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Trends in Biology Learning Innovations for Strengthening 21st Century Skills Toward Achieving the Sustainable Development Goals (SDGs)

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Abstract: This study analyzes publication trends in biology learning innovation linking 21st Century Skills and the Sustainable Development Goals (SDGs) using a bibliometric approach. Data sourced from Google Scholar (n = 637) were extracted using the Publish or Perish tool and converted into CSV and RIS formats., then filtered based on inclusion criteria (journal articles and book chapters; English/Indonesian), resulting in 313 final documents, with 171 documents discussing specific learning innovation (models/approach). Data were analyzed using VOSviewer for keyword co-occurrence and Excel for frequency analysis. The results show an increasing research trend in 2022–2025, with the dominant topic being technology integration, especially artificial intelligence (AI). Indonesia surpasses the UK and US in publications on this topic. The dominant learning innovations are STEM/STEAM (21%; links 27), PjBL (11%; links 19), and PBL (6%; links 16). Co-occurrence analysis links these innovations with critical thinking, creativity, problem-solving, collaboration, and digital literacy. These innovations connect to SDGs 4 and 13 (primary goals), and SDGs 6, 9, 11, and 12 (subsidiary goals), confirming their relevance in strengthening 21st-century skills and sustainable development goals. Their effective implementation depends on teacher preparedness, curriculum adaptability, and institutional support, requiring research across educational contexts.

Keywords: Bibliometric analysis; Education for sustainable development; Problem based learning; Project based learning; STEM/STEAM education

Introduction

Conventional teaching strategies, often based on rote memorization, result in a shallow understanding. This learning approach hinders students' development of 21st-century skills, such as critical thinking, creative idea generation, communication, and collaboration with others in real-life settings (Parry & Metzger, 2023). In the current era, the principles of Educational Sustainable Development (ESD) are essential for fostering students' awareness of sustainability. Learning innovation in education refers to new ideas, techniques, or approaches that improve the teaching and learning process to increase efficiency and adapt to current educational needs (Yanis, 2025). Innovation in biology learning offers an alternative for strengthening 21st-century skills and fostering students' awareness of global phenomena, focusing on experiential learning (Darmastuti et al., 2025; Saidaturrahmi et al., 2021). Current research indicates that certain innovative educational models and approaches effectively foster 21st-century skills and sustainability (Redman & Wiek, 2021). Learning methods such as Project Based Learning (PJBL) and Science, Technology, Engineering, and Mathematics (STEM) can stimulate students' critical thinking in understanding theory and practice and foster creativity through designing solutions based on innovative ideas (Winaryati et al., 2025).

Systematic studies and bibliometric analyses related to mapping learning innovations to strengthen 21st-

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century skills and the Sustainable Development Goals (SDGs) are still minimal, creating a research gap in this field. The fragmentation of previous research makes it difficult to understand the correlation between these three topics, making learning innovations essential because they can improve soft skills, hard skills, and life skills that can be applied to address environmental change (Sa'adah et al., 2023). A good link between biology learning innovations with 21st-century skills and the SDGs is found in materials on ecology, environmental health, and other global issues such as climate change (Yang & Xiu, 2023). Alternative innovations, such as STEM-oriented SDGs, have been shown to directly address SDG 4 (quality education) and SDG 13 (climate action) through environmental awareness (Pada et al., 2025).

A comprehensive bibliometric analysis is crucial in this study because, despite numerous studies related to learning innovation, none have yet examined its integrated relevance in strengthening 21st-century skills and the SDGs. Numerous bibliometric studies on education in sustainable development have been conducted, but few, if any, have focused on the dual perspective of biology education, 21st-century skills, and the SDGs (Mardita, 2024). Therefore, this study aimed to analyze and map scientific publication trends on biology learning innovations that connect 21st-century skills and the SDGs. The results of this bibliometric analysis can present relevant innovations, not just popular ones, serve as a reference for implementing learning models in the classroom, provide data-based mapping of future study focuses, and provide insights and a foundation for developing and implementing curriculum dynamics and sustainable education.

Method

This study applied a quantitative approach to analyze patterns and trends in the scientific literature using analysis, measurement, and visualization techniques. This approach is known as bibliometric analysis, which enables mapping of research developments (Istiawanto et al., 2024). In conducting a comprehensive bibliometric analysis, a good research direction and clear objectives are needed so that specific, focused, and relevant answers to the problems are obtained according to the research topic (Passas, 2024). The data used in this study are scientific works in the last 10 years (2016-2025) obtained through Google Scholar that were extracted by Publish or Perish software using the keywords (biology education OR "biology learning") AND (learning innovation OR "innovative pedagogy") AND 21st century skills AND (sustainable development goals OR "SDGs"). The search results yielded n = 637 journal articles and book chapters converted into Comma Separated Values (CSV) and Research Information Systems (RIS) formats.

