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Project-Based Learning in Science Education: A Bibliometric Analysis of Research Trends on 21st-Century Skills

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A B S T R ACT

The rapid development of science and technology in the 21st century has increased the demand for educational approaches that foster essential competencies, particularly 21st-Century Skills, including critical thinking, creativity, communication, and collaboration. In Science Education, Project-Based Learning (PjBL) has emerged as a promising approach to support the development of these skills. However, existing studies on PjBL remain fragmented, and a comprehensive understanding of research trends in this field is still limited. Therefore, this study aims to analyze the research trends of project-based learning in science education with a focus on 21st-century skills using a bibliometric approach. This study utilized data retrieved from the Scopus database, resulting in 125 documents published between 2015 and 2026. The analysis was conducted using bibliometric tools, including Biblioshiny and VOSviewer, to examine publication trends, citation patterns, collaboration networks, and keyword co-occurrence. The results indicate a significant increase in research productivity, particularly after 2020, reflecting growing global interest in PjBL for developing 21st-century skills. Citation analysis shows that earlier studies have a strong foundational impact, while recent publications demonstrate rapid growth. The findings also reveal that research dissemination is dominated by conference proceedings, while high-impact journals contribute to knowledge consolidation. In terms of collaboration, contributions are globally distributed, with Indonesia, the United States, and China as leading countries, although international collaboration remains relatively limited. Furthermore, keyword analysis highlights dominant themes related to PjBL and 4C skills, as well as emerging trends in technology integration and student-centered learning. However, the limited presence of ethnoscience and local wisdom integration indicates a significant research gap. This study suggests that future research should focus on developing context-based learning approaches, particularly through the integration of ethnoscience into project-based learning, to enhance the relevance and effectiveness of science education.

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1. INTRODUCTION

The rapid advancement of science and technology in the 21st century has significantly reshaped the demands placed on education systems worldwide. Beyond mastering subject content, students are now expected to develop a range of essential competencies that enable them to navigate complex and dynamic global challenges (Pearl, 2025; Perreault & Dimitrova, 2022; Firdaus & Nurohman, 2025). Among these competencies, 21st-Century Skills have become a central focus, particularly the 4C skills: critical thinking (Saikia & Roy, 2024; Pogrebnaya & Mikhailova, 2023), creativity (Silton, 2016; de Alencar, 2012), communication (Setyawan et al., 2021; Heliyon, 2024), and collaboration (Pederson, 2015; , which are widely recognized as crucial for success in both academic and professional contexts (Pearl, 2025; Keane et al., 2016; Firdaus & Nurohman, 2025).

In Science Education, the development of these skills is particularly important due to the nature of scientific inquiry, which requires problem-solving, analytical reasoning, and collaborative investigation (Chengere et al., 2025; Urdanivia Alarcon et al., 2023; Firdaus, 2024). However, traditional instructional approaches that emphasize rote learning and passive knowledge acquisition are often insufficient to foster such competencies (Ramya et al., 2025; Song & Kim, 2015). This condition indicates that a gap still exists between the demands of 21st-century competencies and their implementation in classroom practices, particularly in science education, which remains dominated by teacher-centered approaches, and is further influenced by internal factors such as students' mental health that may contribute to learning difficulties (Firdaus et al., 2024). Consequently, students' higher-order thinking skills have not been optimally developed (Utama, A. P., 2025). Therefore, innovative instructional strategies are needed to bridge this gap, particularly through the adoption of contextual and student-centered learning approaches.

One of the most widely adopted approaches in this regard is Project-Based Learning (PjBL) (Tierney et al., 2024; Green & Plessis, 2023). This pedagogical model emphasizes learning through the completion of real-world projects, enabling students to construct knowledge actively while simultaneously developing key 21st-century skills (Pawar et al., 2020; Zaki et al., 2024). Through collaborative problem-solving tasks, project design, and reflective processes, PjBL provides a learning environment that supports the integration of cognitive, social, and practical skills (Chandra et al., 2026; Di Virgilio et al., 2026; Kokotsaki et al., 2016). A growing body of research has demonstrated that PjBL is effective in enhancing students' critical thinking, creativity, communication, and collaboration skills within science learning contexts.

Despite the increasing number of studies examining the implementation of PjBL in science education, the existing literature remains fragmented and dispersed across various disciplines and publication outlets. Moreover, while many studies focus on specific outcomes such as problem-solving or creativity, there is still limited comprehensive understanding of how research on PjBL has evolved over time, particularly in relation to the broader framework of 21st-century skills (Mudinillah et al., 2024; Riyanti, 2023; Pawar et al., 2020). Identifying research trends, influential publications, and thematic developments is therefore essential to provide a clearer picture of the current state of knowledge in this field. Previous studies have generally tended to focus on learning outcomes in a partial manner, thus failing to provide a comprehensive understanding of the relationship between project-based learning and 21st-century skills as a whole. Meanwhile, bibliometric studies that specifically map the relationship among project-based learning (PjBL), science education, and 4C skills in recent

years remain limited. This indicates a research gap in terms of both the focus of study and the analytical approaches employed (Donthu et al., 2021; Wicaksono et al., 2023). Therefore, more comprehensive studies are needed to systematically identify research developments.

To address this need, bibliometric analysis has emerged as a powerful method for systematically mapping scientific literature and uncovering patterns within a research domain. By analyzing publication data, citation structures, and keyword relationships, bibliometric studies can reveal the evolution of research topics, collaboration networks, and emerging trends, as well as support evidence-based educational and policy decision-making (Karuniasa & Firdaus, 2025). Utilizing data from the Scopus database, this study aims to provide a comprehensive overview of research on project-based learning in science education.

