus database, a more specific screening process revealed that only a small portion of the research was truly relevant to the integration of Problem-Based Learning (PBL) in digital and virtual science learning. After keyword screening, the number of studies was reduced to 235 documents, and further narrowed to 185 documents for the 2015–2025 period. Further selection based on citation and relevance criteria resulted in only 5 studies meeting the final analysis criteria. These findings indicate that, despite the rapid growth of digital learning and PBL, research specifically examining their convergence remains very limited and has not been thoroughly studied. Existing studies are often conducted in specific contexts and focus on particular technologies, making it difficult to obtain a broader understanding of how research in this field has evolved. Therefore, a systematic literature review is needed to identify publication trends, influential research themes, and potential directions for future studies. One approach to achieving this objective is bibliometric analysis, which enables researchers to quantitatively analyze scientific publications and the relationships between research topics (Donthu et al., 2021).

Based on this background, this study uses a bibliometric approach not simply to follow emerging research trends, but to address the limitations of studies that have not been able to systematically and quantitatively map the relationship between Problem-Based Learning (PBL) and digital-virtual science learning. This bibliometric approach was chosen because it can objectively and measurably identify publication patterns, collaboration networks, and the development of research themes, which is difficult to achieve through conventional narrative literature reviews. The novelty of this study lies in its specific focus on examining the convergence between PBL and digital-virtual science learning within a single, integrated analytical framework, a practice not widely practiced in previous bibliometric studies. Previous research has tended to examine PBL or digital learning separately, thereby failing to provide a comprehensive picture of their relationship. Furthermore, this study employed a rigorous selection process, with only 5 of 49,299 initial documents meeting the final criteria, indicating that research on this topic remains very limited. Furthermore, covering the period 2015–2025, this study presents a cutting-edge analysis and identifies research trends, thematic clusters, and open research gaps. Thus, this study not only provides a more integrated bibliometric mapping but also offers a solid foundation for further research development.

RESEARCH METHOD

This study uses bibliometric analysis as part of a quantitative research design to examine developments in research on Problem-Based Learning (PBL) in digital and virtual science learning. Bibliometric analysis is a quantitative approach used to systematically evaluate scientific publications using numerical indicators such as the number of publications, citations, and relationships between keywords and authors (Donthu et al., 2021; Zupic & Čater, 2015). Thus, bibliometric analysis is positioned as a method in quantitative research, particularly in literature-based studies. The research data were obtained from the Scopus database, which has extensive coverage and high-quality journal indexing, making it widely used in bibliometric studies (Donthu et al, 2021; Lintangesukmanjaya et al., 2025). The analysis covered publications from 2015 to 2025 to illustrate the latest developments in research on digital and virtual science learning.

The research procedure was carried out systematically by adapting the bibliometric analysis stages from Zupic and Čater (2015), including: keyword identification, database data retrieval, document screening based on inclusion criteria, quantitative bibliometric analysis, and data visualization. The analysis included publication trends, citation analysis, and keyword co-occurrence to identify dominant themes and research development patterns (Donthu et al, 2021). Next, mapping and visualization were performed using VOSviewer, a software tool designed to build and visualize bibliometric networks such as co-authorship, co-occurrence, and citation relationships (Van & Waltman, 2010). The complete flow of the bibliometric analysis procedure in this study is presented in Figure 1.

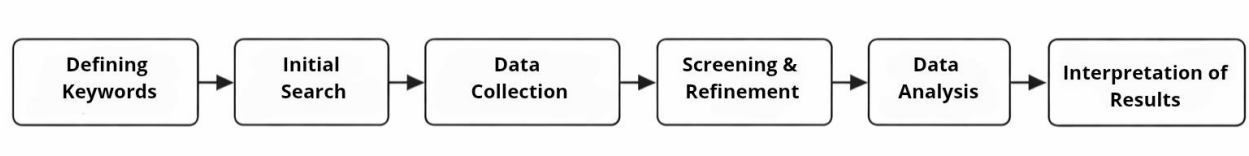

Figure 1. Flowchart of the bibliometric research procedure.