Furthermore, all obtained papers were screened based on the inclusion and exclusion criteria analyzed in the title, abstract, and introduction sections. Inclusion criteria are conditions used by a researcher to determine a sample group to find answers to the research objectives being conducted, while exclusion criteria are conditions not used in the research (Patino & Ferreira, 2018). The inclusion criteria in this study included published full-text scientific papers, including journal articles or book chapters, in both English or Indonesian, focusing on biology learning innovation, 21st-century skills, and relevance to the SDGs. Papers were excluded if they did not meet the inclusion criteria, such as articles with inaccessible full texts and duplicate publications of the same study.

The selection process, based on the inclusion and exclusion criteria, yielded 313 papers relevant to the research, and 324 papers were eliminated. The exported data included the number of citations, author, year, source, publisher, citations per author, abstract, and country. The included papers were extracted again to yield 171 papers related to learning innovations, particularly learning models. VOSviewer software version 1.6.20 was used to create a visual display of the bibliometric network in the form of a keyword co-occurrence map, displaying keywords from this study statistically and simply (Izhar et al., 2023). Excel software was used for descriptive frequency analysis and presentation of data values other than the keywords.

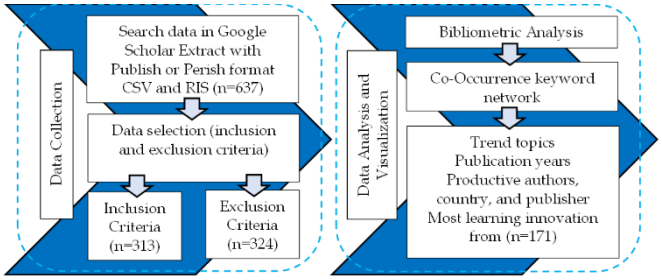

Figure 1. Flowchart of data collection, data analysis, and data visualization

Result and Discussion

Top Ten Most Cited Papers

The ten most cited papers are listed in Table 1. The most-cited paper, "AI and Education: A Guidance for Policymakers," by F. Miao, and W. Holmes, was published by book.google.com in 2021, with a total of 873 citations. Previous research has emphasized the importance of understanding which papers are most influential on other research through citation analysis to

understand the development of a research field (Kılınç, 2024). This study provides a guide for policymakers on the effective and ethical use of artificial intelligence (AI), presenting opportunities, challenges, risks, and impacts in establishing an inclusive, innovative, equitable, and sustainable education system aligned with the SDGs.

In general, the most cited papers were published between 2017 and 2025, indicating a growing interest in research on biology learning innovation and SDGs. This advancement enables data-driven systems and insights to generate new opportunities for expediting progress towards the SDGs (Gohr et al., 2025). The primary focus of the ten papers is the integration and transformation of technology, particularly artificial intelligence (AI), in biology education to achieve the Sustainable Development Goals (SDGs) in the context of the 4.0 Industrial Revolution.

Table 1. Top ten most cited papers

Cites	Authors	Title	Year	Publisher
873	F. Miao; W. Holmes	AI and education: A guidance for policymakers	2021	books.google.com
819	F. Annan-Diab; C. Molinari	Interdisciplinarity: Practical approach to advancing education for sustainability and for the sustainable development goals	2017	Elsevier
522	S.E. Gallagher; T. Savage	Challenge-based learning in higher education: an exploratory literature review	2023	Taylor &Francis
390	J. O'Flaherty; M. Liddy	The impact of development education and education for sustainable development interventions: a synthesis of the research	2018	Taylor &Francis
384	S. Albareda-Tiana; S. Vidal-Raméntol	Implementing the sustainable development goals at university level	2018	emerald.com
348	K.S. Uralovich; T.U. Toshmamatovich; K.F. Kubayevich; I.B. Sapaev	A primary factor in sustainable development and environmental sustainability is environmental education	2023	cjes.guilan.ac.ir
334	K.K.S. Oliveira; R.A.C. De Souza	Digital transformation towards education 4.0	2022	ceeol.com
225	W. Strielkowski; V. Grebennikova; A. Lisovskiy; G. Rakhimova; T. Vasileva	AI-driven adaptive learning for sustainable educational transformation	2025	Wiley Online Library
174	O. Bongomin; A. Yemane; B. Kembabazi; C. Malanda; M.C. Mwape; N.S. Mpofu; D. Tigalana	Industry 4.0 disruption and its neologisms in major industrial sectors: A state of the art	2020	Wiley Online Library
152	L.V. Ávila; T.A. Beuron; L.L. Brandli; L.I. Damke; R.S. Pereira; L.L. Klein	Barriers to innovation and sustainability in universities: an international comparison	2019	emerald.com