Therefore, this study seeks to analyze the research trends of project-based learning in science education through a bibliometric approach, with a particular focus on 21st-century skills. Specifically, this study aims to identify publication trends, influential sources, collaboration patterns, and emerging research themes. The findings are expected to contribute to a deeper understanding of the development of PjBL research and provide insights for future studies aimed at enhancing the integration of 21st-century skills in science education.

2. METHOD

2.1 Data Source and Search Strategies

The data for this study were obtained from the Scopus database, focusing on publications related to Project-Based Learning in the context of Science Education and its connection with 21st-Century Skills. The Scopus database was selected because it provides extensive coverage of peer-reviewed scholarly publications across multiple disciplines and geographical regions, making it a reliable source for bibliometric studies. The search process targeted article titles, abstracts, and keywords using relevant terms related to project-based learning in science education and 21st-century skills. The search query was formulated using the following syntax: (TITLE-ABS-KEY ("project based learning" OR "project-based learning") AND TITLE-ABS-KEY ("science education") AND TITLE-ABS-KEY ("21st century skills" OR "critical thinking" OR creativity OR communication OR collaboration)).

2.2 Research Design and Data Analysis

This study applies a bibliometric analysis approach to examine research trends related to Project-Based Learning in the context of Science Education and its relationship with 21st-Century Skills. Bibliometric analysis is a quantitative technique used to evaluate and map scientific publications in order to understand patterns, developments, and relationships within a particular research domain (Donthu et al., 2021; Roemer & Borchardt, 2015; Zhu et al., 2023). Through this approach, researchers can systematically explore the structure of academic literature and visualize the development of research topics over time.

Bibliometric analysis also employs visualization techniques to illustrate various aspects of scholarly production, including publication growth, journal productivity, citation relationships, and collaboration networks among authors, institutions, and countries (Donthu et al., 2021). As a statistical method, bibliometric analysis is capable of processing large volumes of bibliographic data with a high level of precision, allowing researchers to identify patterns and emerging themes within a specific field of study (Donthu et al., 2021).

The main objective of applying bibliometric analysis in this research is to explore the development and research trends of project-based learning in science education, particularly in relation to the development of 21st-century skills. The analysis focuses on identifying dominant research topics, influential publications, and collaboration patterns within this field over the past decade. In conducting the bibliometric analysis, this study follows three main

stages: defining the research objective, selecting the sample, and conducting statistical analysis.

Defining the Objective

Bibliometric analysis examines several quantitative characteristics of scientific publications. These include the evolution of publication trends, the most influential and highly cited articles, citation sources and their impact, as well as collaboration networks among authors and countries. Additionally, the analysis explores the development of research themes through keyword analysis. Indicators such as the number of publications and citation frequencies help reveal changes in research attention over time. Meanwhile, keyword frequency highlights the dominant research topics, and subject categories and country contributions indicate how research in this field is distributed across disciplines and geographic regions.

Selecting the Sample

The dataset for this study was retrieved from the Scopus database. The search focused on publications related to project-based learning in science education and its connection with 21st-century skills. The initial search process produced 140 documents. To capture the most recent developments in this research area, the dataset was limited to publications from 2015 to 2026, representing a ten-year period of scholarly output. After applying this time filter, a total of 125 documents were retained as the final dataset for bibliometric analysis.

The selected records were exported in BibTeX format, which is compatible with bibliometric analysis tools. Before conducting the analysis, the bibliographic metadata were checked to ensure completeness and suitability for further processing. The results of the metadata examination are summarized in Table 1.

Table 1. The Results of The Metadata

Metadata	Description	Missing Counts	Missing %	Status
AB	Abstract	0	00.00	Excellent
AU	Author	0	00.00	Excellent
DT	Document Type	0	00.00	Excellent
SO	Journal	0	00.00	Excellent
LA	Language	0	00.00	Excellent
PY	Publication Year	0	00.00	Excellent
TI	Title	0	00.00	Excellent
TC	Total Citation	0	00.00	Excellent
C1	Affiliation	6	0,222222	Good
DI	DOI	15	12.00	Acceptable
DE	Keywords	25	20.00	Acceptable
RP	Corresponding Author	51	40.80	Poor
ID	Keywords Plus	63	50.40.00	Critical
CR	Cited References	125	100.00.00	Completely missing
WC	Science Categories	125	100.00.00	Completely missing

Statistical Analysis

The bibliometric analysis in this study was conducted using RStudio together with Biblioshiny. RStudio serves as an integrated development environment for the R

programming language, which is widely used for statistical computation and data visualization. Biblioshiny is a web-based graphical interface of the bibliometrix package that enables researchers to perform comprehensive bibliometric and scientometric analyses.

Using these tools, the bibliographic data obtained from the Scopus database were analyzed to identify publication trends, influential authors and journals, citation patterns, and keyword networks related to project-based learning in science education and the development of 21st-century skills. To perform the keyword co-occurrence analysis, the bibliographic data were processed using VOSviewer. In this study, the co-occurrence analysis was conducted based on author keywords and indexed keywords to identify the main research themes and their interrelationships.

During the mapping process, a threshold was applied to ensure the reliability and clarity of the visualization. Specifically, the minimum number of occurrences of a term was set to 5, meaning that only keywords appearing at least five times in the dataset were included in the analysis. Out of a total of 3,598 identified terms, 237 terms met this threshold and were subsequently used to construct the keyword network.