The article selection process in this study followed the PRISMA framework to ensure systematic and transparent data collection. The Scopus database was chosen as the data source because it provides extensive coverage of internationally reputable scientific publications and comprehensive metadata, such as citations, authors, and keywords, which support bibliometric analysis (Donthu et al., 2021). The publication year range of 2015–2025 was chosen to capture the latest developments in digital and virtual science learning, in line with the rapid development of educational technology over the past decade.

In the identification stage, an initial search using general keywords related to Problem-Based Learning, science, learning, digital, and virtual yielded 49,299 documents. In the filtering stage, a more specific Boolean query, namely "PBL OR problem-based learning AND science AND learning AND digital AND virtual," was used to increase the relevance of the search results. The selection of this keyword combination aims to accommodate the variety of Problem-Based Learning (PBL) terms while maintaining a focus on the context of science learning in digital and virtual environments. The screening resulted in 235 documents, while 49,064 were eliminated as irrelevant. Next, a screening process based on publication year (2015–2025) yielded 185 documents, of which 50 were eliminated for falling outside the specified year range.

In the eligibility stage, 185 documents were analyzed based on the number of citations to identify publications with significant influence on the field of study. The selection results showed that 101 documents met the criteria, while 84 were eliminated for failing to meet the established citation threshold. These 101 documents were then used as the primary dataset for bibliometric analysis and visualization using VOSviewer software, which included keyword co-occurrence, co-authorship, and citation analysis to identify relationship patterns and research trends.

In the inclusion stage, five articles were selected for in-depth analysis based on their relevance to implementing Problem-Based Learning in digital and virtual science learning. This selection aimed to complement the quantitative analysis with a more in-depth qualitative study. The complete flow of the article selection process is presented in Figure 2.