The Quantity of Scholarly Articles from 2016-2025

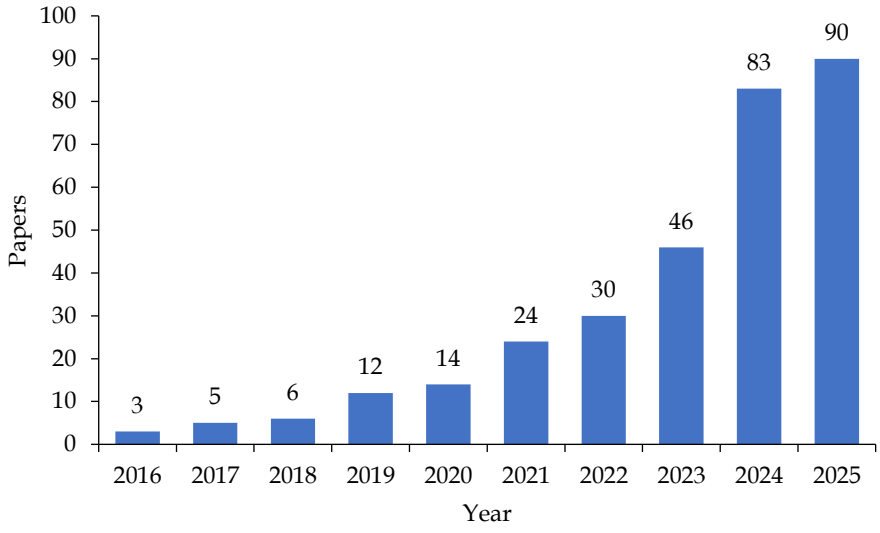

Figure 2. The quantity of scholarly articles on innovations in biology education focused on developing 21st century competencies and supporting the sustainable development goals from 2016 to 2025

Figure 1 illustrates a marked increase in the number of publications concerning innovations in biology education that integrate 21st-Century Skills with the Sustainable Development Goals (SDGs) from 2016 to 2025. The 2016–2018 period is considered an early stage, producing only 3 to 6 articles per year, signaling the beginning of research on this topic. From 2019 to 2021, the number of publications increased steadily from 12 in 2019, 14 in 2020, and 24 in 2021, indicating the beginning of this research trend and increasing awareness among researchers and academics of the importance of integrating biology learning with 21st-Century Skills to achieve the SDGs. The research trend peaked between 2022 and 2025, significantly increasing from 30 papers in 2022 to 90 papers in 2025, approximately eight times the previous period. The results of learning reflections have caused a shift in the research focus to global issues relevant to the 2030 agenda and the orientation of 21st-century learning (Sayadi & Pangandaman, 2025; Tarlochan et al., 2025).

Top Ten Contributing Countries

Based on the graphical analysis in Figure 2, top ten contributing countries in this research over the past ten years are Indonesia, with 70 papers. The United Kingdom ranked second with 56 papers. The United States ranked second, with 33 papers, followed by Germany, with 26 papers, and Switzerland, with 13 papers. Indonesia's success in contributing to this research is closely related to the frequent changes in its education system, especially the curriculum. These changes constantly demand innovation and learning updates so that teaching skills transcend the classroom. These competencies encompass the capacity to develop and implement innovative pedagogical strategies that facilitate student learning in alignment with the evolving demands of 21st-century transformations (Jayanti et al., 2024).

Curriculum changes that demand biology teaching methods that align with 21st-century education demonstrate that learning should not only focus on understanding ideas but also build awareness of the skills, attitudes, and knowledge that students need to become active and useful members of society (Olsson et al., 2022). Furthermore, this trend is reinforced by Indonesia's vast geographic area, large population, and widespread distribution of educational institutions, providing a base for educators to engage in teaching and research (Sari et al., 2025). Consequently, many educators and researchers in Indonesia are developing innovative learning models to strengthen 21st-century skills and support SDG achievement.