This threshold selection aims to filter out less significant or rarely used terms, thereby improving the interpretability of the network and highlighting the most relevant and dominant research topics. The selected keywords were then grouped into clusters automatically by VOSviewer based on their co-occurrence relationships. Each cluster represents a distinct research theme within the field of project-based learning in science education and 21st-century skills. The resulting network visualization displays the frequency of keywords (node size), the strength of relationships between keywords (link strength), and thematic groupings (clusters), which serve as the basis for identifying research trends and emerging topics.

3. RESULT AND DISCUSSION

3.1 Descriptive Analysis: Evolution of Publications and the Most Globally Cited Articles

To provide an overview of the development of research on project-based learning in science education and its relation to 21st-century skills, a descriptive analysis was conducted. This analysis focuses on the annual growth of scientific publications and highlights the overall trend of research productivity over time. Examining publication trends is essential to understand how scholarly interest in this field has evolved and to identify periods of significant growth.

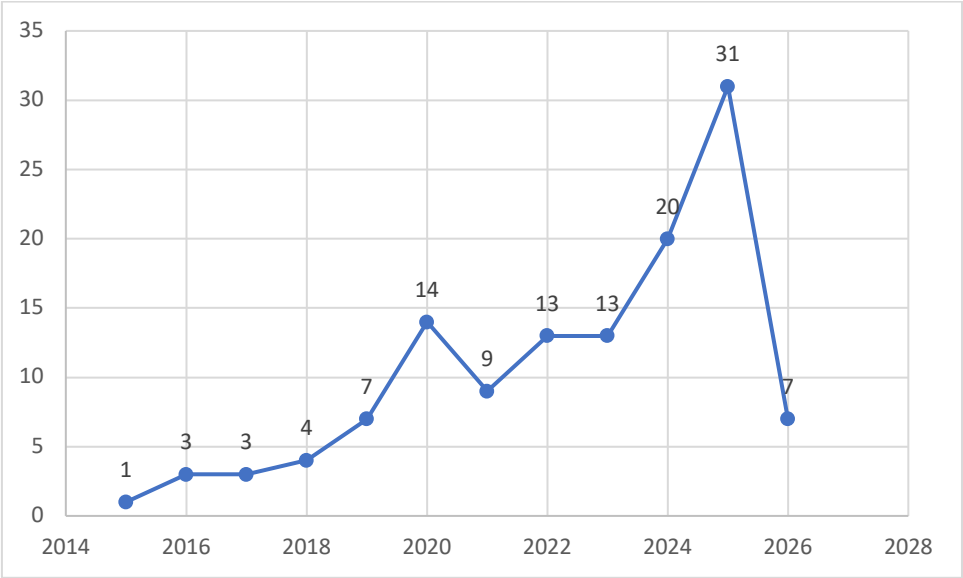

Figure 1. Annual scientific production

As shown in Figure 1, the number of publications on project-based learning in science education demonstrates a generally increasing trend over the observed period. In the early years (2015–2018), the number of publications was relatively low, indicating that research on this topic was still in its initial development phase. A gradual increase began to appear from 2019, followed by a more noticeable rise in 2020, suggesting growing academic interest in the application of project-based learning.

Between 2021 and 2023, the number of publications remained relatively stable with moderate growth, reflecting a consolidation phase in which research themes became more established. A significant increase occurred in 2024 and reached its peak in 2025, with the highest number of publications recorded. This sharp rise indicates a heightened global interest in integrating project-based learning with the development of 21st-century skills, particularly in response to the evolving demands of modern education.

However, a decline is observed in 2026. This decrease does not necessarily indicate a reduction in research interest, but rather can be attributed to the fact that the data for 2026 only represent publications from the early part of the year, making it incomplete compared to previous full-year data. The trend suggests that research on project-based learning in science education has gained significant momentum over the past decade. The increasing number of publications also reflects the growing recognition of project-based learning as an effective approach to fostering key 21st-century skills, including critical thinking, creativity, communication, and collaboration. This upward trend further indicates the relevance and importance of this research area in addressing contemporary educational challenges.

To further examine the impact and influence of publications in this research area, a citation analysis was conducted. This analysis focuses on the average number of citations per article and per year, providing insight into how frequently published studies are referenced within the academic community. Citation metrics are important indicators of the scientific relevance and visibility of research over time.

Table 2 presents the average citation per article (MeanTCperArt), the number of publications (N), the average citation per year (MeanTCperYear), and the number of citable years for each publication period.

Table 2. Average citation per year

Year	MeanTCperArt	N	MeanTCperYear	CitableYears
2015	9,00	1	0,75	12
2016	13,33	3	1,21	11
2017	9,67	3	0,97	10
2018	8,25	4	0,92	9
2019	9,29	7	1,16	8
2020	15,14	14	2,16	7
2021	13,22	9	2,20	6
2022	22,54	13	4,51	5
2023	14,62	13	3,65	4
2024	3,60	20	1,20	3
2025	0,84	31	0,42	2
2026	0,00	7	0,00	1

Based on Table 2, it can be observed that earlier publications tend to have higher average citation values compared to more recent ones. For instance, publications from 2016 show a relatively high average citation per article (13.33), while those from 2020 and 2022 demonstrate even stronger citation performance, with MeanTCperArt values of 15.14 and 22.54

respectively. This indicates that articles published during these years have had a significant impact on subsequent research.

A notable peak appears in 2022, where the average citation per article reaches 22.54 and the average citation per year is 4.51, suggesting that studies published in this period are highly influential and widely referenced. This may reflect the increasing maturity of research on project-based learning in science education, particularly in relation to the development of 21st-century skills.

In contrast, publications from more recent years, such as 2024, 2025, and 2026, show relatively low citation values. This pattern is expected, as newer articles have had less time to accumulate citations. The decreasing number of citable years for recent publications further explains this trend, with 2026 having only one citable year and consequently no recorded citations yet.