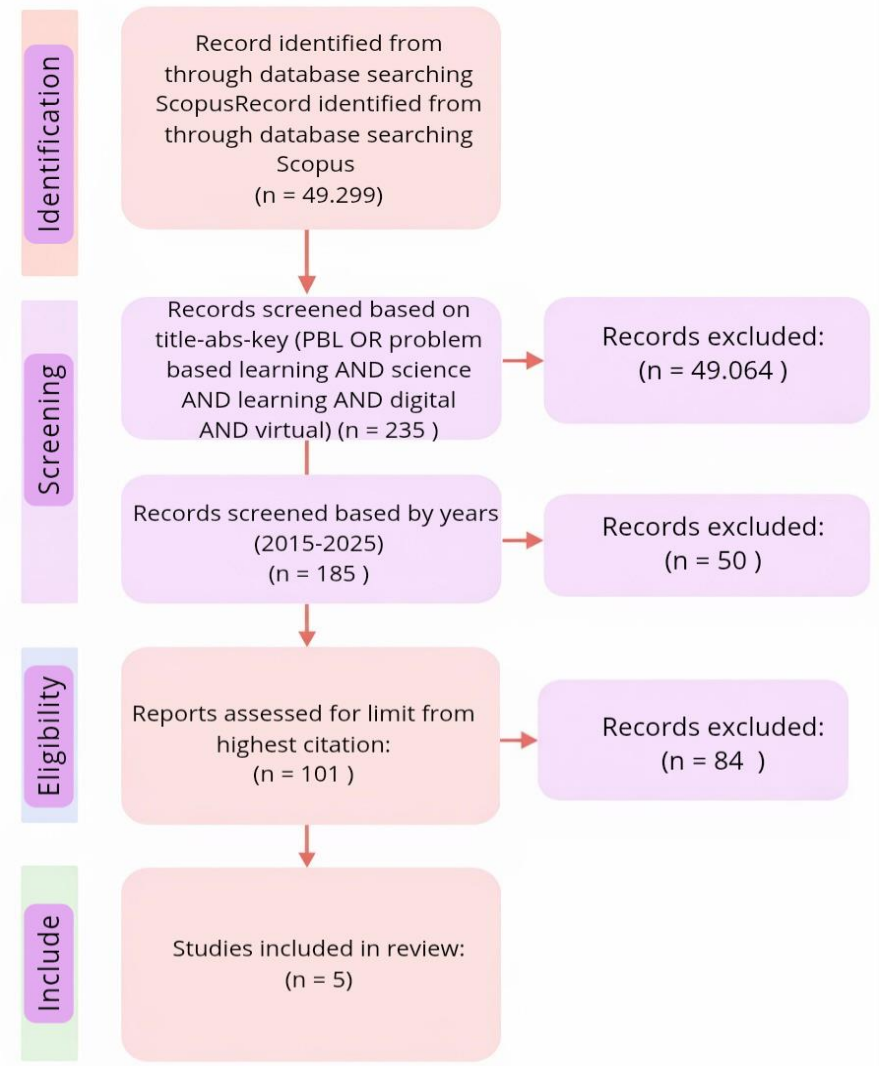

Figure 2. Research stages of bibliometric analysis

RESULTS AND DISCUSSION

Results

Publication Trend (2015–2025)

To identify the development patterns of research on problem-based learning in digital and virtual learning environments, a bibliometric analysis was conducted using publication data extracted from the Scopus database. The analysis focuses on the temporal distribution of publications and the thematic structure of the research field. The following figures present the annual publication trends and the visualization of keyword co-occurrence, providing an overview of research growth and emerging topics in science education. As illustrated in Figure 3.

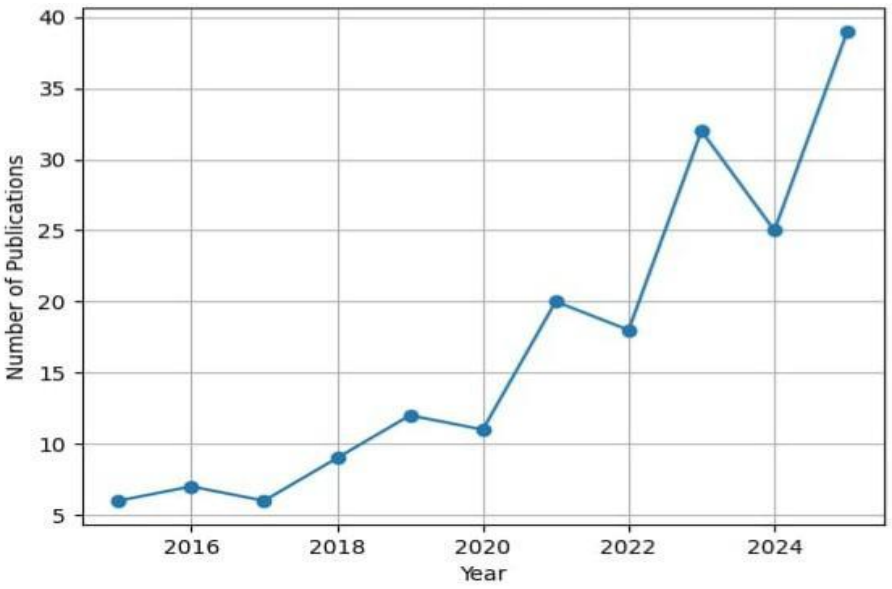

Figure 3. Publication trend (2015–2025)

To further examine the intellectual structure and research impact within the field of problem-based learning in digital and virtual learning environments, a citation-based analysis was conducted on the selected Scopus-indexed publications. Citation analysis is commonly used in bibliometric studies to identify influential works, leading journals, and dominant research directions within a specific domain. Table 1 summarizes the most highly cited articles, providing detailed information on authorship, year of publication, source titles, citation counts, and their respective contributions to the development of science education research. The findings presented in this table offer insights into foundational studies and emerging influential works that have shaped the integration of digital technologies, virtual learning environments, and problem-based learning approaches.

