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USE OF TECHNOLOGY AND DIGITAL TOOLS IN SECONDARY BIOLOGY TEACHING FROM 2016 TO 2025: INSIGHTS FROM A BIBLIOMETRIC ANALYSIS

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Abstract:
The rapid integration of technology and digital tools has significantly transformed secondary biology teaching, reshaping instructional practices and learning environments worldwide. This study examined global research trends on the use of technology and digital tools in secondary biology teaching from 2016 to 2025 through a bibliometric analysis of Scopus-indexed publications. Using a descriptive bibliometric research design, the study analyzed publication growth, authorship patterns, country and institutional productivity, thematic trends, keyword co-occurrence, and collaboration networks, all analyzed using VOSviewer software. Findings revealed a consistent increase in research productivity, particularly after 2020, reflecting the growing global emphasis on digital learning and technology-enhanced science instruction. Frequently occurring themes included digital learning tools, virtual laboratories, online and blended learning, student engagement, inquiry-based learning, and pedagogical innovation. Emerging themes highlighted artificial intelligence (AI), augmented reality (AR), virtual reality (VR), learning analytics, and teacher professional development. Collaboration analysis showed that developed countries dominated scholarly production, while developing regions demonstrated limited participation, indicating disparities in technological access and research capacity. The study further revealed that technology integration positively influenced conceptual understanding, learner motivation, inquiry skills, and interactive learning experiences in secondary biology education. However, challenges such as inadequate infrastructure, limited teacher digital competence, insufficient professional development, and unequal access to digital resources remained significant barriers. The findings emphasized the need for curriculum reforms, sustained teacher training, and stronger institutional support systems to maximize the educational potential of digital technologies. Overall, this study provided a comprehensive mapping of global research patterns and gaps in technology-enhanced secondary biology education. The results provided evidence-based insights for policymakers, curriculum developers, educators, and future researchers to improve instructional practices and

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strengthen digital integration in biology teaching, particularly within the Philippine educational context.

Keywords: technology integration; digital tools; secondary biology teaching; bibliometric analysis; science education; Scopus

1. Introduction

Education has long been recognized as a fundamental pillar of human development and societal progress. In the 21st century, however, traditional paradigms of teaching and learning have faced unprecedented challenges brought about by globalization, rapid technological advancement, and the increasing demand for lifelong learning skills (Bybee, 2013). These transformations have significantly influenced educational practices, particularly in science education, where visualization, inquiry, and interactive learning are essential components of meaningful instruction. In biology education, students frequently encounter difficulties in understanding abstract and complex concepts such as cell division, genetics, molecular processes, and ecological interactions because these topics involve microscopic and highly intricate systems (Tekkaya, Özkan, & Sungur, 2001). Traditional teaching approaches that rely heavily on memorization and textbook-based instruction often limit students' conceptual understanding, critical thinking, and engagement, especially in resource-constrained learning environments.

To address these challenges, educational institutions worldwide have increasingly integrated technology and digital tools into science instruction. Digital innovations such as virtual laboratories, augmented reality (AR), simulations, digital microscopes, mobile applications, and artificial intelligence (AI)-supported platforms have enhanced students' ability to visualize biological structures and processes while promoting inquiry-based and student-centered learning approaches (Ibáñez & Delgado-Kloos, 2018; Makransky, Terkildsen, & Mayer, 2019). Numerous studies have demonstrated that these technologies improve students' conceptual understanding, motivation, collaboration, engagement, and higher-order thinking skills in biology classrooms. The growing adoption of digital learning environments further highlights the importance of technology integration in ensuring continuity, accessibility, and quality in science education.

Despite these advantages, the integration of technology in secondary biology education remains inconsistent, particularly in developing countries such as the Philippines. Challenges such as limited technological infrastructure, inadequate access to digital resources, insufficient teacher training, and varying levels of digital competence continue to hinder effective implementation of technology-enhanced instruction (Ertmer & Ottenbreit-Leftwich, 2010; Scherer, Howard, & Tondeur, 2021). In the Philippine educational context, policy initiatives have encouraged the use of technology to improve teaching and learning processes. The Department of Education, through the MATATAG Curriculum under DepEd Order No. 010, s. 2024, emphasized digital literacy, inquiry-

based learning, and contextualized pedagogy to enhance instructional delivery. Likewise, the UNESCO ICT Competency Framework for Teachers (2018) advocated the integration of digital tools to promote knowledge creation, innovation, and effective learning environments.

The integration of technology in biology teaching can be better understood through several theoretical and conceptual frameworks. The Technological Pedagogical Content Knowledge (TPACK) framework emphasizes the alignment of technology, pedagogy, and content knowledge to achieve effective instruction (Mishra & Koehler, 2006; Koehler & Mishra, 2009). Similarly, the Diffusion of Innovations Theory explains how technological innovations spread and are adopted within social systems (Rogers, 2003). Meanwhile, Socio-Technical Systems Theory posits that successful technology integration occurs only when technical systems are aligned with social and organizational structures (Trist & Bamforth, 1951; Baxter & Sommerville, 2011). Constructivist Learning Theory further supports the use of interactive and technology-enhanced environments that allow learners to construct knowledge through active exploration, inquiry, and engagement (Piaget, 1970; Vygotsky, 1987). These theoretical perspectives collectively suggest that successful technology integration depends not only on access to digital tools but also on teachers' pedagogical readiness, institutional support, and the effective alignment of technological and instructional practices.

The integration of digital technologies in biology education has expanded rapidly since 2016, driven by the growing need to visualize complex scientific processes and provide more interactive, student-centered learning experiences (Hsu, Cheah, & Hughes, 2023; Trust, Krutka, & Carpenter, 2016). Digital tools have become increasingly valuable in teaching complex biological concepts such as microscopic cell structures, DNA replication, gene expression, homeostasis, and ecological dynamics (Chou, Chang, & Lin, 2020). Virtual laboratories and simulations provide safe and scalable environments for conducting biological experiments, particularly in schools with limited laboratory resources (Makransky & Petersen, 2019). Virtual reality (VR)-based laboratories have also gained popularity because they offer immersive environments that improve retention and visualization of scientific concepts (Radianti et al., 2020). Furthermore, augmented reality applications have been shown to enhance students' spatial reasoning skills, which are crucial for understanding three-dimensional biological structures and processes (Akçayır & Akçayır, 2017; Chein et al., 2020). Mobile learning environments likewise enable students to review and explore biological concepts beyond the classroom, thereby supporting continuous and personalized learning experiences (Lee & Han, 2017). In addition, app-based formative assessment tools have improved feedback mechanisms and learner engagement in digital biology instruction (Bai & Guo, 2021). Research also indicates that biology teachers with strong ICT proficiency are significantly more likely to adopt, sustain, and innovate technology-enhanced learning experiences within their classrooms (Philipsen et al., 2019).

Previous studies have revealed that digital tools such as simulations, augmented reality models, and interactive videos significantly improve conceptual understanding

and conceptual change in topics including photosynthesis, respiration, and cell division (Lacey, Francis, & Smith, 2024). Similarly, game-based and interactive technologies provide practical and engaging pathways for enhancing biology learning, even in resource-constrained educational settings (Dicheva et al., 2015; Hamari et al., 2016). Despite the growing body of literature on educational technology in science education, there remains a need to systematically examine publication trends, major contributors, emerging themes, and research gaps in the field of technology integration in secondary biology teaching. Bibliometric studies conducted from 2016 to 2025 reported a significant increase in publications related to augmented reality, virtual reality, mobile learning, and AI-enhanced technologies in science education (Spatioti, Kazanidis, & Pange, 2022). However, limited studies have synthesized these developments specifically within the context of secondary biology education and their implications for teaching practice, curriculum development, and policy implementation.

Therefore, this study aims to examine the trends and developments in the use of technology and digital tools in secondary biology teaching through a bibliometric analysis of publications from 2016 to 2025. Specifically, the study seeks to identify major publication trends, influential authors, leading countries and institutions, frequently occurring keywords, and emerging research themes in the field. The findings of this study are expected to provide evidence-based insights that may contribute to curriculum enhancement, teacher professional development, instructional innovation, and effective technology integration in biology education, particularly within the Philippine educational context.