Additionally, the number of publications (N) shows a substantial increase in recent years, particularly in 2024 and 2025. This suggests that while research productivity is growing rapidly, citation impact typically requires time to develop. Therefore, there is often a lag between publication output and citation accumulation.

Overall, the findings indicate that earlier studies have established a strong foundational influence in this field, while more recent publications reflect a growing research interest that is likely to gain citation impact in the coming years. This pattern highlights the dynamic development of project-based learning research in science education and its increasing relevance in fostering 21st-century skills such as critical thinking, creativity, communication, and collaboration.

3.2 Citation Source Analysis and Local Impact

To identify the most influential publication outlets in this research field, an analysis of the most relevant sources was conducted. This analysis highlights journals and conference proceedings that contribute the highest number of publications related to project-based learning in science education and 21st-century skills. Identifying these sources is important for understanding where research is most frequently disseminated and which outlets play a key role in shaping the development of this field.

Figure 2 presents the most relevant sources based on the number of documents published within the dataset.

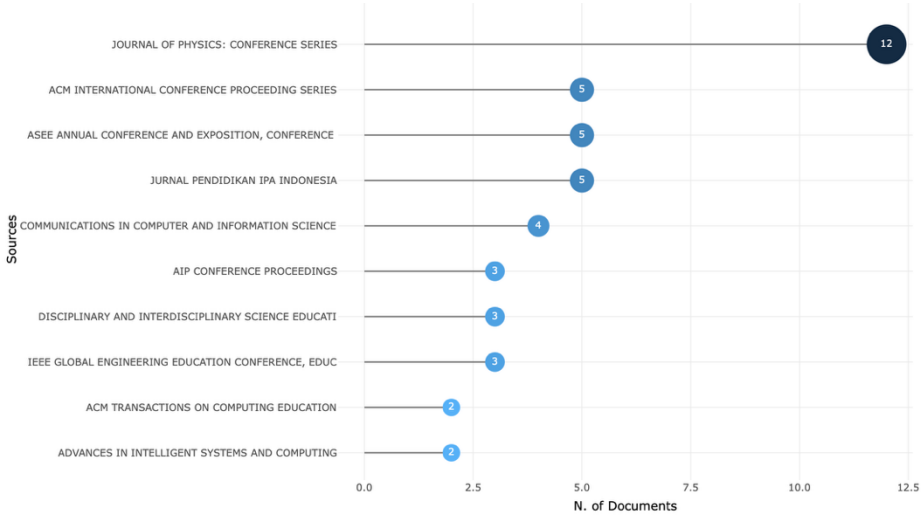

Figure 2. Most Relevant sources

As illustrated in Figure 2, several sources emerge as the most productive in publishing research on project-based learning in science education. Among them, IOP Conference Series: Journal of Physics: Conference Series appears as the most dominant source, contributing the

highest number of documents compared to other outlets. This indicates that conference proceedings play a significant role in disseminating research in this field.

Other prominent sources include conference proceedings such as AIP Conference Proceedings and ASEAN Journal of Science and Engineering Education Conference, as well as journals like Jurnal Pendidikan IPA Indonesia. The presence of both international conference proceedings and regional journals suggests that research on project-based learning is not only globally recognized but also actively developed in specific regional contexts, particularly in science education.

The dominance of conference proceedings among the top sources indicates that this research area is still evolving and dynamic, as conferences are often platforms for presenting emerging ideas and ongoing studies. Meanwhile, the inclusion of peer-reviewed journals reflects the consolidation of knowledge and the maturation of research themes. Furthermore, the distribution of sources highlights that studies on project-based learning and 21st-century skills are interdisciplinary in nature, spanning areas such as science education, engineering education, and applied sciences. This aligns with the characteristics of project-based learning, which integrates multiple disciplines and emphasizes real-world problem solving.

The findings suggest that while high-impact journals contribute to the field, conference proceedings remain a major channel for knowledge dissemination. This pattern indicates both the rapid growth and the continuing development of research on project-based learning in science education.

To further examine the influence of publication sources within the dataset, a local citation analysis was conducted. This analysis evaluates the impact of journals and conference proceedings based on bibliometric indicators such as the h-index, g-index, m-index, total citations (TC), and number of publications (NP). These indicators provide insight into the productivity and citation performance of each source within the specific research domain.

Table 3 presents the local impact of the most relevant sources contributing to research on project-based learning in science education and 21st-century skills.

Table 3. Source Local Impact

Source	h index	g Index	m index	TC	NP	PY_start
Journal of Physics: Conference Series	5	7	0,500	68	12	2017
Disciplinary and Interdisciplinary Science Education Research	3	3	0,600	130	3	2022
Acm International Conference Proceeding Series	2	2	0,286	7	5	2020
Acm Transactions on Computing Education	2	2	0,182	49	2	2016
IEEE Global Engineering Education Conference, Educon	2	2	0,250	7	3	2019
Interactive Learning Environments	2	2	0,667	19	2	2024
Proceedings - Frontiers In Education Conference, Fie	2	2	0,182	11	2	2016
Advances in Intelligent Systems and Computing	1	2	0,111	6	2	2018
Aip Conference Proceedings	1	3	0,167	9	3	2021
American Biology Teacher	1	2	0,200	4	2	2022

Based on Table 3, Journal of Physics: Conference Series demonstrates the highest productivity, with the largest number of publications (NP = 12) and a relatively strong h-index (h = 5). This indicates that the source consistently contributes to the field and has a moderate level of citation impact within the dataset.