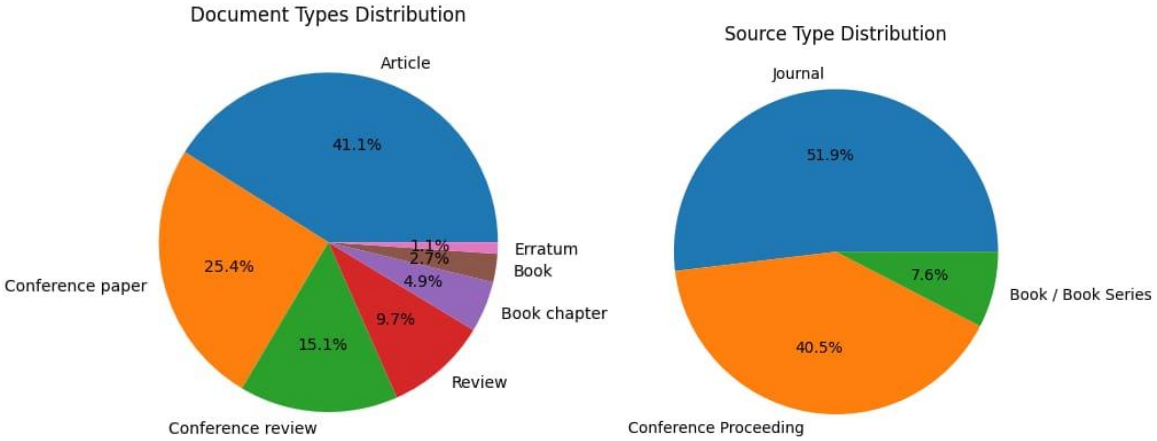

Figure 4. Distribution of document types and source types

The distribution of document types indicates that journal articles constitute the largest proportion of publications in the field of science education within digital and virtual learning environments, accounting for 41.1% of the total documents. This dominance of

journal articles suggests that the research topic has reached a substantial level of academic maturity, with findings being disseminated primarily through peer-reviewed outlets. Conference papers (25.4%) and conference reviews (15.1%) also represent a significant share, reflecting the dynamic and rapidly evolving nature of this research area, particularly in relation to emerging technologies such as virtual reality, simulation, and e-learning systems. Meanwhile, review articles (9.7%), book chapters (4.9%), and books (2.7%) appear less frequently, indicating that although synthesis-based and conceptual contributions exist, empirical research remains the primary driver of knowledge development in this domain.

In terms of source types, journal publications dominate the research landscape, comprising 51.9% of the total sources, followed by conference proceedings at 40.5%, and book or book series at 7.6%. The strong presence of journal sources underscores the scientific rigor and sustained scholarly interest in investigating pedagogical approaches such as Problem-Based Learning and Project-Based Learning within digital and virtual science education contexts. At the same time, the considerable contribution of conference proceedings highlights the role of academic conferences as important venues for presenting innovative ideas, preliminary findings, and technological advancements. The relatively limited proportion of books and book series suggests that comprehensive theoretical frameworks and long-form academic syntheses in this field remain underdeveloped, presenting opportunities for future scholarly contributions.

Keyword Co-occurrence Network

A bibliometric analysis was conducted using VOSviewer to map relationships among keywords in research on problem-based learning, science learning, and digital and virtual learning environments. The analysis produced a keyword linkage network divided into several interconnected clusters.