2. Methodology

This study employed a bibliometric review design to examine research trends, thematic patterns, and scholarly contributions related to the use of technology and digital tools in secondary biology education from 2016 to 2025. Bibliometric analysis is a quantitative research approach used to evaluate scientific publications through citation patterns, keyword relationships, authorship networks, and publication productivity. The study also utilized a scoping approach to map the extent and nature of existing literature within the field.

The data source for this study was the Elsevier Scopus database, selected due to its extensive coverage of peer-reviewed international publications. Relevant studies were retrieved using customized Boolean search strings applied in the TITLE-ABS-KEY field. The search combined terms related to biology education, teaching, and learning, and technology integration, including “digital tools,” “ICT,” “virtual laboratories,” “augmented reality,” “mobile learning,” and “technology integration.” The search was limited to publications from 2016 to 2025 and included journal articles, conference papers, review papers, and book chapters published in English (see Table 1).

The inclusion criteria covered studies focused on the integration of technology and digital tools in secondary biology or science education. Publications unrelated to biology

instruction, higher education-only contexts, or non-digital instructional approaches were excluded. The screening process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure systematic identification and selection of relevant studies (see Figure 1).

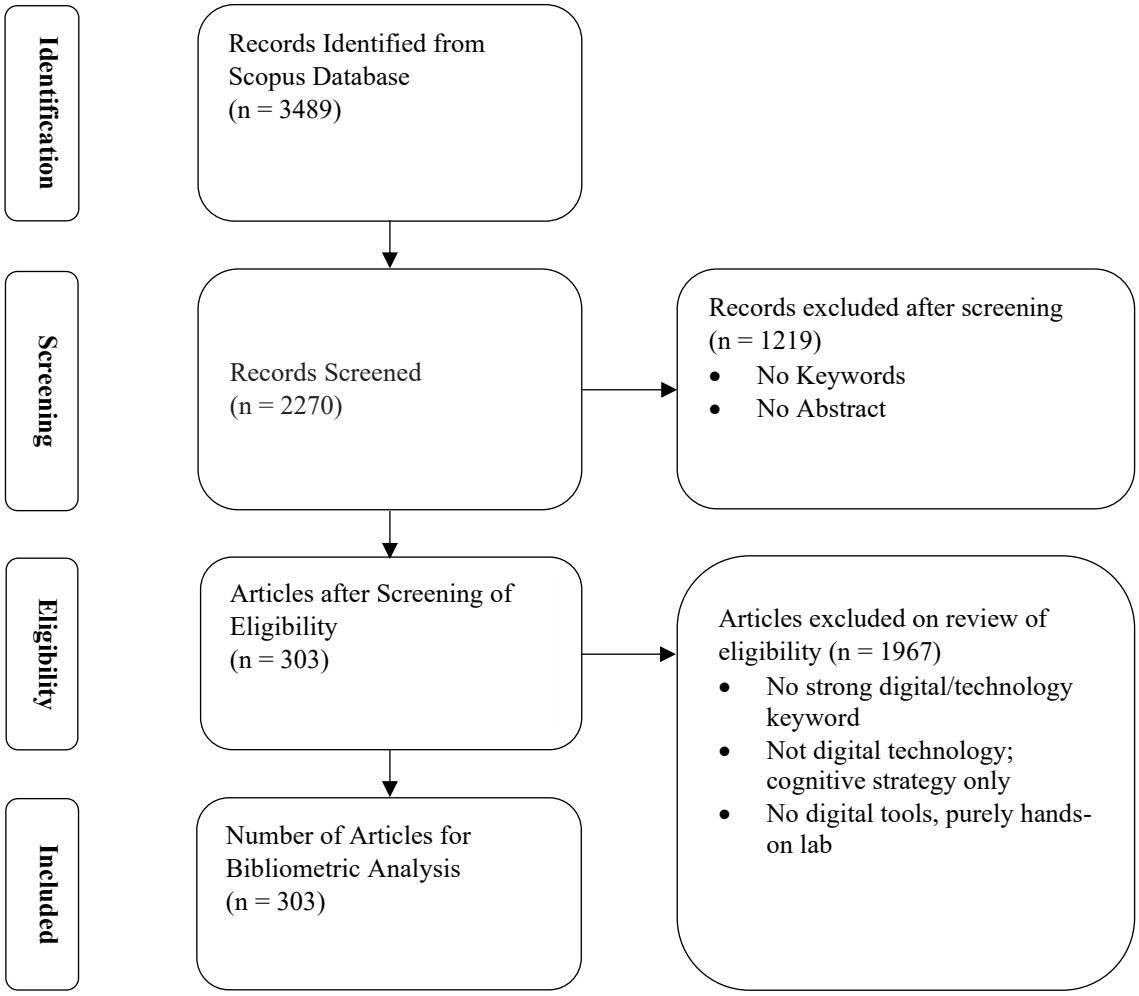

Figure 1: Prisma Method Procedure for Identifying Selecting the Documents

Initially, 3,489 records were identified from the Scopus database. After title, abstract, and keyword screening, irrelevant and duplicate records were removed. A final dataset of 303 publications met the inclusion criteria and was included in the bibliometric analysis. Metadata were exported in CSV and RIS formats for processing and analysis.

The search strategy and Boolean search string were developed based on the inclusion criteria for studies related to technology integration in secondary biology teaching (see Table 1). The search query was conducted in Scopus using the TITLE-ABS-KEY field, which limits the results to documents containing the search terms in the title, abstract, or author keywords. This approach helped ensure the conceptual relevance of the selected studies.

The search string was comprehensive and combined terms related to teaching, learning, instruction, and education with various technology-related keywords,

including "technology," "digital tool*," "ICT," "educational technology," "digital learning," "online learning," "e-learning," "virtual lab*," "simulation*," "augmented reality," "virtual reality," "mobile learning," "game-based learning," "digital platform*," "blended learning," "learning management system," "virtual classroom," and "technology integration."

Data retrieved from Scopus using the Boolean search strategy covered publications from 2016 to 2025 and focused on the integration of technology and digital tools in secondary biology and life sciences education. The search strategy incorporated terms related to biology, science education, STEM, teaching and learning strategies, and a broad range of technological tools, such as virtual laboratories, augmented and virtual reality, mobile learning, simulations, and learning management systems.

The scope of the search was multidisciplinary, encompassing subject areas such as social sciences, psychology, computer science, engineering, agricultural and biological sciences, and medicine. The inclusion criteria covered various document types, including journal articles, conference papers, book chapters, and review articles. In addition, only English-language publications from journals and conference proceedings were included to ensure a diverse and representative dataset of current research trends in technology-enhanced secondary science education.

Table 1: Search Strategy and Boolean Search String

Parameter	**Inclusion Criteria**
Database	Scopus
Search String	TITLE-ABS-KEY (("biology" OR "life science*" OR "science education" OR "STEM education") AND ("teaching" OR "learning" OR "instruction" OR "education") AND ("technology" OR "digital tool*" OR "ICT" OR "educational technology" OR "digital learning" OR "online learning" OR "e-learning" OR "virtual lab*" OR "simulation*" OR "augmented reality" OR "virtual reality" OR "mobile learning" OR "game-based learning" OR "digital platform*" OR "blended learning" OR "learning management system" OR "virtual classroom" OR "technology integration") AND ("secondary education" OR "high school" OR "junior high" OR "senior high" OR "K-12" OR "middle school" OR "secondary student*"))
Time Span	2016 – 2025
Subject Area	Social Sciences, Arts & Humanities, Psychology, Computer Science, Engineering, Decision Sciences, Agricultural & Biological Sciences, Environmental Science, Earth & Planetary Sciences, Biochemistry, Genetics & Molecular Biology, Medicine, Multidisciplinary
Document Type	Article, Conference Paper, Book Chapter, Review
Source Title	All
Publication Stage	Final
Keyword	All
Affiliation	All
Funding Sponsor	All
Country/Territory	All
Source Type	Journal and Conference Proceedings
Language	English
Open Access	All

Descriptive statistics, including frequency counts and citation metrics, were used to identify research productivity and influence within the field. Keyword co-occurrence analysis was applied to determine major thematic clusters and emerging topics in technology-enhanced biology education. Collaboration networks among authors, institutions, and countries were also analyzed to identify patterns of scholarly cooperation and research development. The findings were interpreted quantitatively and qualitatively to provide insights into global research trends and their implications for secondary biology teaching, curriculum development, and technology integration, particularly within the Philippine educational context.

