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The Evolution of Online Physics Education: Insights from a Bibliometric Study

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Abstract. The transformation of physics education through online teaching has prompted the need to understand its development on a global scale. However, a comprehensive bibliometric assessment of this field remains limited. This study addresses this gap by conducting a bibliometric analysis of 1,118 publications from 1990 to 2024 indexed in Scopus, aiming to uncover publication trends, key contributors, collaboration patterns, and emerging research themes. Data were refined through multiple filtering steps and analyzed using Python and Gephi for network visualization. The findings reveal a significant increase in publication output over time, with a notable surge during the COVID-19 pandemic. Notably, journal articles exhibit higher citation rates than conference papers, indicating greater long-term impact. The United States, United Kingdom, and Spain emerged as the most productive countries, while Indonesia and Mexico are among the most active emerging contributors. Co-authorship analysis highlights strong collaboration networks, particularly in Europe, with key contributors such as C. Aramo and L. Caccianiga playing central roles. Thematic analysis through keyword co-occurrence identified dominant research topics such as e-learning, virtual laboratories, augmented reality, and learning analytics, signaling a shift toward technology-enhanced

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instructional methods. This study provides critical implications for future research, including the need for greater international collaboration, interdisciplinary application of technologies, and increased attention to accessibility and inclusivity. Additionally, it highlights the importance of exploring socio-emotional factors such as student motivation and well-being through longitudinal studies. These insights offer a roadmap for advancing effective, equitable, and emotionally supportive online physics education.

Keywords: bibliometric analysis; online teaching; physics education; research trends; academic collaboration

1. Introduction

Driven by advancements in digital technologies and the increasing demand for flexible learning environments, the landscape of education has seen a rapid evolution in recent years (Cui et al., 2023). As such, online education has become a critical alternative to traditional classroom-based teaching (Alajmi et al., 2020). However, while online learning offers several advantages, including flexibility, greater access to educational resources, personalized learning experiences, and the ability to study at one's own pace, it also presents challenges such as maintaining student engagement, ensuring the effectiveness of instructional tools, and replicating hands-on learning experiences in digital formats (Bitzenbauer, 2021; Nasution, 2024). As digital platforms continue to play an essential role in education, particularly after the COVID-19 pandemic, educators and researchers are increasingly focused on improving methods for delivering effective online instruction (Jamali et al., 2017; Raman et al., 2022).

Physics education, in particular, poses unique challenges when transitioning to online formats as it often relies heavily on laboratory experiments, physical demonstrations, and direct interactions between students and instructors, which are difficult to replicate in digital environments. While virtual laboratories and simulations have been developed to help bridge this gap, their effectiveness in fostering deep conceptual understanding remains a topic of ongoing research (Çevik et al., 2022; Raman et al., 2022). In addition, online physics education continues to face challenges related to accessibility for students with limited internet or device access, inclusivity for learners from diverse backgrounds or with special needs, and sustaining engagement with abstract and mathematically intensive subject matter (Godsk & Møller, 2024; Jamali et al., 2017). These difficulties underscore the need for a deeper understanding of how online teaching methods can be optimized for the teaching of physics (Hollister et al., 2022).

Quantitative methods, such as bibliometric analysis, provide an essential tool for assessing trends, collaboration networks, and the impact of research in any given field. Bibliometric analysis allows researchers to track the evolution of scientific knowledge, identify key contributors, and map out emerging research themes (Anasi & Harjunowibowo, 2023; Jing et al., 2024). By analyzing trends in publication outputs, citation patterns, and co-authorship networks, this approach offers valuable insights into the development of educational practices, including online teaching in physics (Bitzenbauer, 2021; Hew et al., 2018). While some studies have applied bibliometric methods to physics education, such as Jatmiko et al. (2021), which focused on online physics learning during the COVID-19 pandemic (2020 to 2021), and Alhusni et al. (2024), which analyzed scientific literacy in physics learning from 1977 to 2023, they are, however, limited either in time span or by focusing on general physics education rather than online learning. As far as we are aware, there has been no comprehensive bibliometric analysis that examines the evolution of online physics education over multiple decades. Accordingly, this study is guided by the following research questions:

1. What are the major publication trends and research themes in online physics education from 1990 to 2024?
2. Who are the most influential authors, institutions, and countries contributing to this field, and what are the patterns of collaboration among them?
3. What are the emerging topics, technologies, and methodological approaches that characterize recent studies in online physics education?
4. What are the potential gaps and future directions for improving accessibility, collaboration, and socio-emotional outcomes in this domain?

This work presents a comprehensive overview of the current state of online physics education through detailed bibliometric analysis of 1,118 publications spanning from 1990 to 2024, covering the full period available in the Scopus database and capturing key developments from the early adoption of online learning technologies to the post-pandemic transformation of digital education. The study's primary objective is to systematically identify global research trends, leading contributors, co-authorship networks, and thematic developments within this domain. By uncovering how online physics education has developed and which areas are gaining momentum, the study contributes to a clearer understanding of where the field currently stands and where it is headed. These insights are intended to support educators in adopting effective digital teaching strategies, assist researchers in identifying research gaps and collaboration opportunities, and guide policymakers in making informed decisions to promote inclusive and innovative physics education in online environments.

2. Materials and methodology

2.1. Data source

This bibliometric analysis focuses on publications related to online physics education as retrieved from the Scopus database. While other major databases such as Web of Science (WoS), Google Scholar, and Dimensions were considered, Scopus was selected as the sole data source due to its comprehensive coverage of peer-reviewed literature, reliable citation tracking, and efficient data export functionalities. In comparison, WoS offers more limited coverage of educational conference proceedings, Google Scholar lacks transparency in indexing and consistent metadata, and Dimensions provides restricted export options (Harzing, 2019; Martín-Martín et al., 2018; Mongeon & Paul-Hus, 2016).

However, Scopus provides broad indexing of journals, conference proceedings, and book chapters in both the fields of physics and education, thereby making it the most suitable database for this bibliometric research (Mongeon & Paul-Hus, 2016).

A search query was developed using combinations of keywords related to online teaching, physics education, blended learning, and other associated terms. The search targeted the title, abstract, and keyword fields to ensure the inclusion of relevant documents. The dataset covers publications from 1990 to 2024, and the data were accessed on August 1, 2024.

2.2. Data refinement

After the initial retrieval of publications, a multi-step refinement process was carried out to ensure the dataset included only relevant and high-quality records. This process is summarized in **Figure 1**.