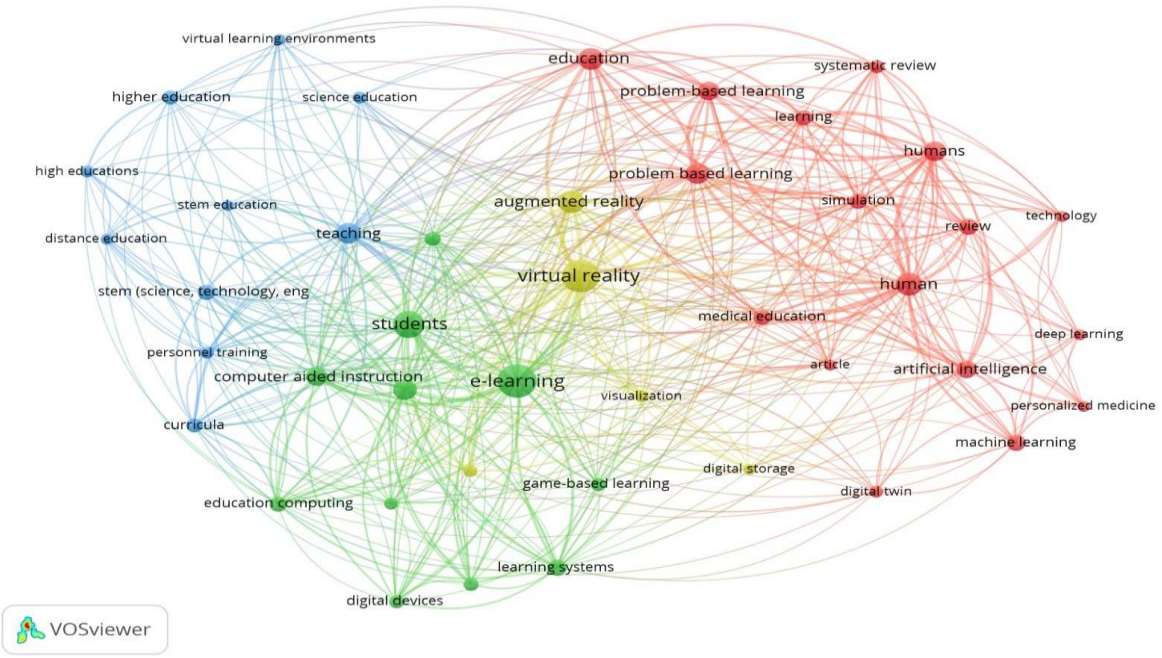

Figure 5. Network visualization of keyword co-occurrence

The network visualization of keyword co-occurrence was generated during the bibliometric analysis stage following the data screening and selection process based on the PRISMA framework. The data were retrieved from the Scopus database and analyzed using VOSviewer to map relationships between keywords. Initially, 49,299 records were identified. After applying keyword filtering (TITLE-ABS-KEY: problem-based learning, science, learning, digital, and virtual), 235 documents were obtained. These were further refined by publication period (2015–2025), yielding 185 documents. Following citation-based selection, 101 documents were retained for the bibliometric analysis. Author keywords from these documents were analyzed using the co-occurrence method in VOSviewer, with a minimum occurrence threshold of 5, to generate the network visualization.

The results show that problem-based learning, e-learning, students, and virtual reality have the largest node sizes, indicating their prominence as core research themes. The strong interconnections among these keywords suggest a well-established linkage between problem-based learning and the integration of digital technologies in science education. Furthermore, the visualization reveals several distinct clusters. The red cluster represents pedagogical aspects and the implementation of problem-based learning. The green cluster reflects digital learning technologies, including e-learning and computer-aided instruction. The blue cluster highlights broader educational contexts such as higher education and STEM. Meanwhile, the yellow cluster indicates emerging technological trends, particularly virtual reality and augmented reality.

Importantly, the presence of these interconnected clusters suggests a convergence of pedagogical approaches and technological innovation, indicating a shift toward more immersive, technology-enhanced problem-based learning environments.