In contrast, Disciplinary and Interdisciplinary Science Education Research shows a notably high total citation count (TC = 130) despite having fewer publications (NP = 3). This suggests that articles published in this journal tend to have a higher impact and are more frequently cited, indicating strong academic influence and quality.

Several other sources, such as ACM Transactions on Computing Education and Interactive Learning Environments, also demonstrate meaningful citation performance, with relatively balanced values across citation metrics. Notably, Interactive Learning Environments has the highest m-index (0.667), suggesting a strong citation rate relative to the number of years since its first publication in this dataset.

Conference proceedings, including AIP Conference Proceedings, IEEE Global Engineering Education Conference (EDUCON), and Frontiers in Education Conference (FIE), also appear among the contributing sources. However, their citation metrics are generally lower compared to journal publications, indicating that while conferences contribute significantly to research dissemination, their citation impact tends to be more limited.

The findings highlight a distinction between productivity and impact. Some sources contribute a large number of publications but have moderate citation influence, while others publish fewer articles but achieve higher citation impact. This pattern reflects the dynamic nature of research on project-based learning in science education, where both conference proceedings and high-impact journals play complementary roles in advancing knowledge, particularly in relation to the development of 21st-century skills such as critical thinking, creativity, communication, and collaboration.

3.3 Collaboration Analysis: Countries and Authors

To explore collaboration patterns in this research field, an analysis of authorship was conducted. Author productivity is an important indicator in bibliometric studies, as it reflects the contribution of individual researchers to the development of a specific topic. Identifying the most productive authors also helps to recognize key contributors and potential research networks within the field of project-based learning in science education and 21st-century skills.

Figure 3 presents the most productive authors based on the number of documents published in the dataset.

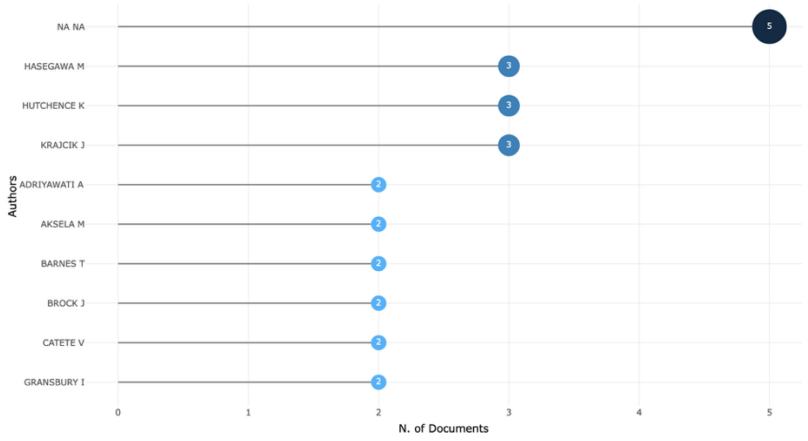

Figure 3. Most productive author

As illustrated in Figure 3, several authors have contributed consistently to research on project-based learning in science education. Among them, one author stands out as the most productive, with the highest number of publications compared to others in the dataset. This indicates a strong and sustained research focus on this topic.

Other authors show relatively similar levels of productivity, with a moderate number of publications. This pattern suggests that research in this field is not dominated by a single author but rather distributed among multiple contributors. Such distribution reflects a collaborative and evolving research landscape. The presence of several authors with comparable publication counts also indicates the emergence of research groups or communities that are actively engaged in studying project-based learning and its role in developing 21st-century skills. These contributions may come from different institutions and countries, highlighting the global relevance of this research area.

Furthermore, the collaborative nature of project-based learning research aligns with its pedagogical principles, which emphasize teamwork, communication, and interdisciplinary approaches. This is reflected not only in classroom practices but also in the way research is conducted and published. The findings suggest that while certain authors play a leading role in advancing the field, the development of research on project-based learning in science education is supported by a diverse and collaborative network of scholars. This collaborative dynamic contributes to the continuous growth and diversification of research topics, particularly those related to critical thinking, creativity, communication, and collaboration.

To further analyze authorship patterns, this study applies Lotka's Law, which describes the distribution of scientific productivity among authors. Lotka's Law suggests that a small number of authors contribute a large number of publications, while the majority of authors produce only a single publication. This analysis is important to understand the structure of author productivity and the concentration of research contributions within the field. Table 5 presents the distribution of authors based on the number of documents they have contributed to in the dataset.

Table 5. Author Productivity through Lotka's Law

Documents written	N. of Authors	Proportion of Authors
1	404	0,953
2	16	0,038
3	3	0,007
5	1	0,002

Based on Table 5, the distribution of author productivity clearly follows the general pattern proposed by Lotka's Law. The majority of authors (404 authors or 95.3%) contributed only one publication, indicating that most researchers in this field are occasional contributors. This suggests that research on project-based learning in science education attracts a wide range of scholars, but many of them are not continuously active in this specific area.

A much smaller proportion of authors contributed two publications (3.8%), while only a few authors produced three publications (0.7%). Notably, only one author (0.2%) contributed five publications, representing the most productive contributor in the dataset. This demonstrates that highly productive authors are relatively rare but play a significant role in shaping the development of the research field.

This pattern indicates a high dispersion of authorship, where contributions are spread across many individuals rather than concentrated within a small group of dominant researchers. Such a distribution is typical in emerging or interdisciplinary research areas, where scholars from different backgrounds contribute to the topic.

In the context of project-based learning in science education and 21st-century skills, this finding suggests that the field is still expanding and attracting new researchers. The

diversity of contributors may also reflect the interdisciplinary nature of the topic, which intersects education, science, and pedagogical innovation.