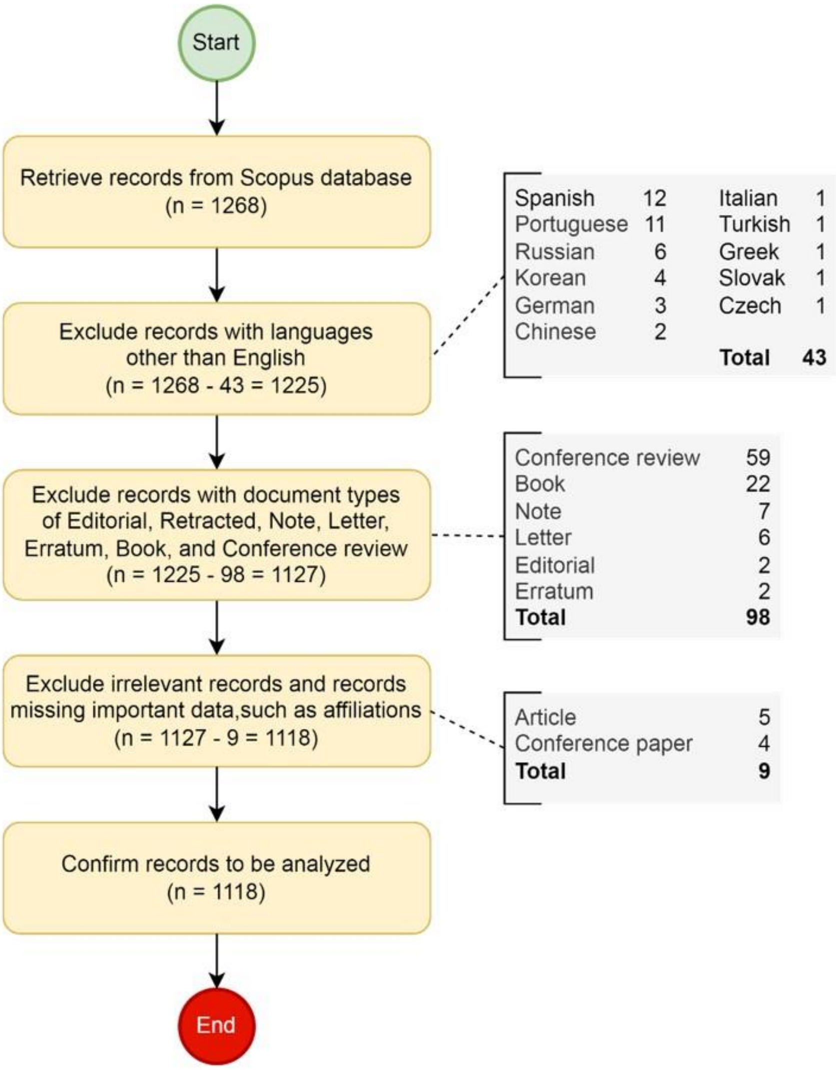

Figure 1: Process flow of record refinement

The refinement process consisted of the following steps:

1. Initial retrieval: The initial search returned 1,268 records from the Scopus database.
2. Language filtering: Non-English documents were excluded, resulting in 1,225 records. The excluded languages included Spanish (12 records), Portuguese (11 records), Russian (6 records), Korean (4 records), and several others. This step was taken to ensure consistency in metadata and keyword analysis.
3. Document type exclusion: Non-research document types, such as editorials, conference reviews, notes, and letters, were removed. After this step, 1,127 records remained.
4. Metadata validation: Finally, records with missing or incomplete metadata, such as missing author affiliations or incomplete publication details, were excluded. This resulted in a final dataset of 1,118 records, which were used for further analysis.

Before being processed, the dataset was manually reviewed to correct missing information or existing typos, as such inconsistencies could lead to inaccurate author counts, misattributed publications, or incorrect keyword analysis. This step ensured that the analysis would generate reliable and valid results.

2.3. Data analysis tools and procedure

The bibliometric analysis was conducted using Python[*] as the primary tool for data processing, along with key libraries for specific tasks:

- Pandas: Employed for data cleaning and manipulation, ensuring the dataset was accurate, complete, and ready for analysis.
- Matplotlib: Used to generate visualizations such as publication trends, and other metrics relevant to the bibliometric analysis.

For network analysis, Gephi[†] was utilized to visualize both co-authorship networks and keyword co-occurrence networks. The ForceAtlas2 layout in Gephi was chosen due to its effectiveness in clustering closely related nodes, making it easier to identify key research groups and thematic clusters within the dataset.

The analysis was conducted in three interconnected stages in order to systematically explore the structure and evolution of online physics education research:

1. Descriptive analysis: This stage involved examining the general characteristics of the dataset, such as the total number of publications, document types, and citation counts. These metrics provided an overview of the growth, visibility, and impact of the field, thereby establishing a foundation for deeper analyses.

[*] https://www.python.org/
[†] https://gephi.org/

2. Citation and co-authorship analysis: Building on the descriptive results, this stage identified the most influential contributors, institutions, and sources based on document and citation counts. Co-authorship network analysis further revealed collaboration patterns among scholars and countries, offering insights into the structure and dynamics of the research community.
3. Keyword co-occurrence analysis: Finally, a keyword co-occurrence network was constructed to uncover the primary research themes and trends. This analysis revealed how different research topics are interconnected and highlighted emerging areas of interest within the field of online physics education.

These comprehensive analyses provide valuable insights into the development of research in online physics education (Anasi & Harjunowibowo, 2023; Jing et al., 2024). The key findings are presented in the following section.

3. Results

3.1. General statistical information and publication trends

An overview of the dataset is shown in **Table 1** and **Table 2**. The dataset analyzed in this study spans from 1990 to 2024, comprising a total of 1,118 documents related to online physics education. The data were sourced from 478 different data sources, reflecting the broad scope of research in this domain. The total number of citations across these documents is 8,377, with an average of 7.5 citations per document. This indicates that while some studies have significantly contributed to the field, the average influence per document remains moderate.

The dataset also includes a rich variety of topics, as reflected by the 3,583 keywords, with 756 unique author-provided keywords. This diversity illustrates the broad range of research themes within the field of online physics education, from technological tools to pedagogical approaches.

Table 1: **Overview of the dataset**

Content	Result
General information	
Period	1990 - 2024
Number of data sources	478
Total number of documents	1,118
Average number of citations per document	7.5
Total documents cited	8,377
Information about document content	
Total keywords	3,583
Author's keywords	756
Information about author	
Total unique authors	3,534
Total authors of single-author document	162
Total authors of multi-author document	3,387

Total authors of both single and multi-author documents	15
Information about author's collaboration	
Total documents of single author	182
Total documents per author	0.3
Total authors per document	3.2

In terms of author contributions, there are 3,534 unique authors in the dataset. A large proportion of the publications involved multiple authors, with 3,387 documents authored by more than one individual, highlighting the collaborative nature of research in this field, where interdisciplinary collaboration is often necessary for addressing complex educational challenges. Single-author publications, on the other hand, account for only 162 documents, reflecting a preference for collaborative research in this domain. On average, each document was co-authored by 3.2 authors, indicating a high level of joint effort in advancing the field.

Collaboration patterns further support this trend, with 182 single-author documents compared to the predominance of multi-author works. The average number of documents per author is 0.3, underscoring the extensive collaboration that characterizes this research area. These figures suggest that online physics education is a field where knowledge-sharing and collaborative efforts are highly valued, leading to the formation of research clusters that drive innovation and progress.

The distribution of document types reveals interesting patterns. As presented in **Table 2**, conference papers make up the largest portion, with 676 documents contributing a total of 1,762 citations. Despite the volume of conference papers, their citation rate stands at 2.61 citations per document, indicating that while frequently presented, they tend to have less long-term impact compared to other document types. This is likely because conference papers often present preliminary findings and are less frequently indexed or cited than peer-reviewed journal articles, which are viewed as more authoritative and enduring sources of knowledge. Journal articles, on the other hand, make up 395 documents, accumulating 5,853 citations, resulting in a citation rate of 14.82 citations per document. This higher citation rate suggests that journal publications tend to have a more substantial influence on the field of online physics education.