Overlay Visualization of Research Trends

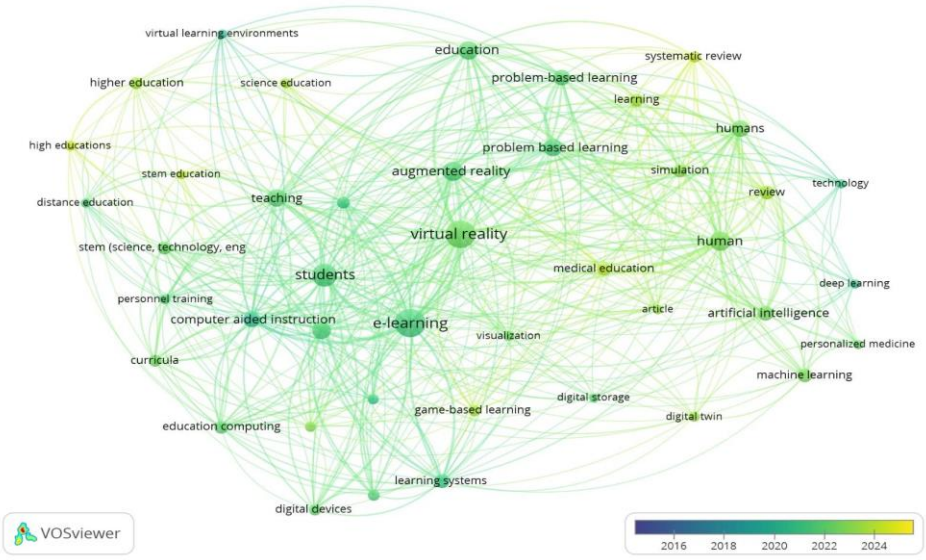

Figure 6. Overlay visualization of research trends

The overlay visualization of research trends was generated during the bibliometric analysis stage using VOSviewer, following the data screening and selection process based

on the PRISMA framework. The analysis was conducted on a final dataset of 101 documents retrieved from the Scopus database. Author keywords were analyzed using the co-occurrence method, and an overlay visualization was constructed based on the average publication year, with the color gradient representing the temporal evolution of research topics. The results indicate that earlier research topics (blue) were primarily centered on higher education, science education, and distance education. Over time, these topics evolved toward the integration of digital technologies in learning, as reflected by the emergence of e-learning, virtual reality, and augmented reality (green).

More recent research trends (yellow) highlight an increasing focus on advanced technologies such as artificial intelligence, machine learning, and digital twins. This progression suggests that research on problem-based learning is increasingly oriented toward the adoption of intelligent and immersive technologies in digital learning environments. Furthermore, the gradual transition of colors across interconnected keywords indicates not only a temporal progression but also a conceptual evolution, reflecting a shift from conventional educational approaches toward more technology-driven and data-informed learning paradigms.

Density Visualization

The density visualization shows the intensity of keyword occurrences in research. Areas in yellow indicate the most frequently occurring topics with a high research density.

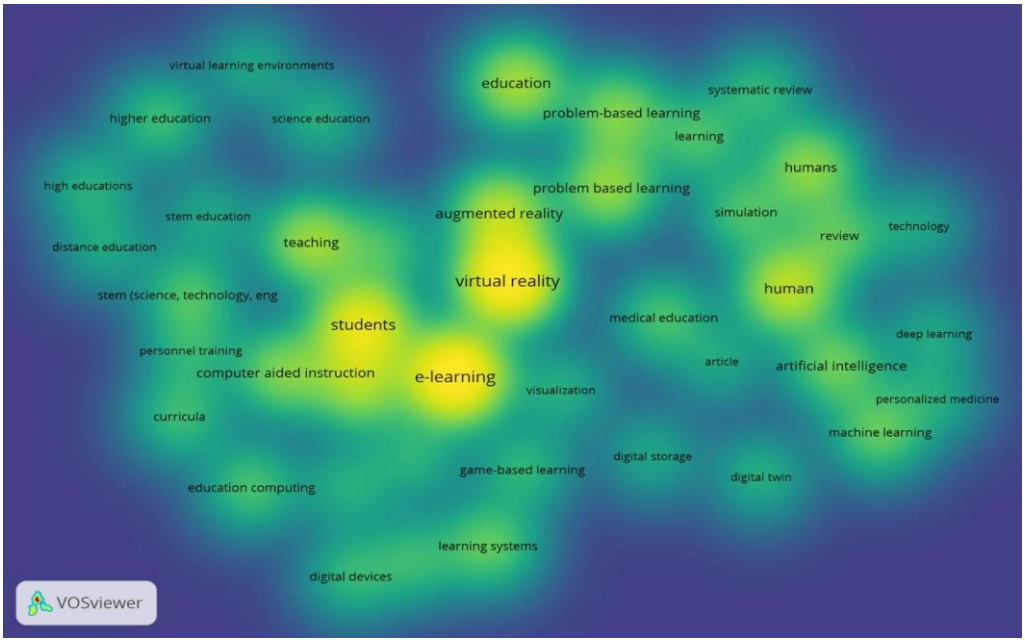

Figure 7. Density visualization of keyword occurrence

Based on this visualization, the keywords "students," "e-learning," "virtual reality," and "problem-based learning" are found in the highest-density areas. This indicates that research in this field focuses heavily on learners' roles and the use of digital technology in problem-based learning. Conversely, several keywords, such as "digital twin," "personalized medicine," and "digital storage," are found in lower-density areas. This

indicates that these topics are relatively new or have not yet been extensively researched in the context of problem-based learning in digital and virtual environments.