The results confirm that author productivity in this field aligns with Lotka's Law, highlighting that while most researchers contribute only once, a small number of core authors drive the continuity and advancement of research. This dynamic supports the ongoing development of knowledge related to critical thinking, creativity, communication, and collaboration within science education.

To examine the geographical distribution and collaboration patterns of research in this field, an analysis of corresponding authors' countries was conducted. This analysis provides insights into which countries contribute most actively to publications on project-based learning in science education and how international collaboration is formed. The distinction between Single Country Publications (SCP) and Multiple Country Publications (MCP) is used to identify the extent of domestic versus international research collaboration. Figure 4 illustrates the distribution of publications by country, along with their collaboration patterns.

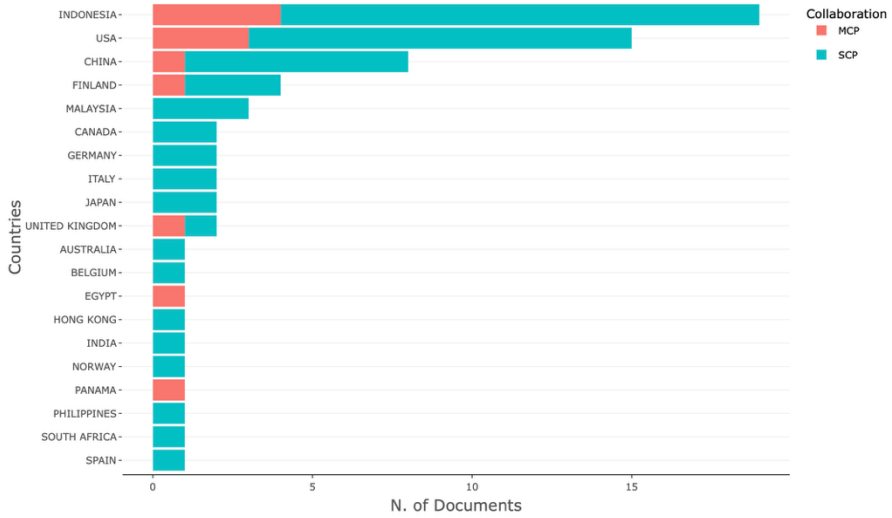

Figure 4. Corresponding authors countries

As shown in Figure 4, Indonesia emerges as the most productive country, contributing the highest number of publications (19 articles or 15.2%). This indicates a strong research interest in project-based learning within science education, particularly in the Indonesian context. The relatively high number of Single Country Publications (SCP = 15) suggests that most studies are conducted domestically, although there is also a notable level of international collaboration (MCP = 4 or 21.1%).

The United States ranks second with 15 publications (12%), demonstrating its consistent contribution to the field. Similar to Indonesia, the majority of publications are domestic (SCP = 12), with a moderate proportion of international collaboration (MCP = 20%). Meanwhile, China holds the third position with 8 publications, but shows a lower level of international collaboration (MCP = 12.5%), indicating a stronger focus on internal research activities.

European countries such as Finland and the United Kingdom exhibit interesting collaboration patterns. Although their total number of publications is relatively smaller, they show higher proportions of international collaboration. For instance, the United Kingdom has an MCP rate of 50%, indicating that half of its publications involve cross-country collaboration. Similarly, Finland demonstrates a relatively high MCP percentage (25%), suggesting active participation in international research networks.

Several countries, including Malaysia, Canada, Germany, Italy, and Japan, contribute modestly to the field, but their publications are predominantly domestic, as indicated by zero

MCP values. On the other hand, countries such as Egypt and Panama, although contributing only one publication each, show 100% MCP, indicating that their contributions are entirely based on international collaboration.

The findings reveal that research on project-based learning in science education is globally distributed, with significant contributions from both developed and developing countries. However, the dominance of Single Country Publications suggests that international collaboration is still limited in many regions. Strengthening cross-country collaboration could enhance the exchange of ideas, promote diverse perspectives, and improve the overall quality of research, particularly in addressing global educational challenges related to the development of 21st-century skills such as critical thinking, creativity, communication, and collaboration.

To provide a broader perspective on the global distribution of research output, an analysis of countries' scientific production was conducted. This analysis visualizes the geographical spread of publications related to project-based learning in science education and 21st-century skills. Mapping scientific production across countries helps to identify leading contributors, regional patterns, and the global reach of research in this field. Figure 5 illustrates the global distribution of scientific publications based on countries, highlighting differences in research productivity and international engagement.

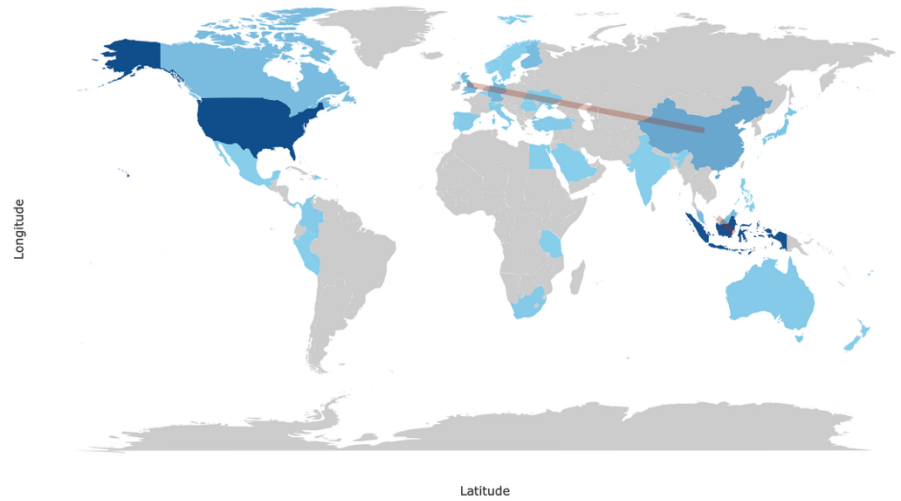

Figure 5. Countries scientific productions

As shown in Figure 5, the distribution of scientific production demonstrates a global engagement in research on project-based learning in science education. However, the intensity of contributions varies significantly across regions. Countries with darker color intensity, such as the United States and Indonesia, indicate higher levels of research productivity, confirming their dominant roles as observed in previous analyses.