Table 2: Types of documents and their associated information

Document type	Total documents (a)	Total citations (b)	Citation rate (b/a)
Article	395 (35.3%)	5,853 (69.9%)	14.82
Book chapter	31 (2.8%)	73 (0.9%)	2.35
Conference paper	676 (60.5%)	1,762 (21.0%)	2.61
Review	14 (1.3%)	478 (5.7%)	34.14
Short survey	2 (0.2%)	211 (2.5%)	105.5
Sum	1,118 (100%)	8,377 (100%)	7.49

Further analysis of document types shows that book chapters represent 31 documents, with a citation rate of 2.35 citations per document, while review articles - though only 14 in number - have a much greater impact, with 478 total citations and an impressive citation rate of 34.14 citations per document. This underscores the importance of reviews in providing comprehensive syntheses that guide future research. Short surveys, though limited to just two documents, show the highest citation rate of 105.5 citations per document, indicating their significant influence despite their small representation in the dataset.

In **Figure 2**, the bar and line graph illustrates the annual publications (blue bars) and the cumulative citations (red line) related to online physics education from 1990 to 2024. The trends observed in this figure reflect the growing interest in the field over the last three decades.

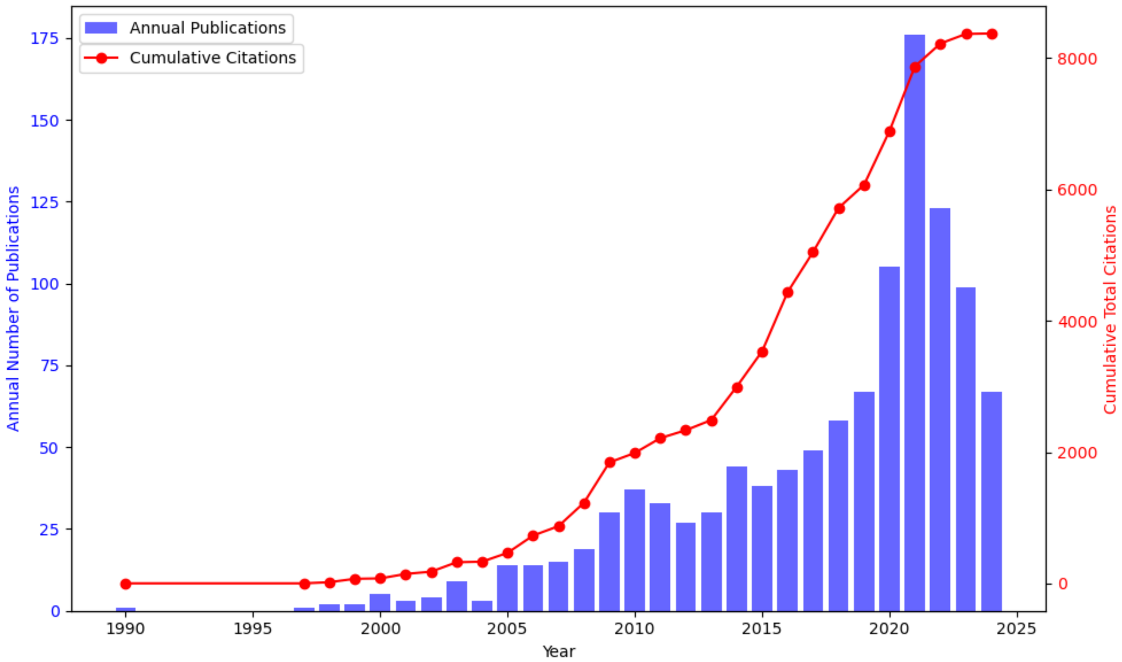

Figure 2: The increment of annual publications and cumulative citations

Between 1990 and 2009, the number of publications remained relatively low, with fewer than 30 publications per year, indicating that research on online physics education was still in its nascent stages. However, starting around 2010, the number of annual publications began to increase steadily, likely driven by advancements in digital learning technologies and a growing interest in integrating online teaching methods into physics education. The most significant surge occurred after 2019, reaching a peak in 2021 with around 175 publications, corresponding to the rapid shift toward online learning during the COVID-19 pandemic. After the peak, the number of annual publications declined but remained higher than pre-pandemic levels, reflecting sustained interest in the field.

The cumulative citation trend (red line) shows a consistent and steep rise, especially after 2010, indicating the increasing influence of research in this domain. By 2022, cumulative citations exceeded 8,000, demonstrating the long-term impact of studies published in this field. Notably, the cumulative citations continued to grow sharply even after the peak of annual publications in 2021, suggesting that many studies published during the pandemic have had lasting influence. The continued rise in citations, despite a slight drop in annual publications, reflects the high quality and relevance of the research conducted during and immediately following the pandemic.

The trends presented in **Figure 2** have important implications for the field of online physics education. The surge in publications during the pandemic period highlights the global response to the urgent need for effective online teaching methods, while the subsequent decline in publications may indicate a transition from exploratory research to more focused, refined studies aimed at improving existing methodologies. The sustained growth in cumulative citations can be attributed to the increasing relevance of online physics education, especially during and after the COVID-19 pandemic, when digital learning became essential. This growth emphasizes the importance and influence of research produced during this time, which continues to shape future studies and innovations in online teaching strategies.

3.2. Key contributors: Leading countries, institutions, and scholars

To identify key contributors in online physics education, we analyzed the top countries, institutions, and scholars regarding their total documents and citations.

3.2.1. Leading countries

A total of 89 countries have contributed to research in this domain, reflecting the global interest in the field. **Table 3** highlights the top 10 countries based on total documents, total citations, and citation rate. Notably, if a document has multiple authors from different countries, it is credited to each unique country.

Table 3: The 10 leading countries in online physics education

No.	Country	TD	TC	CR
1	United States	239	2,371 (#1)	9.92 (#19)
2	Indonesia	108	487 (#8)	4.51 (#36)
3	China	78	284 (#12)	3.64 (#44)
4	Germany	57	445 (#9)	7.81 (#22)
5	Spain	42	749 (#4)	17.83 (#8)
6	Russian Federation	42	134 (#19)	3.19 (#49)
7	Italy	40	162 (#16)	4.05 (#40)
8	India	36	123 (#21)	3.42 (#47)
9	United Kingdom	35	972 (#2)	27.77 (#5)
10	Brazil	33	126 (#20)	3.82 (#43)

TD: Total documents; TC: Total citations; CR: Citation rate (citations per document).

The United States leads with the highest number of publications (239) and total citations (2,371). Despite this, its citation rate of 9.92 indicates that the average impact per publication is moderate compared to other countries. This suggests that while the United States produces a significant volume of research, not every publication has a high citation impact, making its contribution substantial in quantity but more varied in terms of influence.

Countries like the United Kingdom and Spain are distinguished by their high citation rates relative to the number of publications. The United Kingdom, with only 35 publications, has a remarkable citation rate of 27.77, indicating that each of its publications is highly influential. Similarly, Spain has a citation rate of 17.83 from 42 publications, showing that its research is well-regarded and frequently cited. These countries contribute fewer publications but achieve significant impact per document, highlighting the quality of their research in online physics education.