3. Results and Discussion

3.1 Main Contributors: Publication Trends and Patterns over time in Technology and Digital Tools in Secondary Biology Teaching

The bibliometric analysis of Scopus data from 2016-2025 identified a total of 303 documents published across 123 sources, with an annual growth rate of 8.24%, indicating steadily increasing interest in the integration of technology and digital tools in biology education. The documents had an average age of 3.71 years and an average of 7.684 citations per document, supported by 2,637 references, reflecting the field's emerging yet growing scholarly impact. A total of 1,244 Keywords Plus and 915 authors' keywords were identified, demonstrating diverse research themes related to technology-enhanced biology teaching. In terms of authorship, 1,125 authors contributed to the publications, with only 30 single-author papers, while the average of 4.08 co-authors per document and 11.18% international collaboration indicated that research in the field is largely collaborative. Among the document types, journal articles comprised the majority (181), followed by conference papers (111) and book chapters (11), highlighting peer-reviewed journals as the primary platform for disseminating research findings in this area (See Table 2, 3).

The findings highlight a growing, collaborative, and diverse research landscape in technology-enhanced biology education, with increasing publication output and expanding thematic focus over time.

Table 2: Main Contributors: Publication Trends and Patterns Over Time (2016-2025) in Research on Technology and Digital Tools in Secondary Biology Teaching

General Information	Results
Data Set Properties	
Timespan	2016:2025
Sources (Journals, Books)	123
Document	303
Annual Growth Rate (%)	8.24
Document Average Age	3.71
Average Citations per Document	7.684

References	2637
Document Contents	
Keywords Plus (ID)	1244
Author's Keywords (DE)	915
Authors	
Authors	1125
Authors of Single-Authored Docs	30
Authors Collaboration	
Single-authored Docs	35
Co-authors per Doc	4.08
International co-authorships (%)	11.18
Document Types	
Article	181
Book Chapter	11
Conference Paper	11

Table 3: Publication Trends and Patterns Over Time (2016-2025)

Year	Mean TC per Art	N Art	Mean TC per Year	Citable Years
2016	12.56	25	1.26	10
2017	12.70	20	1.41	9
2018	16.50	16	2.06	8
2019	11.56	27	1.65	7
2020	9.12	26	1.52	6
2021	8.50	36	1.70	5
2022	9.10	30	2.28	4
2023	7.25	28	2.42	3
2024	2.70	44	1.35	2
2025	1.06	51	1.06	1

Note: TC = Total Citation, N Art = Number of Articles.

The findings suggest that technology integration in biology education has evolved into a rapidly expanding research domain characterized by sustained scholarly engagement and increasing academic relevance. The growing number of studies also reflects the global shift toward learner-centered and digitally supported science instruction.

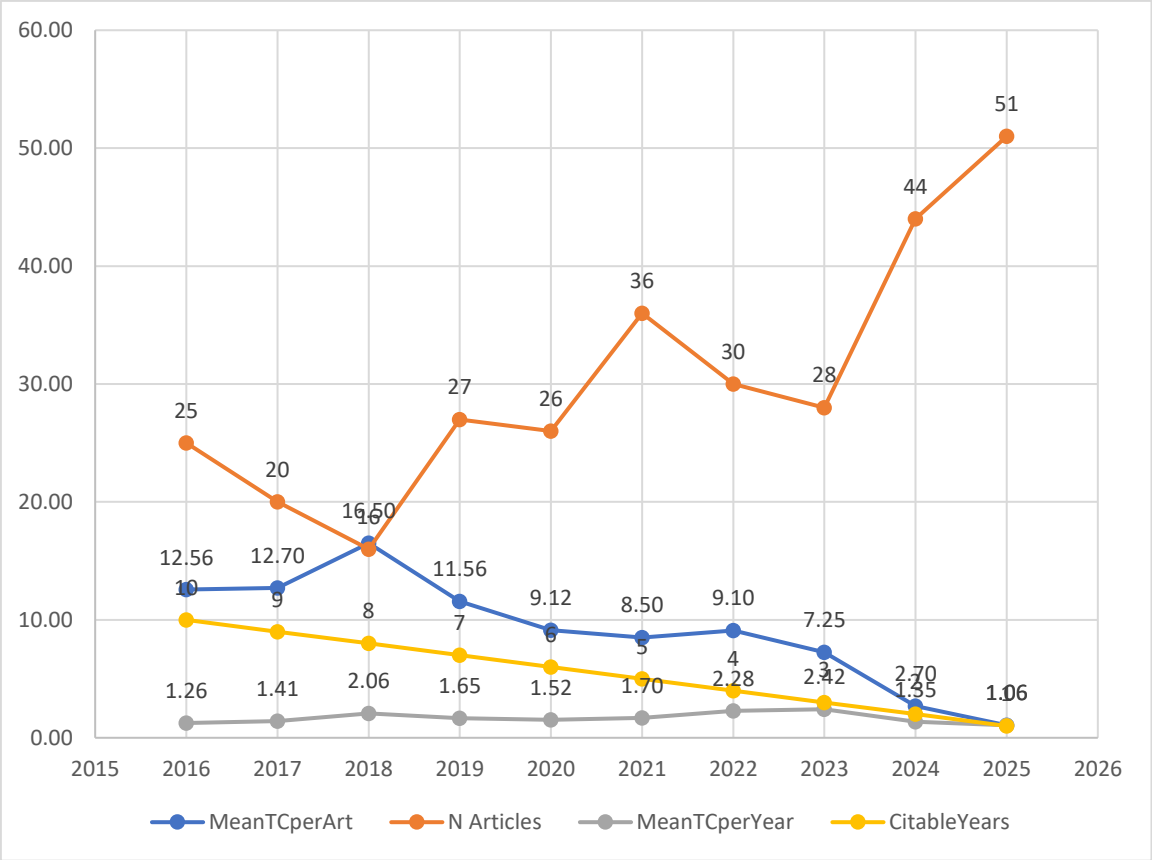

Figure 2: Publication Trends and Patterns Over Time (2016-2025)

3.2 Contribution of Countries, Institutions, Authors, Journals, and Scholarly Collaboration Patterns

The analysis identified the United States as the leading contributor to research on technology integration in secondary biology education, followed by Indonesia, China, and the Philippines. This pattern highlights the dominant role of developed and emerging economies in advancing digital innovation in science education. Several universities, including Northwestern University and Khon Kaen University, emerged as major institutional contributors, reflecting the significant role of higher education institutions in promoting technology-enhanced biology instruction (see Tables 4, 5, 6, 7).

Among publication venues, American Biology Teacher and other technology-oriented educational journals demonstrated substantial research productivity, emphasizing the importance of discipline-specific journals in disseminating innovations in biology teaching and learning.

Collaboration network analysis further revealed that research in the field is highly collaborative, with an average of 4.08 co-authors per publication. International collaboration networks were primarily concentrated among countries with strong research infrastructures, particularly the United States, China, Australia, and several European countries. However, collaboration involving developing countries,

institutions, journals, and authors, remained comparatively limited, indicating unequal global participation in educational technology research (see Figures 3, 4, 5, 6, 7, 8).