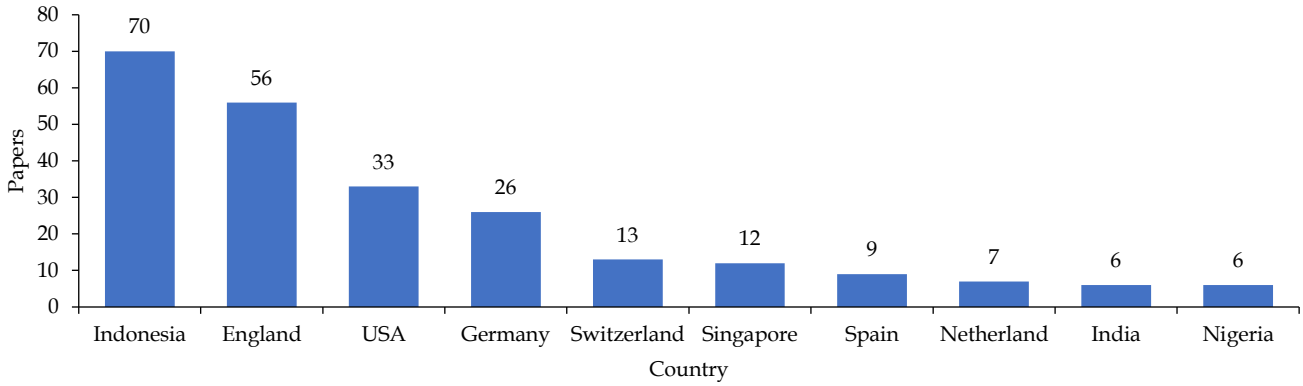

Figure 3. The ten contributing countries in biology learning innovation research to support 21st century skills and SDGs

Most Prolific Publishers

Based on Figure 4, the graph shows that there are a number of publishers dominating the number of publications. Springer Publishers holds the top ranks as the most productive publisher, with 42 published works. Springer has made a considerable contribution to the development of this research. The next position is filled by Taylor & Francis and ERIC, with a smaller number of publications each, but still has a major contribution to the existence of this research. The dominance seen in the graph shows that this research is widely published by reputable, large international publishers. A company with a good reputation will indirectly gain trust and appreciation from the market because a good reputation benefits all parties (Castilla-Polo & Sánchez-Hernández, 2025). This indicates that the existence and visibility of research topics are highly dependent on large publishers, as they act as the main key to influencing the reach, credibility, and accessibility of research results in the academic world.