On the other hand, Indonesia and China, which rank second and third in terms of publication volume, show lower citation rates, at 4.51 and 3.64, respectively. While these countries are emerging as key contributors in terms of research output, their work has not yet achieved the same level of international recognition. Their relatively low citation rates suggest that the research may be more regionally focused or that the global influence of their work is still developing. Germany, with 57 publications and a citation rate of 7.81, shows a balance between productivity and influence, indicating that its research has a growing international presence, though not yet at the same level as that of the United Kingdom or Spain.

Countries like Russia, Italy, India, and Brazil have moderate publication numbers but relatively low citation rates. For example, Russia and Italy both have around 40 publications, yet their citation rates are 3.19 and 4.05, respectively, reflecting limited global influence. India and Brazil also have lower citation rates, suggesting that while these countries are contributing to the research volume, their publications have not yet reached a high level of impact internationally. Increasing visibility through international collaborations or targeting high-impact journals could help these countries enhance the recognition and influence of their research in the future.

3.2.2. Leading institutions

Table 4 shows the top 10 institutions contributing to research on online physics education, ranked by total documents and citations. The percentage contribution for both documents and citations shows each institution's share of the global research output in this field. As with **Table 3**, if a document has multiple authors from different institutions, it is counted for each unique institution.

Table 4: The 10 leading institutions in online physics education

No.	Institution	Country	Documents		Citations	
			Count	%	Count	%
1	Tecnológico de Monterrey	Mexico	21	1.88	132 (#22)	1.58
2	Universitas Negeri Padang	Indonesia	11	0.98	76 (#44)	0.91
3	Universitas Pendidikan Indonesia	Indonesia	11	0.98	28 (#120)	0.33
4	University of Ljubljana	Slovenia	10	0.89	43 (#78)	0.51
5	University of Pittsburgh	United States	8	0.72	129 (#24)	1.54
6	Harvard University	United States	8	0.72	62 (#55)	0.74
7	Universitas Negeri Jakarta	Indonesia	8	0.72	22 (#153)	0.26
8	Universitas Negeri Surabaya	Indonesia	7	0.63	50 (#62)	0.6
9	Massachusetts Institute of Technology	United States	7	0.63	47 (#69)	0.56
10	Charles University	Czech Republic	7	0.63	44 (#75)	0.53

Specifically, Tecnológico de Monterrey in Mexico leads with 21 publications (1.88% of global output) and 132 citations (1.58%), demonstrating high productivity, although its citation impact is only moderate, ranked #22 globally. Indonesia is well-represented with Universitas Negeri Padang, Universitas Pendidikan Indonesia, Universitas Negeri Jakarta, and Universitas Negeri Surabaya making the top 10. However, while these institutions contribute significantly in terms of document count, their citation impact, particularly for Universitas Pendidikan Indonesia and Universitas Negeri Jakarta, is limited, indicating that their research may be more regionally focused or lacking broader international visibility. In the United States, the University of Pittsburgh stands out with eight publications and 129 citations, placing it #24 globally for citations, showing strong impact relative to its output. In comparison, Harvard University and Massachusetts Institute of Technology have similar publication counts but lower citation impacts, suggesting that while they are active in the field, their contributions have not achieved the same level of influence. European institutions, such as the University of Ljubljana and Charles University, also appear among the leaders, but both institutions show relatively low citation counts (ranked #78 and #75, respectively), suggesting that their research, while productive, has yet to make a significant mark on the global stage. This indicates that, for many of these institutions, there is potential for growth in terms of increasing the international visibility and citation impact of their research, despite their contributions to the overall volume of work in the field.

3.2.3. Leading scholars

Table 5 presents the top 10 scholars contributing to research on online physics education, based on their total documents, total citations, and citation rate. The years of the first and last articles indicate the active period of each scholar in this domain, providing a clearer view of their research timeline and impact.

Scholars from Tecnológico de Monterrey, including Luis Neri, Julieta Noguez, and Victor Robledo-Rella, lead in publication volume, with nine and seven publications, respectively. However, despite their productivity, their citation rates (5.89 for Neri and Noguez and 4.71 for Robledo-Rella) suggest a moderate impact. In contrast, Teresa L. Larkin from American University has a higher citation rate of 10.33 from six publications, reflecting stronger influence per paper while P. Sprawls from Sprawls Educational Foundation, although having six publications, shows a lower impact with just eight citations and a citation rate of 1.33.

Scholars like Viktor Yurjevich Shurygin from Kazan Federal University and Dan Budny from the University of Pittsburgh stand out for their high impact, with citation rates of 14.2 and 12 from five publications each, indicating that their research is well-regarded. On the other hand, J.A. Tiili from Tampere University and Oleg Yavoruk, an independent scholar, have low citation rates of 0.67 and 0.8 despite similar publication counts, suggesting that their work is yet to gain wider recognition. Niwat Srisawasdi from Khon Kaen University shows moderate impact with a citation rate of 4.4 from five publications, positioning him as a contributor with potential for further growth.

3.3. Prominent sources and influential documents

3.3.1. Prominent sources

Table 6 lists the top 10 journals contributing to research on online physics education by publication volume, with their quartile (Q) classification. Journals are ranked into quartiles based on their impact factor and citation influence in the field.

Table 5: The 10 leading scholars in online physics education

No.	Author name	Affiliation	Year of first article	Year of last article	TD	TC	CR
1	Neri, Luis	Tecnológico de Monterrey, Mexico	2007	2016	9	53 (#105)	5.89 (#886)
2	Noguez, Julieta	Tecnológico de Monterrey, Mexico	2007	2016	9	53 (#105)	5.89 (#886)
3	Robledo-Rella, Victor	Tecnológico de Monterrey, Mexico	2007	2022	7	33 (#200)	4.71 (#1034)
4	Larkin, Teresa L.	American University, United States	2001	2023	6	62 (#96)	10.33 (#503)
5	Sprawls, P.	Sprawls Educational Foundation, United States	2005	2012	6	8 (#693)	1.33 (#1808)
6	Tiili, J.A.	Tampere University of Applied Sciences, Finland	2015	2021	6	4 (#1119)	0.67 (#2324)
7	Shurygin, Viktor Yurjevich	Kazan Federal University, Russian Federation	2017	2020	5	71 (#84)	14.2 (#335)
8	Budny, Dan	University of Pittsburgh, United States	2001	2003	5	60 (#97)	12.0 (#386)
9	Srisawasdi, Niwat	Khon Kaen University, Thailand	2015	2023	5	22 (#279)	4.4 (#1040)
10	Yavoruk, Oleg	Independent Scholar, Russian Federation	2019	2024	5	4 (#1119)	0.8 (#2323)

TD: Total documents; TC: Total citations; CR: Citation rate (citations per document).