Table 4: Countries Contributed to Research on Technology Integration in Secondary Biology Education

Country	No. of Articles
United States of America	289
Indonesia	47
China	44
Philippines	25
Thailand	19
Chile	17
Turkey	17
Australia	16
Germany	15
Greece	15

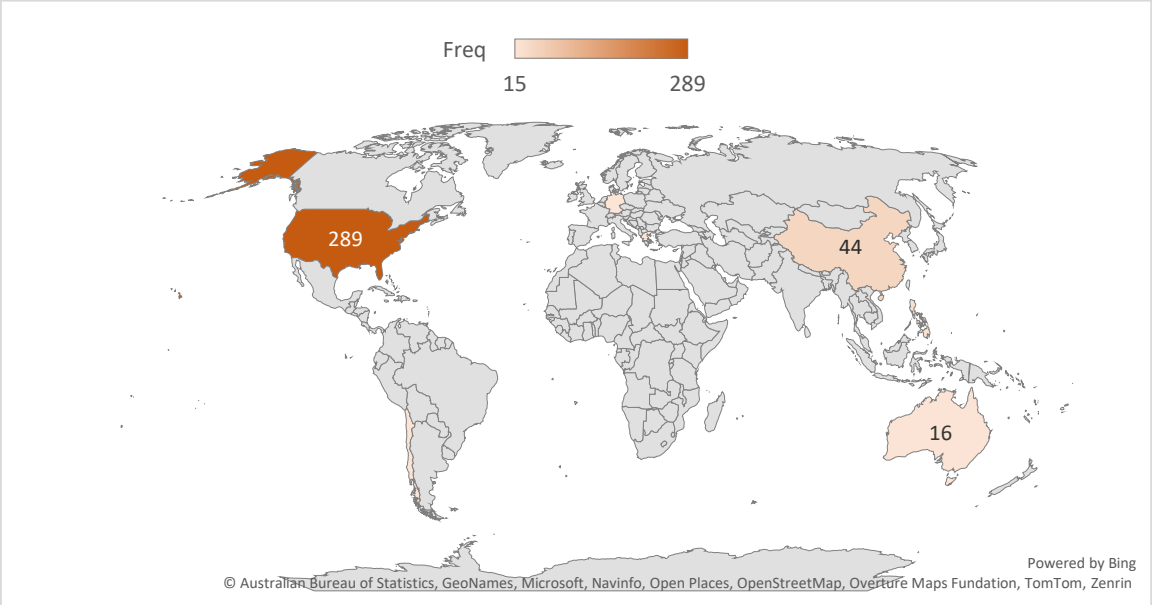

Figure 3: Countries Contributed to Research on Technology Integration in Secondary Biology Education

Table 5: Institutions Contributed to Research on Technology Integration in Secondary Biology Education

Institution	No. of Articles
Northwestern University	11
Khon Kaen University	10
Pontificia Universidad Católica De Chile	9
University of Pennsylvania	7
University of California	6
University of Georgia	6
Université De Bretagne Occidentale	6
Columbia University	5

Hellenic Open University	5
Rutgers New Jersey Medical School	5

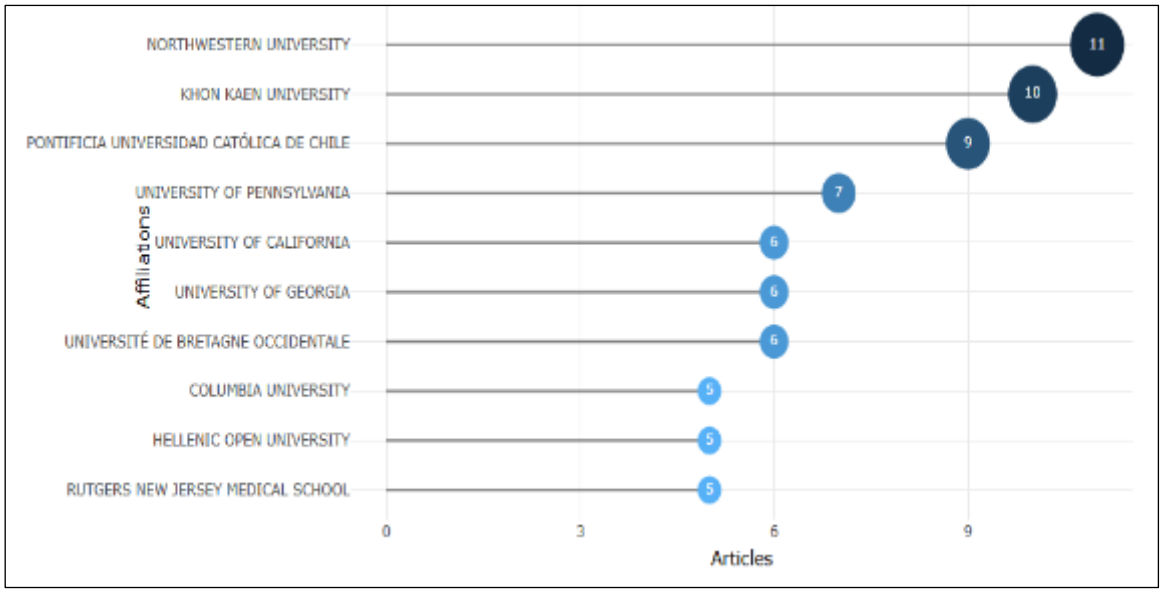

Figure 4: Institutions Contributed to Research on Technology Integration in Secondary Biology Education

Table 6: Journals Contributed to Research on Technology Integration in Secondary Biology Education

Sources	**Articles**	**Year**
Technology Integration in Secondary Biology Education	59	2016
American Biology Teacher	17	2017
Lecture Notes in Computer Science	12	2018
Proceedings of the International Conference of the Learning Sciences, ICLS	12	2019
ACM International Conference Proceeding Series	8	2020
Education And Information Technologies	7	2021
Frontiers In Education	5	2022
See Annual Conference and Exposition, Conference Proceedings	4	2023
Cogent Education	4	2024
Communications In Computer and Information Science	4	2025

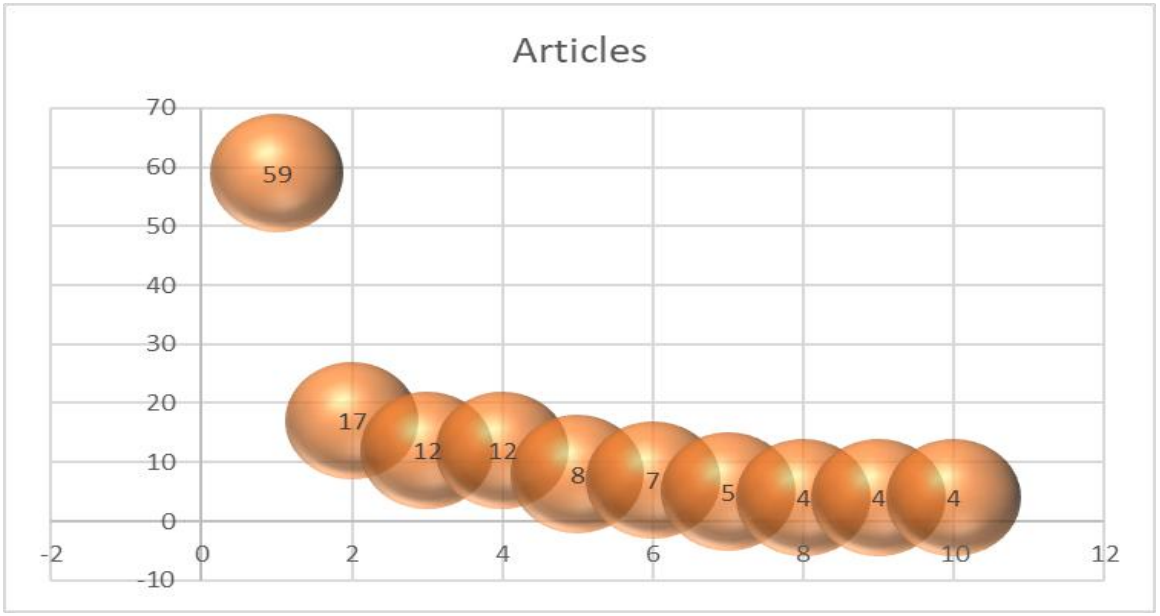

Figure 5: Journals Contributed to Research on Technology Integration in Secondary Biology Education

Table 7: The Authors Contributed to Research on Technology Integration in Secondary Biology Education

Author	Year	Article	TC	TC p Y
Ates, Huseyin	2024	1	17	8.5
Ates, Huseyin	2025	2	26	26
Blikstein, Paulo	2016	1	29	2.9
Blikstein, Paulo	2018	1	0	0
Blikstein, Paulo	2021	1	11	2.2
Blikstein, Paulo	2024	1	1	0.5
Bumbacher, Engin W.	2018	1	0	0
Bumbacher, Engin W.	2021	1	15	3
Bumbacher, Engin W.	2024	1	1	0.5
Christopoulos, Athanasios	2021	1	3	0.6

Note: TC- Total Citation, TCPY- Total Citation Per Year.