Top 5 Most Cited Documents

Citation analysis was conducted to identify the most influential publications in research related to problem-based learning in digital and virtual learning environments. The number of citations indicates the level of influence an article has had on the development of research in a particular field. The five articles with the highest number of citations in this study are shown in Table 1.

Tabel 1. Top 5 most cited documents

Author(s).	Title & Year	Source	Cititations	Fundamental Findings
Keith T. Butler et al.	Data-Driven Strategies for Accelerated Materials Discovery (2021)	Accounts of Chemical Research	331	Data-driven methods accelerate materials discovery.
Fei Tao et al.	Digital Twin for Deep Reinforcement Learning (2021)	Journal of Manufacturing Systems	289	Digital twins enhance reinforcement learning via simulation.
Xiaoliang Wang et al.	TFL-DT: Federated Learning Trust Scheme (2023)	IEEE JSAC	175	Federated learning improves secure collaborative systems.
S. Arora et al	AI-Assisted Parkinson's Diagnosis Survey (2019)	Artificial Intelligence in Medicine	121	AI improves accuracy in medical diagnosis.
Y. Liu et al.	Digital Twin and Spatial Cognition (2023)	Mathematics	101	Digital twins support spatial cognition development.

Based on Table 1, the articles with the highest number of citations indicate that research developments in this field are dominated by the use of digital technology, particularly data-driven approaches, digital twins, artificial intelligence (AI), and federated learning. Key findings from these studies confirm that these technologies play a crucial role in improving the efficiency of learning, decision-making, and cognitive development.

Furthermore, data-driven approaches have been shown to accelerate problem discovery and problem-solving, while digital twins provide a simulation environment that supports experiential learning. Furthermore, the application of AI has demonstrated increased accuracy in analysis and diagnosis, as well as enhanced visualization in

educational contexts. Meanwhile, federated learning contributes to the creation of safer and more reliable collaborative learning systems. Thus, research trends focus not only on the application of problem-based learning but also on integrating advanced technologies to support modern learning processes. This integration is a key factor in improving learning effectiveness and problem-solving capabilities in digital and virtual environments.

Discussion

The results of this bibliometric analysis indicate a significant development in research on problem-based learning (PBL) within digital and virtual learning environments during the period 2015–2025. In line with the study objectives, the trend analysis shows a clear progression from conventional educational contexts toward the integration of advanced digital technologies. Early studies (around 2015–2018) primarily focused on higher education, science education, and distance learning contexts, consistent with previous findings highlighting the foundational role of PBL in fostering student-centered learning in formal education settings (Hmelo-Silver et al., 2020).

As the field evolved (2019–2022), research increasingly incorporated digital technologies such as e-learning, virtual reality, and augmented reality. This shift aligns with studies suggesting that digital tools enhance the effectiveness of PBL by enabling interactive, immersive, and context-rich learning experiences (Makransky & Petersen, 2019). The keyword network visualization in this study supports this trend, showing strong connections between PBL and digital learning technologies, particularly e-learning and virtual reality.

In more recent years (2023–2025), the emergence of topics such as artificial intelligence, machine learning, and data-driven systems indicates a further transformation toward intelligent learning environments. This finding is consistent with recent literature emphasizing the role of artificial intelligence in personalizing learning and improving problem-solving processes in PBL settings (Zawacki-Richter et al, 2019). The overlay visualization confirms this temporal evolution, showing a shift from traditional pedagogical contexts to more technology-driven, adaptive learning systems.