Table 6: The 10 leading journals in online physics education

No.	Journal title	Publisher	Quartile	TD	TC	CR
1	Physics Education	IOP Publishing Ltd.	Q2	30	180 (#8)	6.0 (#90)
2	European Journal of Physics	Institute of Physics	Q2	21	224 (#3)	10.67 (#62)
3	Physics Teacher	American Institute of Physics	Q2	20	157 (#11)	7.85 (#80)
4	Education Sciences	Multidisciplinary Digital Publishing Institute	Q2	14	91 (#20)	6.5 (#88)
5	Physical Review Physics Education Research	American Physical Society	Q1	10	220 (#4)	22.0 (#36)
6	Computers and Education	Elsevier Ltd.	Q1	8	1268 (#1)	158.5 (#5)
7	Computer Applications in Engineering Education	John Wiley and Sons Inc.	Q1	7	246 (#2)	35.14 (#20)
8	Int. J. of Emerging Technologies in Learning	Int. Association of Online Engineering	N/A	7	105 (#18)	15.0 (#49)
9	Int. J. of Science and Mathematics Education	Springer Netherlands	Q1	6	74 (#23)	12.33 (#55)
10	Sustainability (Switzerland)	Multidisciplinary Digital Publishing Institute	Q1	5	73 (#24)	14.6 (#50)

Quartile is classified by the SCImago Journal & Country Rank (https://www.scimagojr.com), retrieved on Sep. 01, 2024.
TD: Total documents; TC: Total citations; CR: Citation rate (citations per document).

Physics Education, ranked Q2, leads with 30 publications and 180 citations, though its citation rate of 6.0 reflects moderate influence relative to higher-ranking journals. Despite being Q2, the *European Journal of Physics* stands out with 21 publications and a citation rate of 10.67, indicating stronger per-document impact, and a solid global standing. *Physics Teacher* and *Education Sciences*, both Q2 journals, also contribute significantly, with 20 and 14 publications, respectively. However, the former performs better in terms of citation rate (7.85) compared to the latter (6.5), indicating a higher impact per publication. On the other hand, *Physical Review Physics Education Research* and *Computers and Education*, both Q1 journals, demonstrate much higher influence. The former has a high citation rate of 22.0, underscoring its global reputation as a top-tier journal, despite contributing fewer articles (10 publications) although the latter is the most impactful, with 1,268 citations and a remarkable citation rate of 158.5, reflecting the journal's prominence in educational technology research. *Computer Applications in Engineering Education* (Q1) and the *International Journal of Emerging Technologies in Learning* show strong influence, with citation rates of 35.14 and 15.0, respectively. These journals, while not leading in publication volume, consistently publish high-impact research. Lastly, *Sustainability (Switzerland)*, though classified as Q1, demonstrates a moderate citation rate of 14.6, showing its growing influence in interdisciplinary educational research.

Journals ranked in Q1 (such as *Computers and Education*, *Physical Review Physics Education Research*, and *Computer Applications in Engineering Education*) are the most impactful in terms of citation rates, highlighting their strong influence in the field. On the other hand, Q2 journals like *Physics Education* and *European Journal of Physics* produce a high volume of research, but their influence per document is more moderate, suggesting they are respected venues but not as high-impact as Q1 journals. The quartile ranking thus provides additional context about the journals' overall standing in the broader academic publishing landscape.

Regarding conference studies, the top 10 conferences contributing significantly to research on online physics education are shown in **Table 7**. These conferences serve as major platforms for presenting and disseminating research, playing a crucial role in shaping advancements in the field.

The Journal of Physics: Conference Series leads with 131 publications but has a moderate citation rate of 3.05, reflecting lower impact per paper despite high volume. Similarly, the *ASEE Annual Conference* ranks second with 43 documents and a citation rate of 2.44, showing moderate influence. *AIP Conference Proceedings*, with 34 publications, has one of the lowest citation rates (0.56), suggesting limited impact despite its productivity. *Lecture Notes in Computer Science*, with 19 publications, stands out with the highest citation rate (7.11), indicating strong influence despite a smaller publication volume. Other notable conferences include the *ACM International Conference Proceeding Series* (30 publications, 2.3 citation rate) and *Frontiers in Education* (18 publications, 2.94 citation rate), which show moderate productivity and impact. At the lower end, *Proceedings of Science* and *AIP Conference Proceedings* have low citation rates (0.36 and 0.56, respectively), reflecting limited recognition within the academic community.

3.3.2. Influential documents

Based on citation counts, **Table 8** highlights the top 10 most influential documents in online physics education. These documents span key areas of educational innovation and continue to shape research in the field.

The most cited paper is "Virtual laboratories for education in science, technology, and engineering: A review" by Potkonjak et al. (2016), with 604 citations, emphasizing the importance of virtual labs in physics education. Similarly, Martín-Blas and Serrano-Fernández's (2009) article on Moodle as a teaching tool has 279 citations, reflecting the long-term relevance of learning management systems in physics education. Older works such as Linn et al. (2006), Garvin-Doxas and Klymkowsky (2008), and Nye et al. (2014) remain highly influential, with 211, 163, and 198 citations, respectively. These studies highlight key topics like knowledge integration, randomness in learning, and intelligent tutoring systems, showing that foundational research from the 2000s continues to be widely referenced. Recent publications related to the COVID-19 pandemic, such as those by Azlan et al. (2020) and Lancaster and Cotarlan (2021) have quickly garnered 136 and 144 citations, respectively. These papers address the shift to online education and ethical challenges, indicating the field's responsiveness to current educational issues.

In short, older foundational papers from the 2000s continue to dominate citations, reflecting their lasting relevance in physics education research. Review articles, in particular, are key resources. Meanwhile, recent works related to the pandemic are rapidly gaining influence, demonstrating the field's ability to adapt to emerging educational challenges. This blend of long-standing and contemporary research highlights the dynamic nature of online physics education.

3.4. Co-authorship network analysis

In this subsection, we analyze the co-authorship networks in online physics education, focusing on two key aspects: international cooperation among countries and collaboration among individual scholars. Understanding these networks helps reveal the patterns of cooperation and the central contributors to the field.

3.4.1. International cooperation among countries

Figure 3 highlights the global collaboration patterns in research on online physics education. The network is constructed using countries that have collaborated with others on at least one published paper. The size of each node reflects the total number of publications associated with each country, while the thickness of the links between nodes indicates the strength of cooperation between two countries. Countries with frequent collaborations are grouped into clusters, represented by similar colors, illustrating regional or thematic patterns of cooperation.

Table 7: The 10 leading conferences in online physics education by publication volume

No.	Conference title	Publisher	TD	TC	CR
1	Journal of Physics: Conference Series	IOP Publishing Ltd.	131	399 (#1)	3.05 (#49)
2	ASEE Annual Conference and Exposition, Conference Proceedings	N/A	43	105 (#3)	2.44 (#67)
3	AIP Conference Proceedings	American Institute of Physics	34	19 (#17)	0.56 (#145)
4	ACM International Conference Proceeding Series	Association for Computing Machinery	30	69 (#5)	2.3 (#69)
5	Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	Springer Verlag	19	135 (#2)	7.11 (#23)
6	Proceedings - Frontiers in Education Conference, FIE	Institute of Electrical and Electronics Engineers Inc.	18	53 (#7)	2.94 (#64)
7	IEEE Global Engineering Education Conference, EDUCON	N/A	12	57 (#6)	4.75 (#38)
8	CEUR Workshop Proceedings	CEUR-WS	12	26 (#11)	2.17 (#71)
9	Proceedings of Science	Sissa Medialab Srl	11	4 (#62)	0.36 (#154)
10	Communications in Computer and Information Science	Springer Science and Business Media Deutschland GmbH	10	26 (#11)	2.6 (#65)

TD: Total documents; TC: Total citations; CR: Citation rate (citations per document).