Table 8: The Authors' Index Contributed to Research on Technology Integration in Secondary Biology Education

Author	h_ index	g_ index	m_ index	TC	NP	PY _start
American Biology Teachers	8	16	0.8	320	59	2016
ACM International Conference Proceeding Series	4	8	0.444	69	8	2017
Journal Of Research in Science Teaching	4	4	0.571	90	4	2019
Journal Of Science Education and Technology	4	4	0.4	154	4	2016
Education And Information Technologies	3	6	0.75	45	7	2022
Acs Synthetic Biology	2	2	0.286	85	2	2019
Biochemistry And Molecular Biology Education	2	3	0.25	46	3	2018
Cogent Education	2	4	1	31	4	2024
Communications In Computer and Information Science	2	3	0.2	9	4	2016

Note: TC = Total Citations; NP = Number of Publications, PY start = Publication Starting year

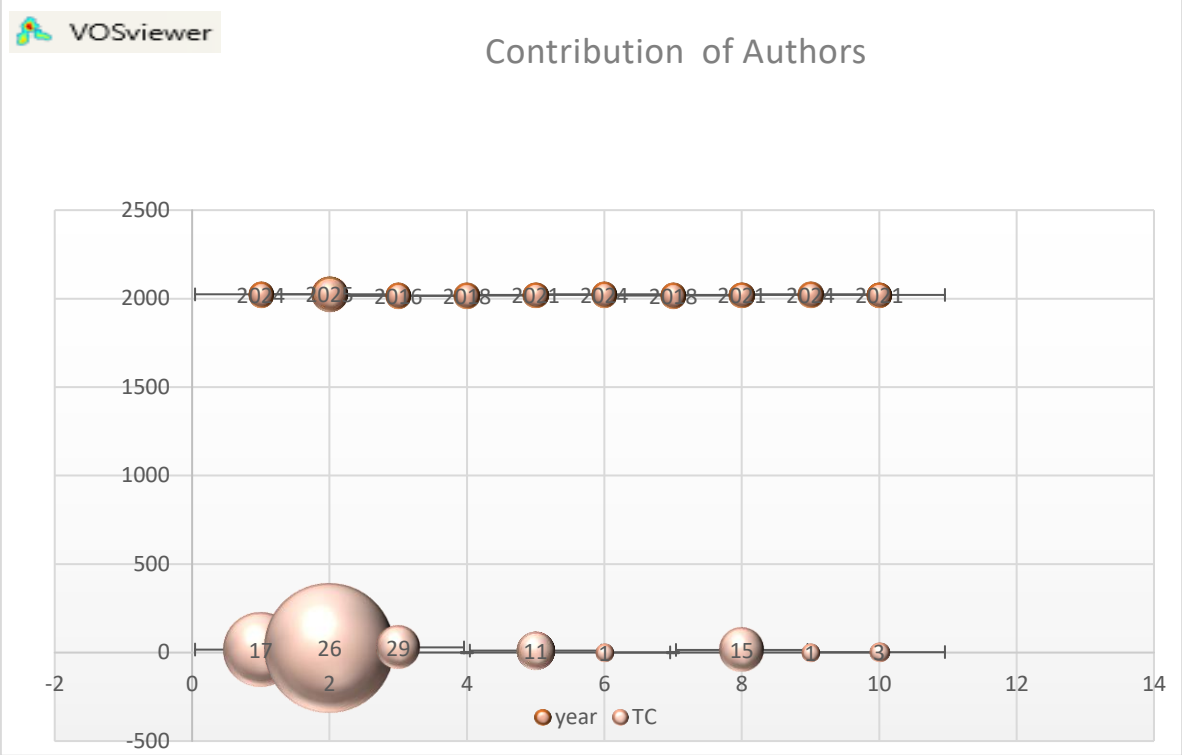

Figure 6: Authors Contributed to Research on Technology Integration in Secondary Biology Education

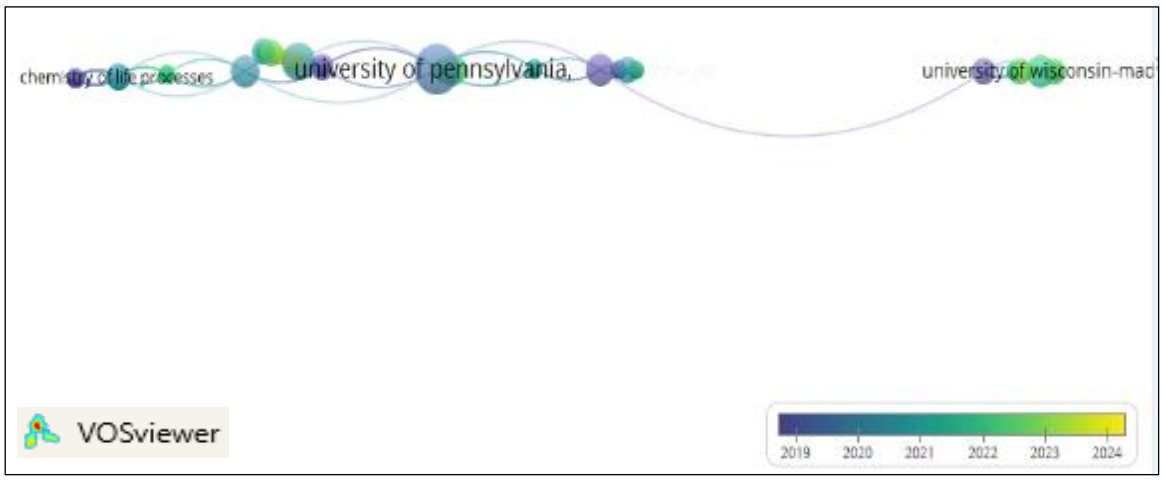

Figure 7A: Collaboration Patterns Visualization Network on Co-Authors among (Institutions)

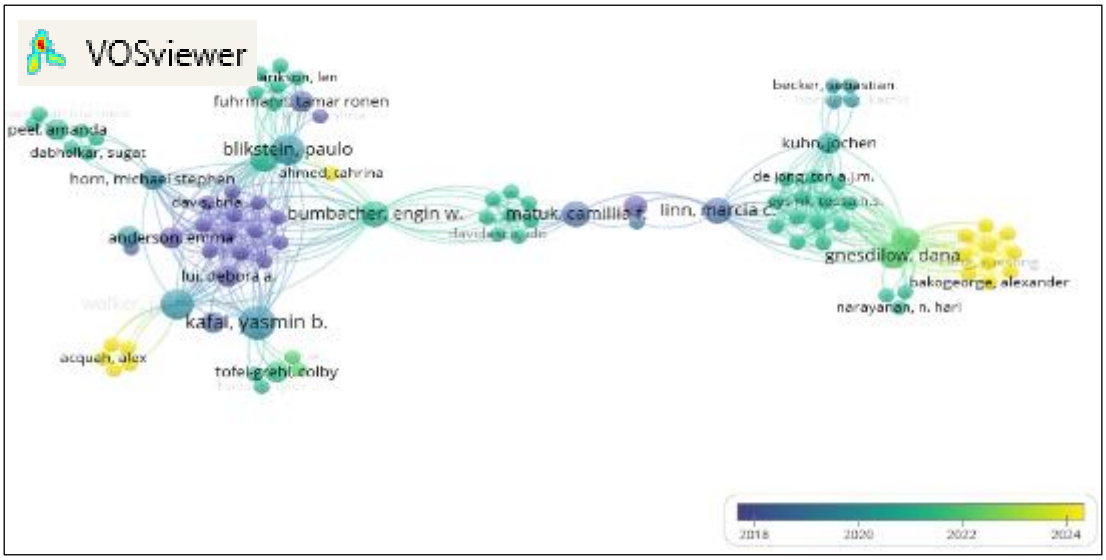

Figure 7B: Collaboration Patterns Visualization Network on Co-Authors among (Authors)