The map also reveals that research activity is not limited to a specific region but is spread across multiple continents, including Asia, Europe, North America, and parts of Africa. This widespread distribution suggests that project-based learning and the development of 21st-century skills are recognized as important educational priorities worldwide.

In Asia, countries such as Indonesia, China, and Malaysia show notable contributions, reflecting the growing emphasis on innovative learning approaches in developing educational systems. Meanwhile, European countries demonstrate a more distributed pattern of contributions, often associated with collaborative research networks. North America, particularly the United States, continues to play a central role in advancing research in this area.

Despite this global distribution, certain regions, particularly in Africa and South America, appear to have lower levels of research output. This indicates potential gaps in research participation and highlights opportunities for expanding studies and collaborations in underrepresented regions.

The visualization confirms that research on project-based learning in science education is globally relevant and continues to expand across different regions. However, disparities in research productivity suggest the need for increased international collaboration and support to ensure a more balanced global contribution. Strengthening such collaboration could further enhance the development and implementation of project-based learning approaches aimed at fostering critical thinking, creativity, communication, and collaboration in diverse educational contexts.

3.4 Emerging Research Topics in Project-Based Learning for 21st-Century Skills

To identify emerging research topics and influential studies within the field, a citation-based analysis was conducted focusing on the most cited documents. Highly cited articles are considered key references, as they reflect significant contributions, widely recognized findings, and dominant research directions. This analysis provides insight into the core themes and evolving trends in project-based learning, particularly in relation to the development of 21st-century skills. Table 6 presents the most cited documents based on total citations, citations per year, and normalized citation impact.

Table 6. Most Cited Document

Paper	DOI	Total Citations	TC per Year	Normalized TC
Markula A, 2022, Discip Interdscip Sci Educ Res	10.1186/s43031-021-00042-x	121	24,20	5,37
Owens Ad, 2020, Res Sci Technol Educ	10.1080/02635143.2020.1778663	65	9,29	4,29
Chang Cy, 2023, Virtual Reality	10.1007/s10055-023-00817-9	61	15,25	4,17
Krajcik J, 2023, Am Educ Res J	10.3102/00028312221129247	61	15,25	4,17
Adriyawati A, 2020, Univers J Edu Res	10.13189/ujer.2020.080523	54	7,71	3,57
Haatainen O, 2021, Lumat	10.31129/LUMAT.9.1.1392	45	7,50	3,40
Domenici V, 2022, Educ Sci	10.3390/educsci12010030	45	9,00	2,00
Chen Cs, 2019, Int J Sci Math Educ	10.1007/s10763-019-09961-8	41	5,13	4,42
Wang Yh, 2020, Educational Technology And Society	NA	36	5,14	2,38
Chistyakov Aa, 2023, Eurasia J Math Sci Technol Educ	10.29333/EJMSTE/13128	35	8,75	2,39

Based on Table 6, several highly cited studies have played a crucial role in shaping research on project-based learning in science education. The study by Markula (2022) stands out as the most influential, with the highest total citations (121) and the highest citation rate per year (24.20). This indicates that the study has gained substantial attention in a relatively short period, suggesting its strong relevance to current research trends.

Other influential studies, such as Owens (2020) and Chang (2023), also demonstrate high citation impact, reflecting the growing interest in integrating innovative approaches, including technology and immersive learning environments, into project-based learning. Similarly, works by Krajcik (2023) and Chen (2019) highlight the importance of inquiry-based and student-centered approaches in enhancing science learning outcomes.

An interesting pattern emerging from the table is the strong presence of studies related to educational technology, such as virtual reality and digital learning environments. This suggests that recent research trends are increasingly integrating technology with project-based learning to support the development of 21st-century skills. Additionally, several studies emphasize the role of project-based learning in fostering critical thinking, creativity, and problem-solving skills, which are key components of the 4C framework.

Despite these advancements, there appears to be limited representation of studies explicitly focusing on ethnoscience or local wisdom integration within project-based learning. This indicates a potential research gap, particularly in exploring how culturally relevant contexts can be incorporated into science education to enhance students' engagement and contextual understanding.

Furthermore, while many highly cited studies focus on general pedagogical approaches and technology integration, fewer studies address the development of structured teaching materials or modules that systematically integrate project-based learning with 21st-century skills. This highlights an opportunity for future research to design and develop instructional materials that bridge this gap.

The findings indicate that current research trends are moving toward the integration of project-based learning with technology and 21st-century skills development. However, the limited focus on ethnoscience and instructional module development suggests a clear direction for future studies, particularly in creating context-based learning innovations that are culturally relevant and pedagogically effective.

To further explore the structure and emerging themes of research in this field, a keyword co-occurrence analysis was conducted using VOSviewer. This analysis visualizes the relationships between frequently occurring keywords and groups them into clusters, representing major research themes. The size of each node indicates the frequency of keyword occurrence, while the links between nodes represent the strength of co-occurrence relationships. Figure 6 illustrates the network visualization of keywords related to project-based learning in science education and 21st-century skills.