Table 8: The 10 influential documents in online physics education by number of citations

No.	Title	Document type	Source	Citing	No. of Citations
1	Virtual laboratories for education in science, technology, and engineering: A review	Article	Computers and Education	Potkonjak et al. (2016)	604
2	The role of new technologies in the learning process: Moodle as a teaching tool in Physics	Article	Computers and Education	Martín-Blas & Serrano-Fernández (2009)	279
3	Teaching and assessing knowledge integration in science	Short survey	Science	Linn et al. (2006)	211
4	A review of research on augmented reality in education: Advantages and applications	Article	International Education Studies	Saidin et al. (2015)	207
5	AutoTutor and family: A review of 17 years of natural language tutoring	Review	International Journal of Artificial Intelligence in Education	Nye et al. (2014)	198
6	Understanding randomness and its impact on student learning: Lessons learned from building the Biology Concept Inventory (BCI)	Review	CBE Life Sciences Education	Garvin-Doxas & Klymkowsky (2008)	163
7	Contract cheating by STEM students through a file sharing website: a Covid-19 pandemic perspective	Article	International Journal for Educational Integrity	Lancaster & Cotarlan (2021)	144
8	ALAS-KA: A learning analytics extension for better understanding the learning process in the Khan Academy platform	Article	Computers in Human Behavior	Ruipérez-Valiente et al. (2015)	140
9	Teaching and learning of postgraduate medical physics using Internet-based e-learning during the COVID-19 pandemic – A case study from Malaysia	Article	Physica Medica	Azlan et al. (2020)	136
10	The effect of the flipped classroom approach to OpenCourseWare instruction on students' self-regulation	Article	British Journal of Educational Technology	Sun et al. (2017)	134

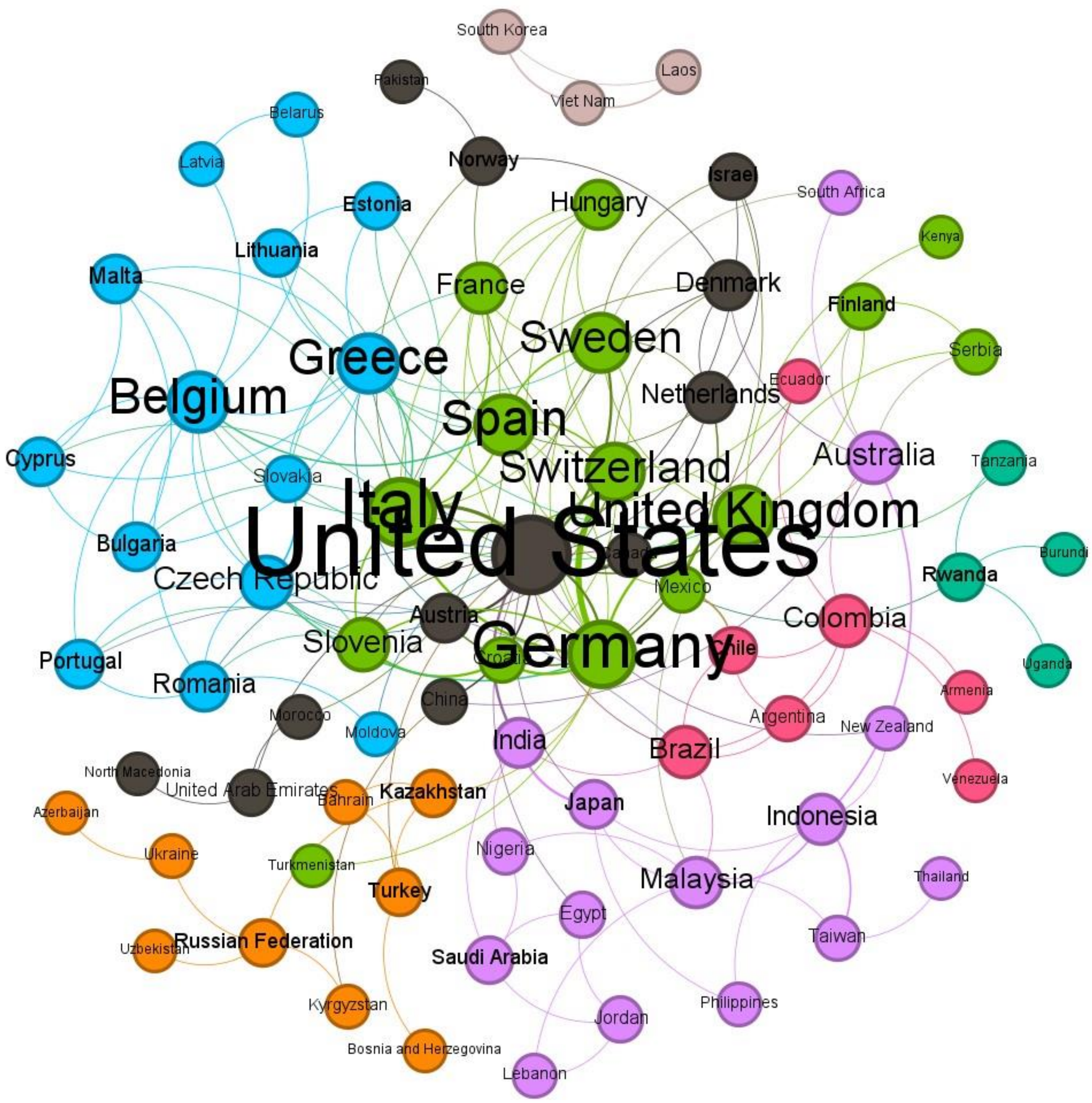

Figure 3: Network of international cooperation among countries in research on online physics education

Specifically, the United States emerges as the most central and influential country in this network, with the largest node and numerous connections to other countries. This reflects its leading role in fostering international collaboration in the field of online physics education. The United States maintains strong partnerships with many European nations, including Germany, Italy, Spain, Belgium, and Greece, as well as other key countries such as Australia, India, and Brazil. This extensive network suggests that the United States is a major hub of global research cooperation, contributing significantly to the exchange of knowledge and expertise across borders.

Germany and United Kingdom are also prominent nodes, indicating their active participation in international collaborations. Both countries show strong ties with European neighbors such as France, Switzerland, Italy, and Spain, underscoring the importance of regional cooperation within Europe. The United Kingdom also exhibits connections to countries in Asia and Oceania, reflecting its global research partnerships.

Interestingly, several countries from regions like Eastern Europe and Southeast Asia (such as Lithuania, Slovakia, Bulgaria, Malaysia, and Indonesia) have smaller but notable roles in this network, often linked to larger hubs like the United States or Germany. This suggests emerging collaborations from these regions, contributing to the growing diversity of perspectives in the field.

Countries from regions such as the Middle East (e.g., Saudi Arabia, United Arab Emirates, Turkey) and Central Asia (e.g., Kazakhstan, Russian Federation) show more localized collaboration, often connected to neighboring countries rather than participating in broad international networks. This could indicate region-specific research priorities or constraints in establishing broader global partnerships.