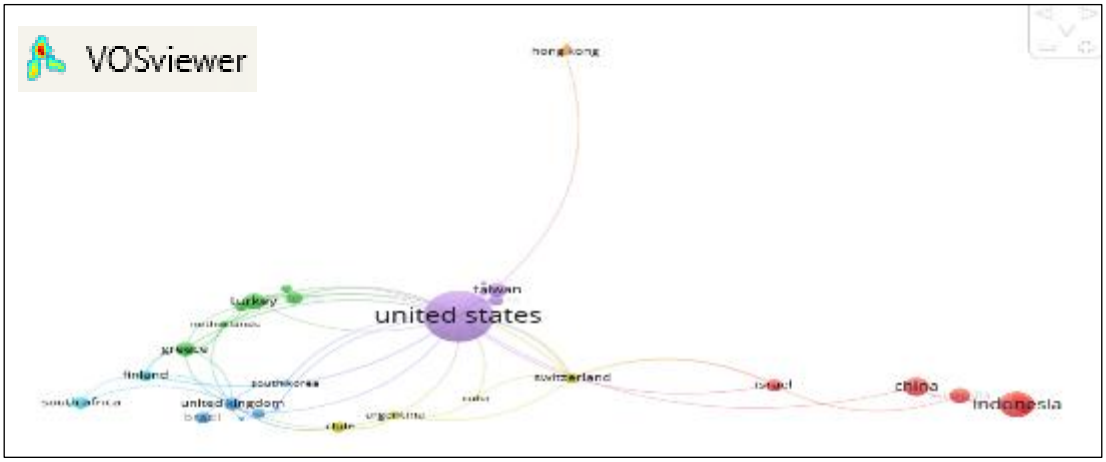

Figure 7C: Collaboration Patterns Visualization Network on Co-Authors among (Countries)

The findings imply that the collaboration pattern in research on technology and digital tools in secondary biology teaching is concentrated among a limited number of institutions, authors, and countries, indicating uneven global involvement in this research, particularly in resource-limited educational settings such as the Philippines.

3.3 Emerging Research Themes Keyword Co-occurrence

The emerging themes keyword co-occurrence analysis identified "science education" as the dominant thematic cluster, confirming that research on digital tools in biology teaching is strongly grounded in broader science education frameworks. Other frequently occurring themes included educational technology, secondary education, gamification, game-based learning, student engagement, and self-efficacy (see Table 9).

The thematic evolution analysis demonstrated a transition from general e-learning and technology integration themes toward more advanced and interactive approaches, including augmented reality, simulations, artificial intelligence, computational thinking, and personalized learning. This progression indicates a growing emphasis on immersive,

inquiry-based, and cognitively oriented instructional strategies in biology education (see Figures 8, 9).

Table 9: Emerging Research Themes Keywords Co-Occurrence

Occurrences	Words	Cluster	Cluster Label	Btw Centrality	Clos Centrality	Rank Centrality
41	Science Education	1	Science Education	5,331.798	0.002	0.041
15	Educational Technology	1	Science Education	1,022.967	0.002	0.015
14	Game-Based Learning	1	Science Education	596.037	0.002	0.01
14	Secondary Education	1	Science Education	2,482.292	0.002	0.017
8	Gamification	1	Science Education	1,387.926	0.002	0.011
5	Student Engagement	1	Science Education	247.519	0.002	0.006
4	Self-Efficacy	1	Science Education	228.624	0.002	0.005
3	Academic Achievement	1	Science Education	121.131	0.002	0.005
3	Cognitive Load	1	Science Education	56.065	0.001	0.004
3	Games	1	Science Education	280.112	0.002	0.003

Note: Btw Centrality = Betweenness Centrality; Clos Centrality = Closeness Centrality.

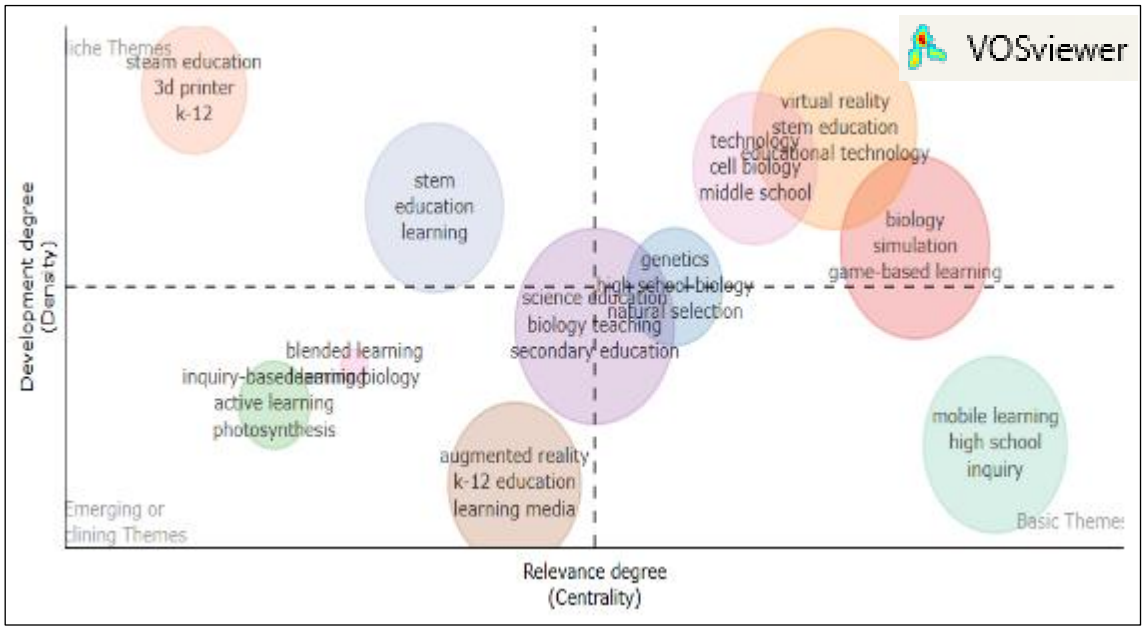

Figure 8: Thematic Map Evolution on Co-Occurrence

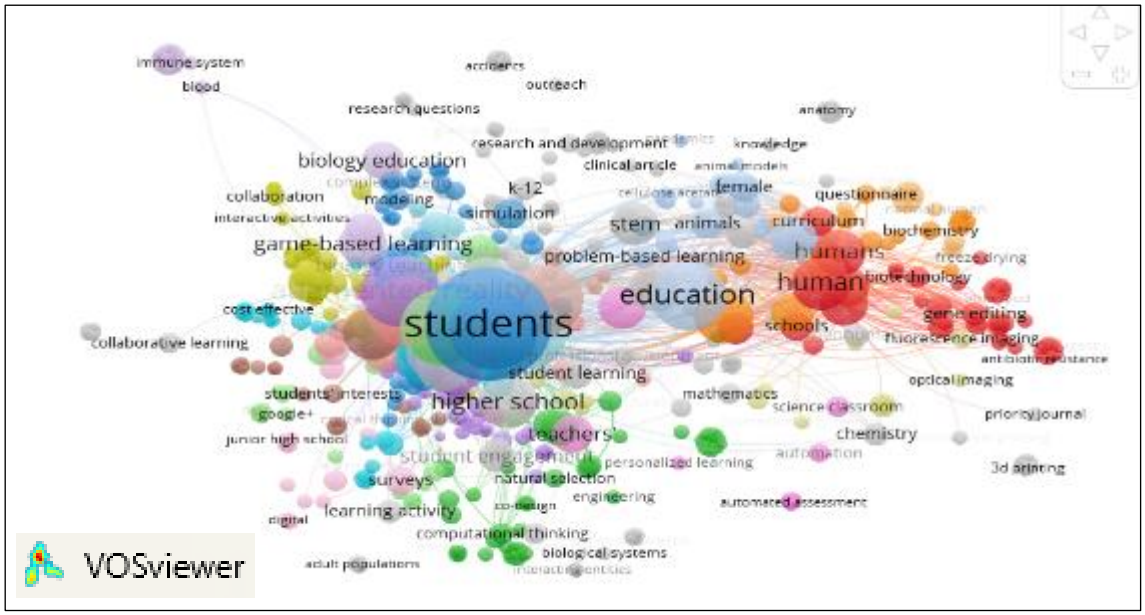

Figure 9A: Collaboration Patterns Visualization
Network keyword on Co-Occurrence (all keywords)