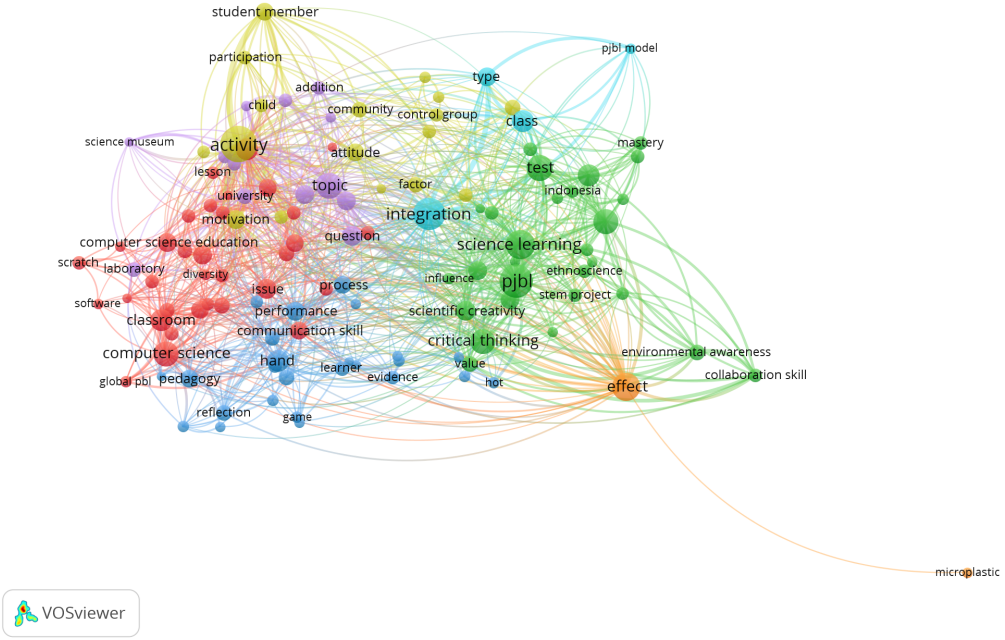

Figure 6. Keyword Co-occurrence Network Visualization

As shown in Figure 6, the keyword co-occurrence network reveals several interconnected clusters that represent dominant research themes in the field. The largest and most central cluster (green) is centered around terms such as "project-based learning (PjBL)," "science learning," and "critical thinking." This indicates that a significant portion of research focuses on the role of PjBL in enhancing students' cognitive skills, particularly critical thinking as part of 21st-century competencies.

Another prominent cluster (red) is associated with "education," "students," "learning process," and "classroom," highlighting research that emphasizes instructional practices and learning environments. Meanwhile, the blue cluster includes terms such as "communication," "collaboration," and "skills," which directly correspond to components of the 4C framework. This confirms that research on project-based learning is strongly aligned with the development of 21st-century skills.

Additionally, the yellow and purple clusters indicate emerging topics related to student engagement, activity-based learning, and integration approaches, suggesting a shift toward more interactive and student-centered pedagogies. The presence of terms such as "effect," "performance," and "outcomes" further shows that many studies focus on evaluating the effectiveness of PjBL in improving learning outcomes.

However, an important observation from the network is the limited presence of keywords related to ethnoscience, local wisdom, or culturally contextual learning. Although there are some indications of contextual and environmental themes, these are not yet strongly connected to the main clusters of project-based learning and 21st-century skills.

This finding highlights a significant research gap. While current research trends are heavily focused on integrating PjBL with 4C skills and, in some cases, technology-enhanced learning, the incorporation of ethnoscience as a contextual and culturally relevant approach remains underexplored. Given the importance of contextual learning in science education,

integrating ethnoscience into project-based learning has strong potential to enhance students' understanding by connecting scientific concepts with real-life cultural practices.

Furthermore, the weak linkage between ethnoscience-related concepts and core PjBL themes suggests that future research should explore how culturally grounded content can be systematically embedded into project-based learning designs. This includes the development of instructional materials or modules that integrate local wisdom with scientific inquiry.

The keyword network confirms that the current research landscape is dominated by studies on PjBL and 21st-century skills, particularly critical thinking, collaboration, and communication. However, the lack of strong representation of ethnoscience indicates a promising direction for future research. This gap provides a clear justification for developing ethnoscience-integrated project-based learning modules, which can bridge global competencies with local cultural contexts in science education.

4. CONCLUSION

This study examined research trends on Project-Based Learning in Science Education with a focus on 21st-Century Skills using a bibliometric approach. The findings indicate a significant increase in research productivity over the past decade, particularly after 2020, reflecting the growing global interest in utilizing project-based learning to develop key competencies such as critical thinking, creativity, communication, and collaboration. Citation analysis highlights the strong foundational influence of earlier studies, while more recent publications demonstrate rapid growth despite lower citation counts due to limited exposure time. The results also reveal that research dissemination is dominated by conference proceedings, supported by high-impact journals, and that global contributions are led by countries such as Indonesia, the United States, and China, although international collaboration remains relatively limited.

The analysis of highly cited documents and keyword co-occurrence networks shows that current research trends are strongly oriented toward the integration of project-based learning with 21st-century skills and technology-enhanced learning. However, the limited representation of ethnoscience and local wisdom indicates a significant research gap. This suggests that future research should focus on integrating culturally relevant contexts into project-based learning, particularly through the development of instructional materials or modules. Such efforts are expected to bridge global competencies with local contexts and enhance the effectiveness of science learning in fostering meaningful and contextualized understanding.

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