Smaller nodes such as South Korea, Vietnam, and Laos appear more isolated with fewer international collaborations, reflecting limited participation in global research on online physics education. This highlights the potential for future growth in international cooperation from these countries.

3.4.2. Collaboration among individual scholars

As shown in **Figure 4**, the relationships and collaborations among individual scholars in the field of online physics education were analyzed. The network is created with scholars who have collaborated with others on at least three published studies. The size of each node reflects the publication volume of each author, while the thickness of the links indicates the strength of collaboration between two scholars. Scholars with frequent collaborations are grouped into clusters, represented by similar colors, which helps to visualize the dynamics of co-authorship and the emergence of collaborative research groups.

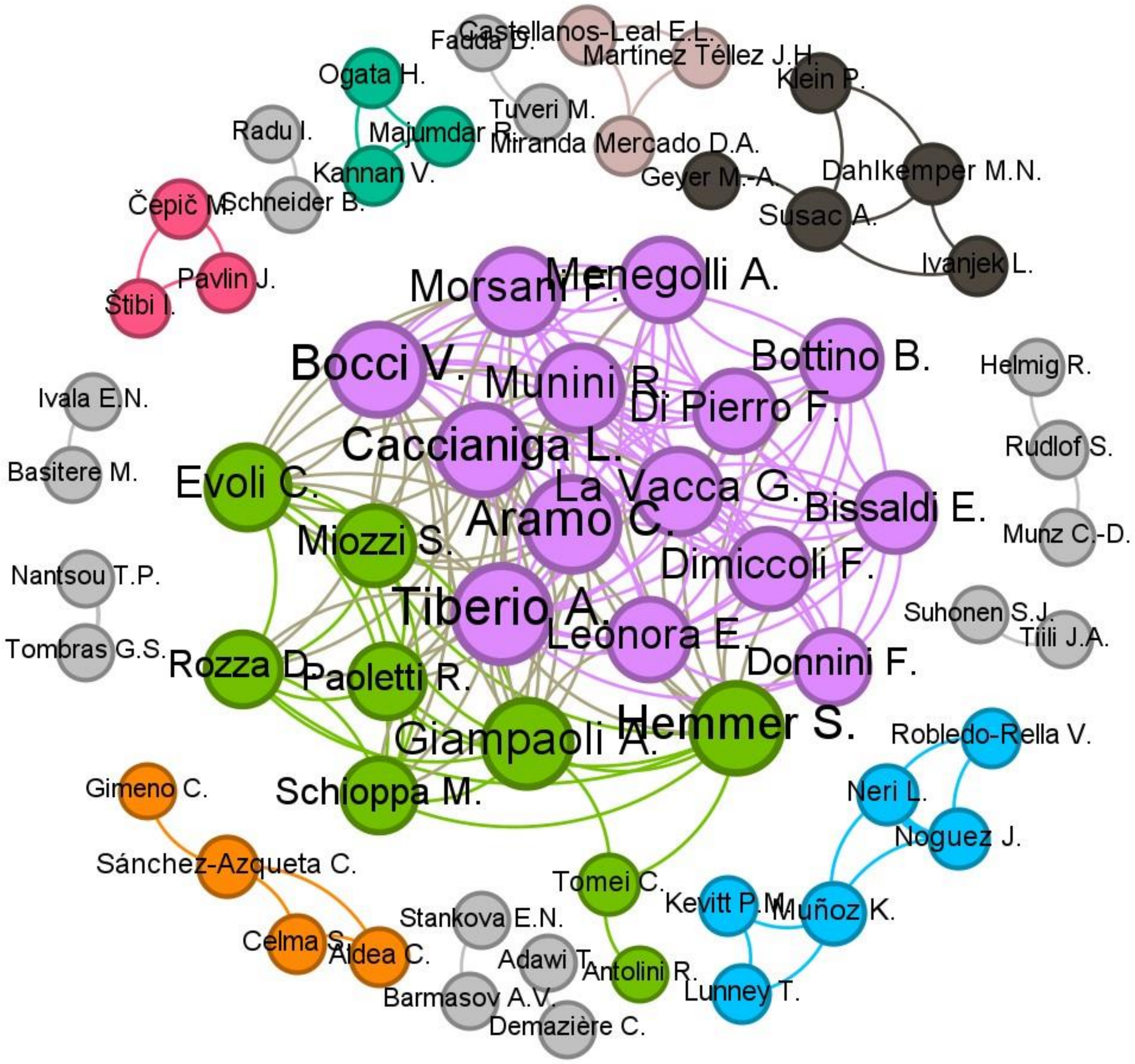

Figure 4: Network of collaboration among individual scholars in research on online physics education

At the center of the network, C. Aramo (Aramo et al., 2021) and L. Caccianiga (Hemmer et al., 2022) stand out as key figures with large nodes and strong connections, indicating their high productivity and significant collaborative efforts. These scholars are part of a dense purple cluster that includes A. Tiberio, V. Bocci, and R. Munini, among others (Aramo et al., 2021; Hemmer et al., 2022). This group forms a highly interconnected research team, suggesting they are likely involved in joint projects or large-scale collaborations in the field. Their close-knit structure reflects a strong research alliance that may be driving significant advancements in online physics education.

Another prominent group is the green cluster, where S. Hemmer, A. Giampaoli, and M. Schioppa are key contributors. This cluster is closely linked to the purple group, indicating overlapping or related research interests. The frequent collaborations among these scholars suggest they are part of a larger research initiative, fostering innovation and collective progress through joint publications.

On the network's periphery, scholars like L. Neri, J. Noguez, and V. Robledo-Rella form a smaller blue cluster, signifying a more specialized or focused research group. While they are active contributors, their work appears more independent from the central hubs, possibly representing niche research areas or separate project efforts. Similarly, the orange cluster featuring C. Sánchez-Azqueta and S. Celma reflects smaller-scale collaborations that may be regionally or project-based, with limited connections to the broader network.

Smaller, isolated collaborations are also present in the network. For instance, scholars like J. Pavlin and M. Čepič in the red cluster and C.-D. Munz and S. Rudlof in the gray cluster are part of tightly-knit but independent groups. These scholars work closely with a few collaborators but are not integrated into the larger co-authorship network, suggesting they may be focused on emerging or highly specialized areas within online physics education.

In summary, the author collaboration network reveals a clear distinction between central, highly collaborative research groups and more isolated, independent clusters. Key scholars like C. Aramo, L. Caccianiga, and A. Tiberio are influential drivers of research through their extensive networks, while smaller groups like those involving L. Neri and C. Sánchez-Azqueta suggest the presence of niche or emerging research areas. Increasing collaboration between these central and peripheral groups could enhance the diversity and impact of research in the field.

3.5. Keyword co-occurrence network analysis

In this subsection, we explore the co-occurrence of keywords used in publications on online physics education. By analyzing how frequently certain keywords appear together, we can gain insights into the main research themes, emerging trends, and potential areas for future investigation in the field. In this network (**Figure 5**), the size of each node represents the frequency of the keyword's occurrence in the dataset, while the links between keywords indicate how often they appear together in the same publications. Keywords frequently appearing together are clustered into thematic groups, represented by distinct colors. It is important to note that keyword pairs appearing less than three times were filtered out from the network.