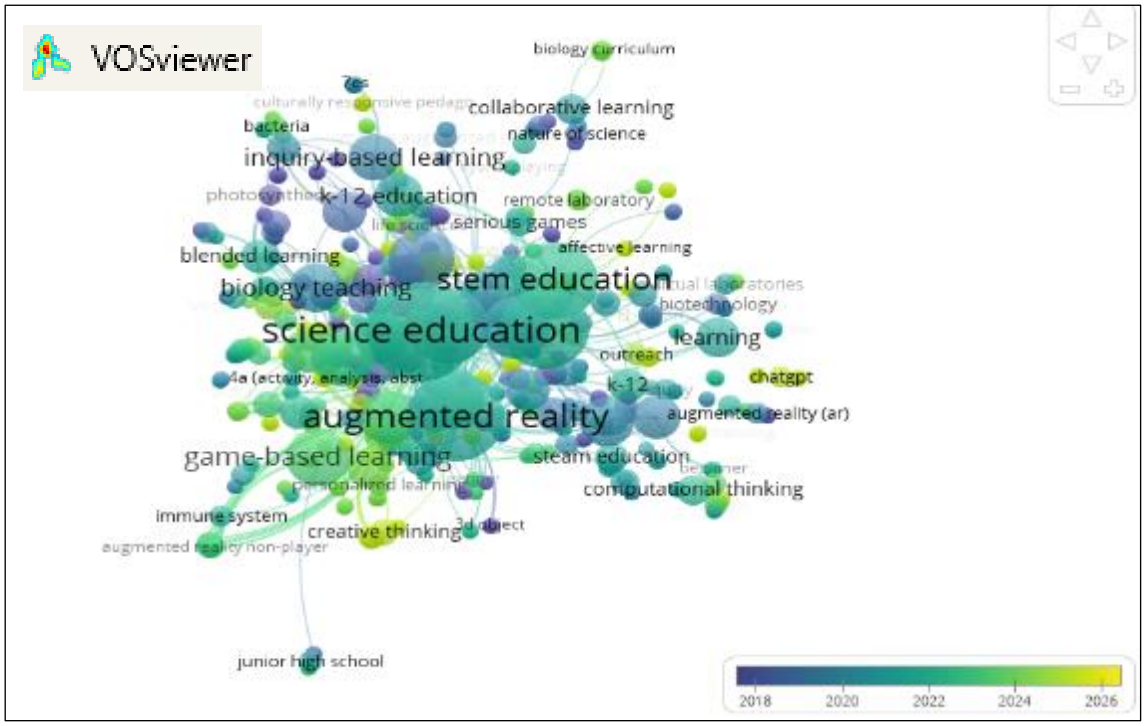

Figure 9B: Collaboration Patterns Visualization Network
Keyword on Co-Occurrence (Emerging Trends)

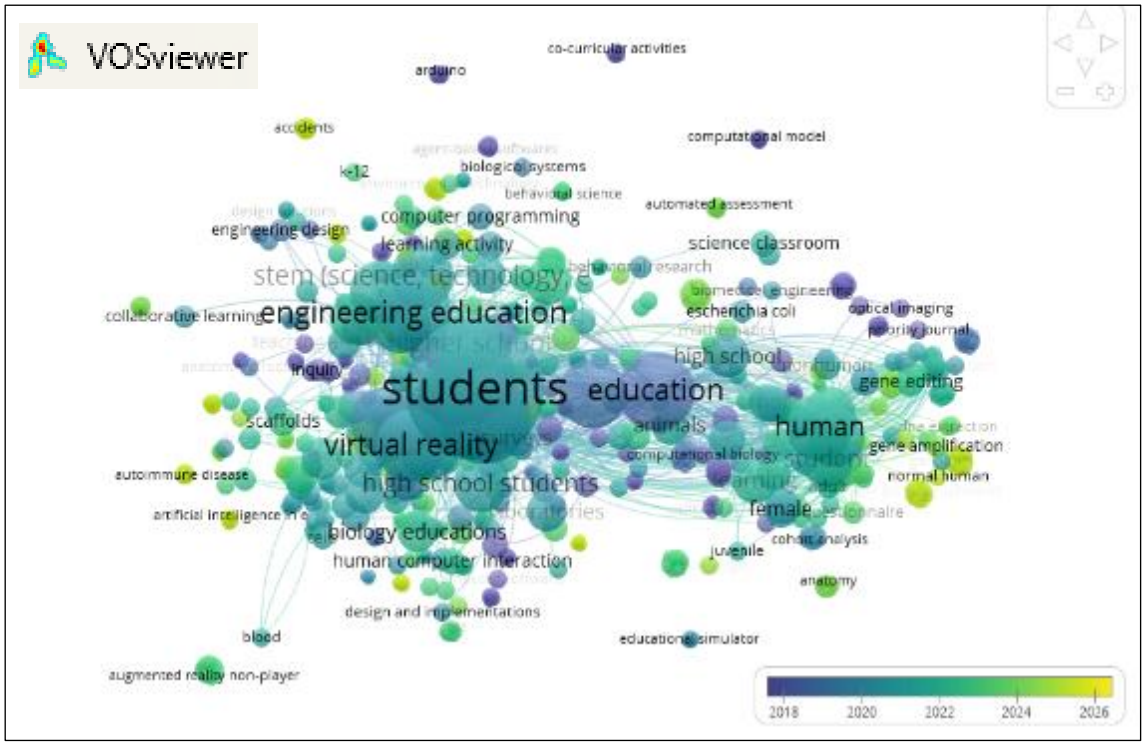

Figure 9C: Collaboration Patterns Visualization Network keyword on Co-Occurrence (Index)

The emergence of themes related to artificial intelligence and critical thinking in recent years suggests that research is increasingly focused on higher-order learning outcomes and adaptive educational technologies. These findings align with contemporary educational reforms that prioritize digital literacy, scientific inquiry, and learner-centered pedagogies.

Furthermore, the visualization networks generated through VOSviewer revealed strong thematic interconnections among STEM education, biology instruction, and technology-enhanced learning. However, the limited representation of Philippine-based keywords and institutions indicates the need for stronger localized research initiatives and international research engagement.

3.4 Implications of Bibliometrics Trends for Secondary Biology Teaching

The bibliometric findings demonstrate that technology integration in secondary biology education is increasingly associated with learner-centered instruction, inquiry-based learning, and enhanced student engagement. Digital tools such as simulations, augmented reality, mobile learning applications, and virtual laboratories have become central strategies for improving conceptual understanding of complex biological processes (see Table 10).

The increasing prominence of themes such as STEM education, gamification, and artificial intelligence suggests that future biology curricula should integrate emerging technologies with pedagogical strategies that promote critical thinking, collaboration, and problem-solving skills. These developments support educational frameworks emphasizing 21st-century competencies and digital literacy (see Fig 10, 11).

Table 10: Implications of Bibliometrics Trends

Implication Trends	No. of Article	Year (Q1)	Year (Median)	Year (Q3)
Inquiry	5	2016	2016	2019
Education	40	2016	2017	2022
Student Learning	8	2016	2019	2021
Life-Sciences	5	2017	2017	2019
Simulation	8	2017	2018	2022
Mobile Augmented Reality	5	2017	2019	2020
STEM (Science, Technology, Engineering, and Mathematics)	23	2017	2020	2025
Chemistry	5	2018	2018	2019
Problem-Based Learning	5	2018	2018	2019
Biology	43	2018	2020	2022
Learning Systems	23	2018	2020	2022
Students	110	2018	2021	2024
E-Learning	51	2018	2021	2022
Teaching	40	2018	2022	2025
Education Computing	21	2018	2022	2025
Synthetic Biology	5	2019	2019	2022
Augmented Reality	43	2019	2021	2023
Human	24	2019	2023	2024
Genetics	14	2019	2024	2024
Science Education	54	2020	2022	2024
Article	16	2020	2023	2024
Stem Education	28	2020	2024	2025
Secondary Education	16	2021	2023	2024
Game-Based Learning	16	2021	2024	2024
Critical Thinking	7	2024	2025	2025
Artificial Intelligence	5	2024	2025	2025