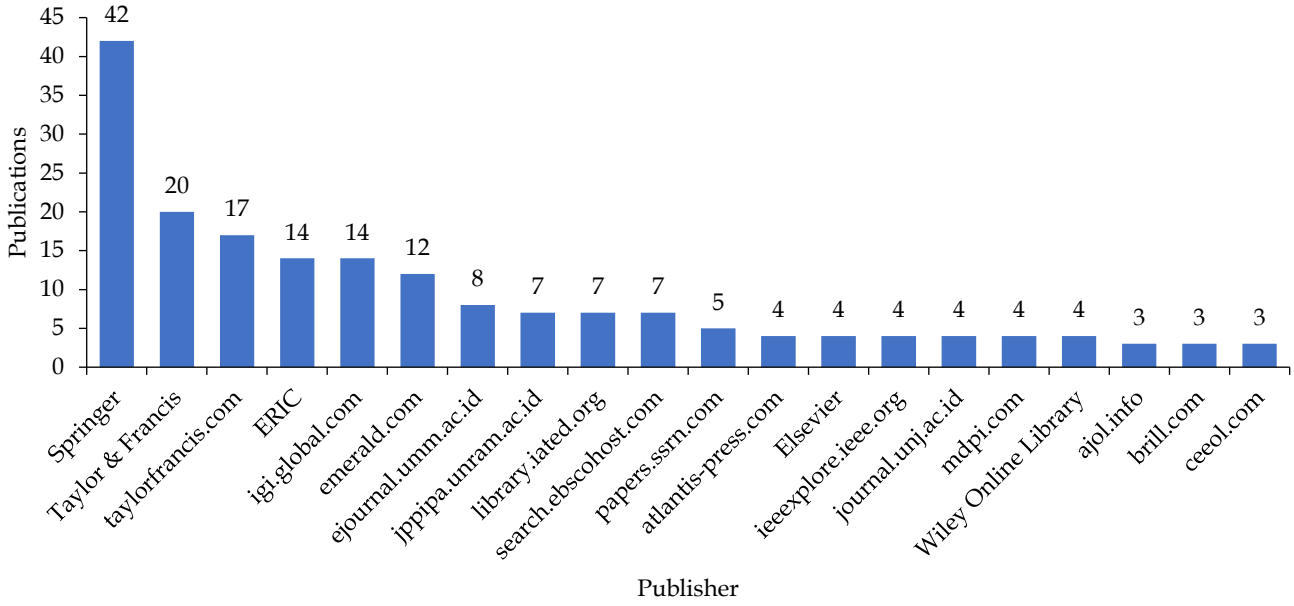

Figure 4. The most prolific publishers

Most Widely Adopted Learning Innovations

Data analysis is illustrated in Figure 5, which shows that 171 of the 313 papers specifically discussed and analyzed the implementation of learning models/approaches that support 21st-century skills and the SDGs. Specifically, Science, Technology, Engineering, and Mathematics (STEM)/Science, Technology, Engineering, Art, and Mathematics (STEAM) was the most widely used and discussed approach in this study, with 36 articles (21%). STEM learning connects science, technology, and other closely related and inseparable disciplines (Afriana et al., 2016). Project Based Learning (PjBL) was the second most widely discussed model, with 19 articles (11%). PjBL can help students address complex problems that require investigation and understanding (Rosaria et al., 2023). Problem Based Learning (PBL) was the third most popular model, with 11 articles (6%). The implementation of PBL can facilitate students in constructing their own knowledge, enhancing critical thinking skills, and promoting self-confidence and autonomy in problem-solving (Mutiara et al., 2024).

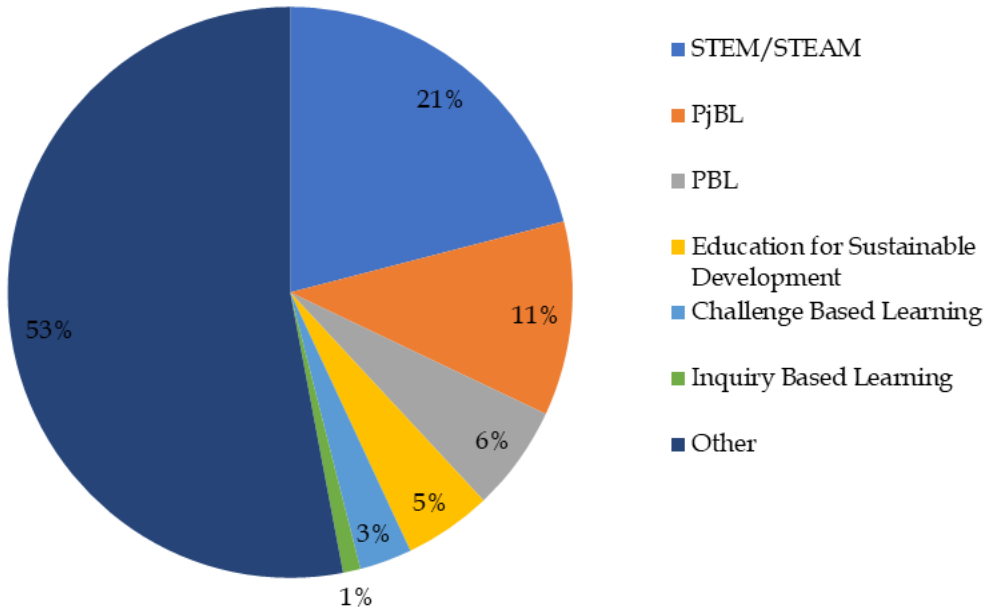

Figure 5. The most widely adopted learning innovations

Most Relevant and Trending Keywords

Researchers studying technology often use a method called co-occurrence analysis. This is a way to measure how frequently certain keywords appear together when looking at a large body of data (Scharp, 2021). The goal of this analysis was to find and organize the main ideas represented by these keywords (Hidayat et al., 2024). Keywords were automatically grouped into different clusters using VOSViewer's built-in clustering algorithm (Huang et al., 2025). Observing the co-occurrence of keywords, we found 66 items, consisting of 7 clusters, 476 links, and 842 total link strengths. The items in this network can be connected through co-mentions or citations from various scientific databases and reference management tools such as RIS (Martins et al., 2024). This information is based on the analysis shown in Figure 6. The most frequently presented learning model/approach keywords are "STEM Education" with a total of 17 occurrences, followed by "Project Based Learning" with 12 occurrences, then "Problem Based Learning" with 8 occurrences, and so on.

In addition to co-occurrence, Table 2 also shows the dominance of the use of learning innovation (STEM/STEAM, PjBL, and PBL) compared to other models/approaches based on the number of links and total link strength. In line with previous research, STEM/STEAM (links: 27, TLS: 50) can condition students to learn to use technology in experimental activities that prove and connect a science concept (Putri et al., 2023a). PjBL (links: 19, TLS: 25) is ranked second because the application of this model based on the 4C framework which consists of critical thinking, communication, collaboration, and creativity to encourage students to solve real-world and meaningful problems through project design as its goal (Battele for Kids, 2019; Subiki et al., 2023; Tafakur et al., 2023). The third most popular model is PBL (links: 16, TLS: 24), which can help develop and improve creative thinking and effective problem-solving skills in students (Oktavia et al., 2025).