Furthermore, the density visualization highlights that keywords such as students, e-learning, and virtual reality dominate the research landscape, reinforcing the central role of learners and digital environments in contemporary PBL research. This finding supports constructivist learning theories, which emphasize active student engagement and experiential learning (Jonassen, 1999). Conversely, emerging topics such as digital twins and machine learning exhibit relatively low density, indicating that these areas remain underexplored and offer promising directions for future research.

The citation analysis further reveals that highly influential studies tend to focus on integrating digital technologies, artificial intelligence, and data-driven approaches into education. This suggests that PBL's effectiveness is increasingly dependent on its integration with technological innovations rather than on pedagogical design alone.

The findings of this study have several important implications. First, they highlight the need for educators to integrate digital technologies such as virtual reality and artificial intelligence into PBL to create more immersive and effective learning experiences. Second, policymakers and curriculum developers should better incorporate technology-enhanced PBL models to support 21st-century skills, particularly critical thinking and problem-solving. Third, future research should explore emerging technologies, such as digital twins and machine learning, to expand the scope and impact of PBL in digital learning environments.

Despite its contributions, this study has several limitations. First, the analysis is limited to the Scopus database, which may exclude relevant studies indexed in other databases such as Web of Science or Google Scholar. Second, the study relies primarily on bibliometric visualization techniques, which emphasize patterns and relationships but do not provide in-depth qualitative or statistical analysis of research findings. Third, the use of keyword co-occurrence may not fully capture the conceptual depth of each study. Therefore, future research is recommended to combine bibliometric analysis with systematic or meta-analytic approaches to obtain more comprehensive insights.

CONCLUSION

Fundamental Findings: This study demonstrates that the strong integration between pedagogical approaches and digital technologies characterizes research on problem-based learning in digital and virtual learning environments. The bibliometric results show that keywords such as problem-based learning, students, e-learning, and virtual reality form the core structure of the research field and are closely interconnected. **Implications:** The findings imply that problem-based learning is no longer limited to conventional instructional settings but is increasingly associated with technology-enhanced learning environments. The integration of digital technologies has the potential to support more interactive, contextual, and student-centered learning experiences, particularly in developing problem-solving skills. Furthermore, emerging topics such as artificial intelligence and immersive technologies provide new directions for innovation in educational practices and curriculum design. **Limitations:** This study has several limitations. First, the analysis is limited to publications indexed in Scopus, which may not fully represent the field's literature. Second, the results are based on bibliometric visualization techniques, which emphasize patterns and relationships rather than in-depth qualitative or statistical analysis. Third, the selection of keywords may influence the scope of the analysis, potentially excluding relevant studies that use different terminologies. **Future Research:** Future studies are recommended to explore the integration of emerging technologies, such as artificial intelligence, machine learning, and digital twins, within problem-based learning frameworks. In addition, further research combining bibliometric analysis with systematic or empirical approaches is needed to provide deeper insights into the effectiveness and implementation of technology-enhanced problem-based learning in various educational contexts.

AUTHOR CONTRIBUTIONS

Safina Radika Pratiwi contributed to the conceptual framework, research design, and methodology development; **Dwikoranto** was involved in validation process, data analysis, sourcing references, and drafting the manuscript; **Indri Hapsari Khansa** contributed to the sourching references and analysis data; **Lindsay Natalia Bergsma** handled data management, and final manuscript drafting. All listed authors have reviewed and approved the final version of this submission.

CONFLICT OF INTEREST STATEMENT

The authors confirm that there are no conflicts of interest, either financial or personal, that may have influenced the content or outcome of this study.

ETHICAL COMPLIANCE STATEMENT

This manuscript complies with research and publication ethics. The authors affirm that the work is original, conducted with academic integrity, and free from any unethical practices, including plagiarism.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors acknowledge the use of digital tools, including AI-based technologies, as support in the research and writing stages of this article. Specifically, Grammarly is used to help sharpen the quality of language, understanding and use of international standard words. All outputs generated with digital assistance were critically evaluated and revised to ensure academic rigor and ethical standards were upheld. The final responsibility for the manuscript rests entirely with the authors.

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