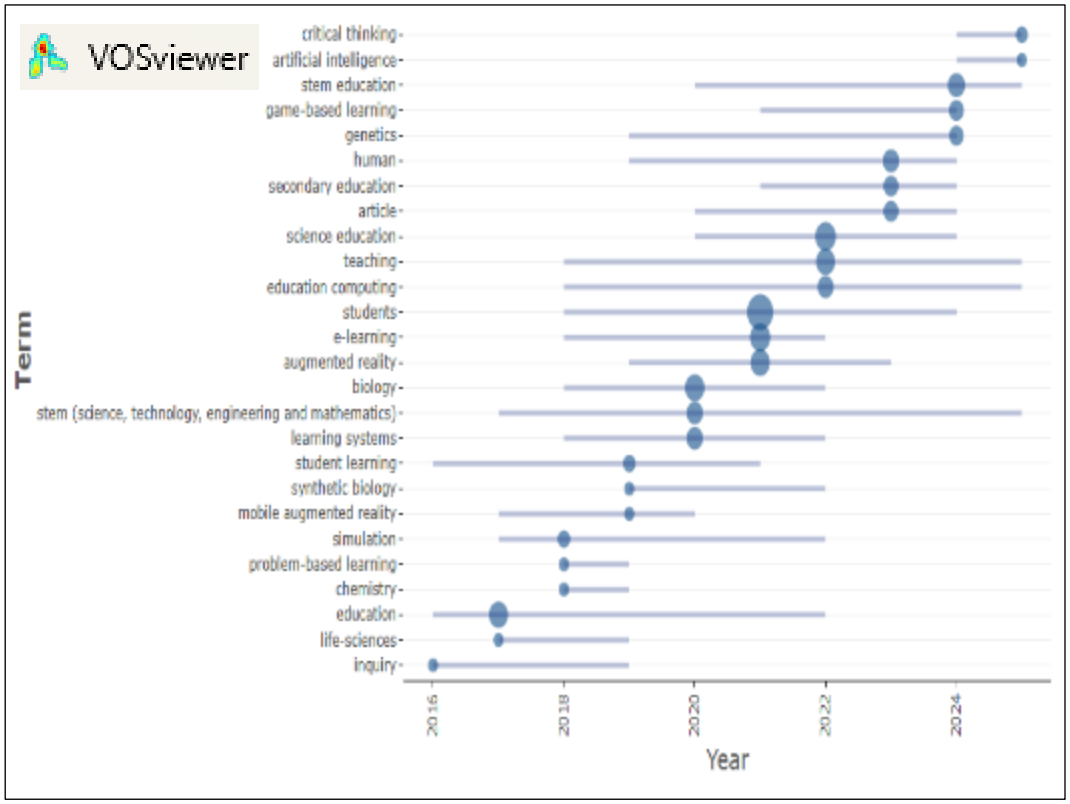

Figure 10: Implication of Bibliometric Trends

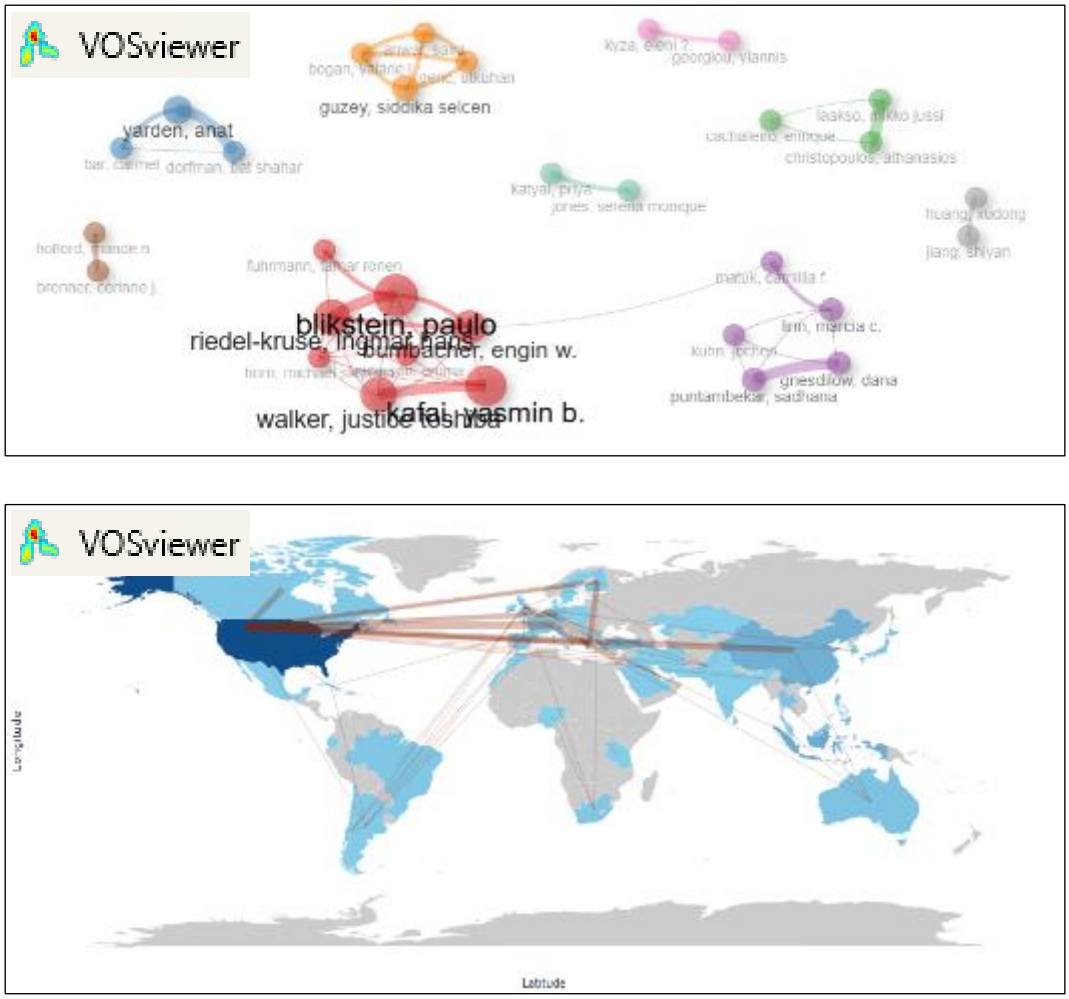

Figure 11: Implication of Bibliometric Collaboration Network

In the Philippine context, the findings highlight the importance of strengthening teacher professional development, digital infrastructure, and institutional support to facilitate meaningful technology integration in biology instruction. While global research demonstrates substantial innovation in technology-enhanced science education, local implementation remains constrained by unequal access to digital resources and limited technological readiness.

The study further suggests that curriculum reforms aligned with the Department of Education MATATAG curriculum should prioritize contextualized digital instruction, blended learning approaches, and technology-supported inquiry activities. Strengthening research collaboration and localized innovation may also help bridge gaps between global technological advancements and the realities of Philippine secondary education.

4. Conclusion

This bibliometric analysis revealed a significant and sustained increase in global research on technology and digital tools in secondary biology education from 2016 to 2025. The

findings demonstrate that technology integration has evolved from basic digital instruction toward more learner-centered, inquiry-based, and interactive pedagogical approaches supported by innovations such as simulations, augmented reality, mobile learning, and artificial intelligence.

The study further showed that effective technology integration depends not only on the availability of digital tools but also on teacher competence, pedagogical readiness, and institutional support. Emerging research themes emphasized student engagement, critical thinking, self-efficacy, and technology-supported inquiry, reflecting the growing importance of meaningful and pedagogically grounded digital instruction in biology education.

Collaboration and publication patterns highlighted the dominant contributions of developed countries and research-intensive institutions, while limited participation from developing contexts, including the Philippines, remains evident. This gap underscores the need for more localized and context-sensitive studies that address the realities of Philippine secondary biology classrooms.

Overall, the findings suggest that future curriculum reforms and professional development initiatives should prioritize evidence-based technology integration, digital literacy, and inquiry-driven instructional practices aligned with 21st-century learning goals and the Department of Education MATATAG curriculum framework. Strengthening research collaboration and supporting teachers' digital pedagogical competencies may further enhance the quality and effectiveness of secondary biology education in both global and local contexts.

Conflict of Interest Statement

The author declares no conflict of interest related to this study. The research was conducted independently, and no financial or personal interests influenced the results and interpretation of the findings.

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