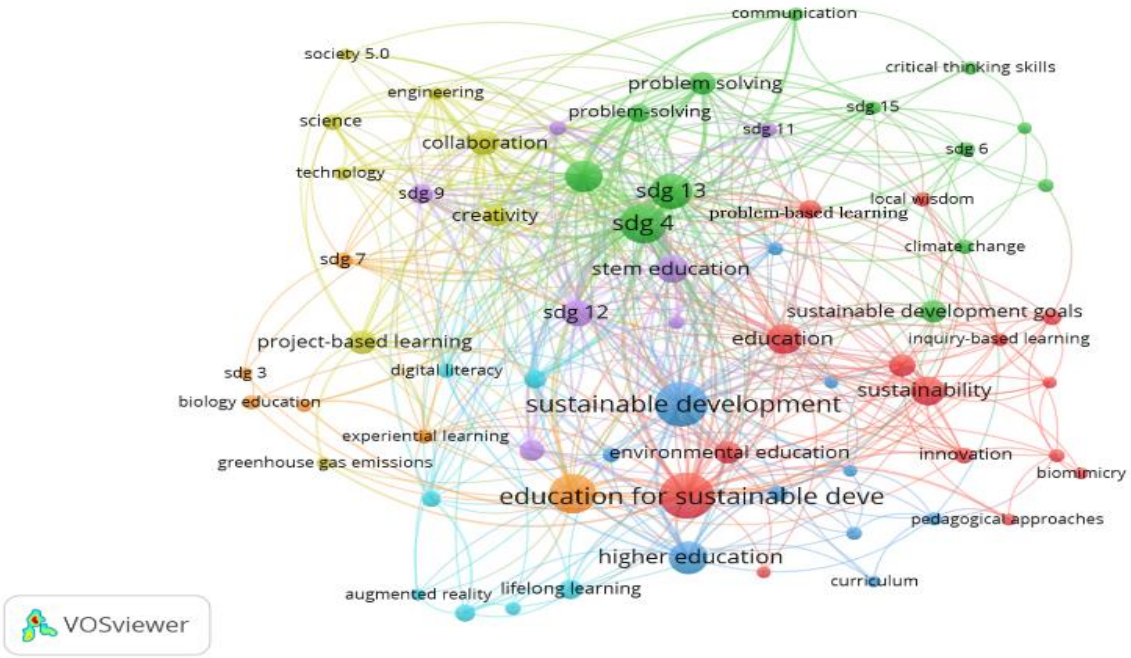

Figure 6. Network map showing co-occurrence of keywords

Table 2. Co-Occurrence of Learning Models, 21st Century Skills, and SDGs keywords

Clusters	Item	Links	Total Link Strength	Occurrences
1 (Red)	Inquiry-based learning	12	13	4
	Interdisciplinary learning	8	8	4
	Pedagogical approaches	4	6	3
	Problem based learning	16	24	8
	Scientific literacy	11	11	6
2 (Green)	Communication	10	16	4
	Critical thinking	35	86	22
	Problem solving	25	48	11
	SDG 13	35	117	28
	SDG 15	13	20	4

Clusters	Item	Links	Total Link Strength	Occurrences
	SDG 4	44	143	33
	SDG 6	10	12	5
3 (Navy)	Environmental awareness	8	8	3
	Environmental literacy	14	18	4
	Indigenous knowledge	9	9	4
4 (Yellow)	Collaboration	29	75	14
	Creativity	26	52	10
	Project-based learning	19	25	12
5 (Purple)	SDG 11	17	25	5
	SDG 12	30	75	16
	SDG 8	16	24	5
	SDG 9	21	46	9
	Stem education	27	50	17
	System thinking	11	15	4
6 (Blue)	Digital literacy	14	20	5
	SDG 17	20	33	8
7 (Orange)	Design thinking	6	8	4
	SDG 3	4	4	3
	SDG 7	13	18	6

The Role of the Three Predominant Learning Models in Enhancing 21st Century Skills to Achieve the Sustainable Development Goals (SDGs)

Table 3. Top three predominant learning models and distribution of the top 5 21st century skills

Learning Models	21st Century Skills Related (Percentage)
STEM/STEAM	Critical thinking (33%)
	Creativity (31%)
	Problem solving (25%)
	Collaboration (22%)
	Digital literacy (11%)
Project based learning (PjBL)	Critical thinking (37%)
	Problem solving (26%)
	Creativity (21%)
	Collaboration (16%)
	System thinking (11%)
Problem based learning (PBL)	Problem solving (64%)
	Critical thinking (36%)
	Collaboration (18%)
	Scientific literacy (18%)
	Analitycal thinking (9%)

STEM/STEAM is the most dominant innovation compared with the other two learning models. Integration of various aspects of science into learning allows STEM to connect broader concepts and have a direct impact on learning (Lafifa et al., 2023; Rahmawati et al., 2025). Based on the results of this study (Table 3), STEAM can encourage critical thinking (33%), creativity (31%), and problem solving (25%). The implementation of STEM, which underlies various scientific disciplines and complex systems with the principles of systems thinking, is highly relevant for application to high-level cognitive objectives in laboratory or technical contexts (Husun et al., 2025; Li et al., 2020; Momsen et al., 2022). STEM can also develop students' cognitive skills through effective real-life problem-solving (Hebebci & Usta, 2022; Istiana et al., 2021). Referring to the keyword map in Figure 7, the publication database (n = 313) shows that STEM directly supports SDG 4 (quality education) and SDG 13 (climate action). Furthermore, STEM is also related to SDG 6 (Clean Water), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 11 (Sustainable Cities and Communities). Given its interdisciplinary nature and focus on the application of technology and engineering to global problems, it is necessary to design climate change mitigation solutions (Hakim et al., 2023). The bibliometric dominance of this study shows that STEM/STEAM not only has a high frequency but is also the most comprehensive in strengthening 21st-century skills and the SDGs.

The findings of this study reveal that PjBL supports 21st-century skills through project-based activities in real contexts, effectively encouraging students to actively think critically in analyzing problems (37%), solving problems (26%), and designing creative solutions (21%), going beyond mere conceptual understanding. PjBL encourages students to create a product as a solution to a given problem and provides significant benefits from the process (Purbianti et al., 2025; Wróblewska & Okraszewska, 2020). In addition, clear and challenging criteria and guidelines increase student engagement because they encourage students to build their own knowledge through investigation and discussion (Lozano et al., 2022; Selasmawati & Lidyasari, 2023). Based on keywords from the database (n = 313), it can be confirmed in Figure 7 that PjBL also plays a role in advancing SDGs 4 (Quality Education). Through project activities, a sense of ecological and social responsibility can be fostered as a non-academic output as part of the goals of 21st century education (Condliffe et al., 2017).

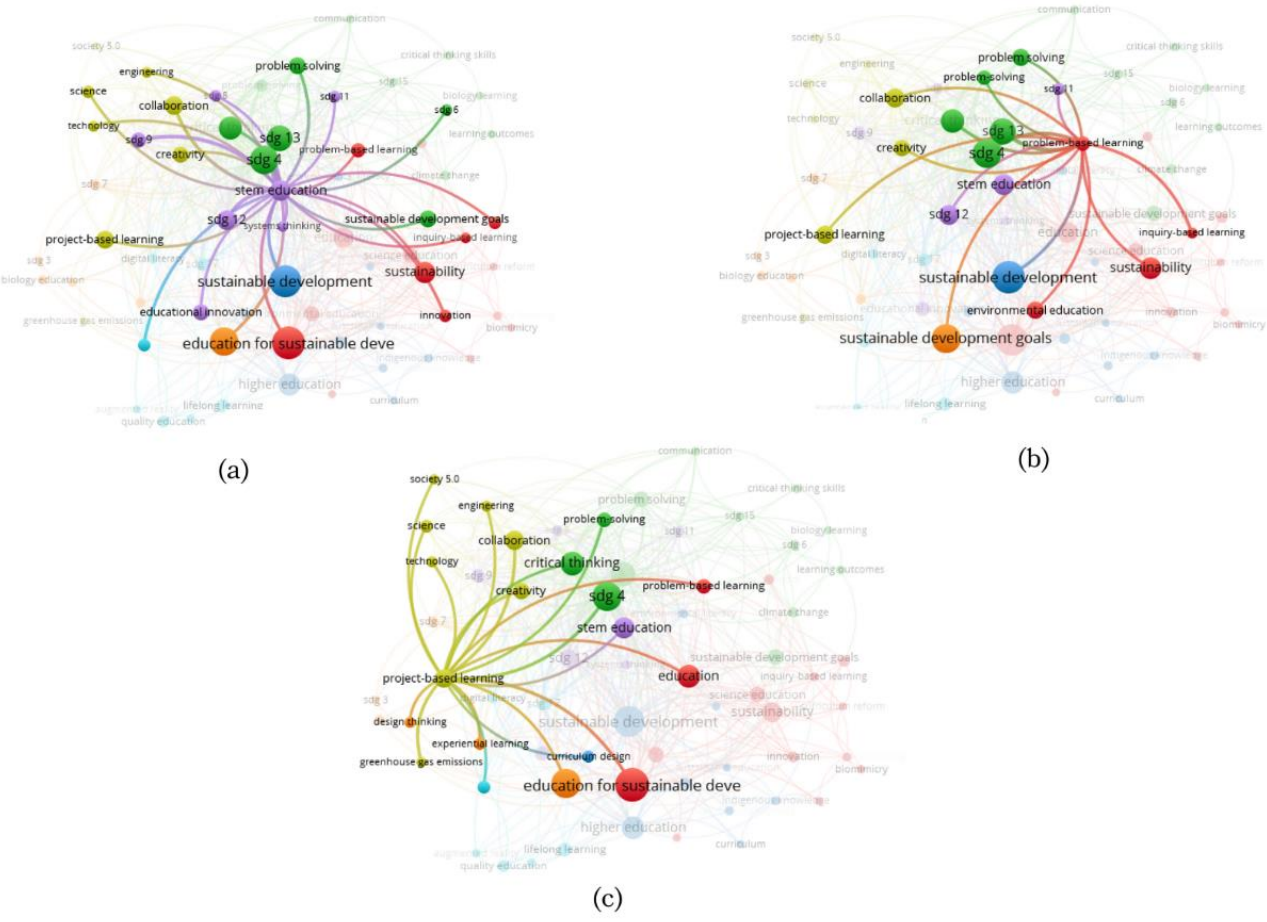

Figure 7. Network map of the (a) STEM approach (b) Project based learning model (c) Problem based learning model

Problem Based Learning (PBL) is equally important in strengthening 21st century skills, such as problem-solving (64%), critical thinking (36%), and collaboration (18%), especially in learning contexts that require in-depth analysis, case-based discussions, and scientific inquiry (Fitria et al., 2023). Previous research has revealed that the PBL model has characteristics that can engage students in problem-solving, thereby stimulating active, critical, creative, and collaborative attitudes toward learning (Putri et al., 2023b). The PBL model can produce a student-centered problem-solving process through communication skills and empathy towards real-life environmental issues (Ilwandri et al., 2023; Sunarni & Wakhudin, 2025). This can be confirmed by Figure 7, which also shows that Problem-Based Learning is related to SDG 4 (quality education) and SDG 13 (climate action), similar to the STEM/STEAM model. Furthermore, it is related to SDG 11 (sustainable cities and communities) and SDG 12 (responsible consumption and production). Quality education remains the primary focus of Problem Based Learning, although it can also change mindsets regarding consumption behavior and lifestyles, thereby reducing the ecological footprint (García-González et al., 2022; Nguyen et al., 2024).

These findings suggest that the STEM/STEAM approach, PjBL, and PBL transcend mere pedagogical strategies for skill development. They function as comprehensive learning frameworks that integrate higher-order cognitive processes and sustainability-oriented values within biology education, particularly when addressing complex challenges related to the Sustainable Development Goals (SDGs). However, this study has limitations inherent in bibliometric analysis, as findings are derived from publication metadata and thematic relationships that reflect research trends rather than empirical evidence of instructional effectiveness. The results may be influenced by database selection, document types, and keyword constraints. The practical implementation of these frameworks depends on contextual factors such as teacher preparedness, curriculum adaptability, and institutional support, which cannot be fully captured through bibliometric approaches. Future research is necessary to reinforce these findings through meta-analytical, quasi-experimental, or longitudinal research designs that examine the effectiveness and contextual variability of these learning models across diverse educational settings.

Conclusion

This bibliometric study identifies Indonesia as the leading nation in terms of productivity within this research, surpassing both the United Kingdom and the United States. This finding reflects Indonesia's dynamic education system and its diverse geographical and demographic contexts. The analysis reveals that STEM/STEAM, Project-Based Learning (PjBL), and Problem-Based Learning (PBL) are highly relevant for enhancing 21st-century skills while supporting Sustainable Development Goals (SDG) 4 and SDG 13. Among these educational approaches, STEM/STEAM is identified as the most comprehensive model, fostering creativity through integrated scientific learning. This is followed by PjBL, which emphasizes critical thinking through SDG-oriented, real-world projects that promote ecological and social responsibility, and PBL, which effectively develops analytical problem-solving skills through case-based learning. Collectively, these educational innovations align with broader sustainability agendas, including SDG 6, SDG 9, SDG 11, and SDG 12. However, their successful implementation is contingent upon contextual factors such as teacher readiness, curriculum flexibility, and institutional support, highlighting the need for further empirical research across diverse educational levels and learning environments.

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Author Contributions

I.R. contributed to the conceptualization, methodology, software utilization, data analysis, investigation, data curation, visualization, drafting of the original manuscript, writing observations and proof of concept, and project administration; D.D.R.T. was involved in conceptualization, methodology, resource acquisition, validation, supervision, and writing insights and proofs of concept. All authors have reviewed and approved the final version of this manuscript for publication.

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Conflicts of Interest

The authors declare that there are no conflicts of interest associated with the publication of this scientific article.

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