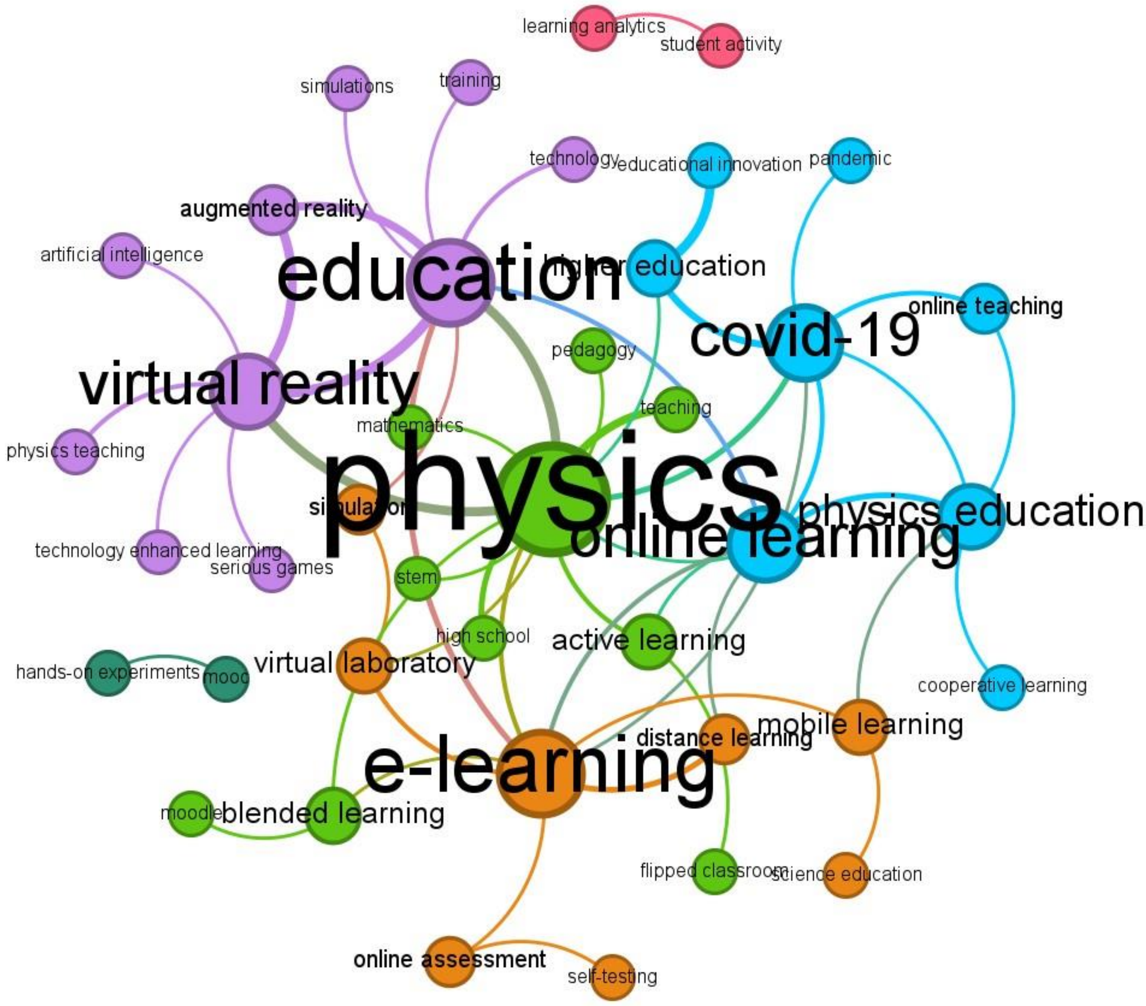

Figure 5: Keywords that appear most frequently and occur in at least three keyword pairs

Key research themes

At the center of the network, "physics" and "education" are the most prominent terms, reflecting the primary focus of research in this domain. The frequent co-occurrence of these terms with others such as "e-learning," "online learning," and "virtual reality" suggests that a significant portion of research is dedicated to exploring the intersection of technology and physics education. The integration of digital tools and online environments into physics instruction is a central theme in the field.

Terms like "virtual laboratory," "simulation," and "active learning" are also highly connected to the main nodes, indicating a focus on practical, hands-on learning experiences in virtual settings. These keywords reflect ongoing efforts to replicate or enhance traditional laboratory experiences using digital platforms, which is a core aspect of online physics education.

Emerging trends

Several clusters in the network highlight emerging trends in the field. The purple cluster includes terms such as "augmented reality," "virtual reality," and "simulations," pointing to growing interest in immersive technologies. These tools are being increasingly explored for their potential to create interactive, engaging learning environments in physics education.

The red cluster, featuring terms like "learning analytics" and "student activity," suggests an emerging focus on data-driven approaches to monitor and enhance student performance. The application of learning analytics in online physics education is becoming more prominent, reflecting a shift toward personalized and adaptive learning experiences based on student data.

Another key trend is represented by the blue cluster, where "COVID-19" is a central term. This cluster includes related keywords like "online teaching," "pandemic," and "distance learning," highlighting the impact of the pandemic on the rapid adoption of online learning tools. The global shift to remote education due to COVID-19 has prompted extensive research into online teaching practices and the challenges associated with it, especially in physics education.

Areas for future research

As digital learning becomes more widespread, ensuring that all students benefit from these tools, regardless of their background or location, remains a critical area for further exploration. The network reveals significant gaps in addressing "accessibility," "equity," and "inclusivity" in online physics education, suggesting these areas have not yet received sufficient attention. Future research should prioritize developing affordable and scalable technologies, such as mobile-first solutions and low-cost virtual labs, that can be widely adopted in regions with limited technological infrastructure. Additionally, interdisciplinary tools from other fields, such as medical simulations and crowdsourced research platforms, could be adapted to enhance the accessibility and engagement of physics education.

The socio-emotional impact of online learning remains an underexplored area in the current research landscape. Topics such as "well-being" and "stress" are not widely represented in the dataset, indicating the need for more research on how online learning environments affect students' emotional and psychological health. As physics is often considered a challenging subject, it is crucial that online learning strategies address not only academic challenges but also the emotional well-being of students.

4. Discussion

This bibliometric analysis provides a comprehensive overview of the research trends, collaboration patterns, and thematic areas in online physics education. The study reveals several key insights, along with implications for the future of research in this domain.

Key findings from this study include:

1. Growth and trends in publication: The data from 1990 to 2024 show a steady increase in research on online physics education, with a notable surge during

the COVID-19 pandemic. The pandemic accelerated the global adoption of online education, leading to a surge in related publications, particularly in 2020 and 2021. The subsequent stabilization of publication volume suggests that researchers are transitioning from exploratory research to more focused and refined studies. This highlights the growing importance of online education in physics and signals a sustained interest in improving digital teaching methods.

2. Key contributors and global collaboration: The United States, Spain, and the United Kingdom are the most influential contributors in this field, as reflected by their high number of publications and citation rates. The United States, in particular, plays a central role in international collaborations, as shown in the co-authorship network. However, countries like Indonesia and China are emerging as major contributors, although their work is yet to achieve the same global recognition as some European counterparts. This suggests opportunities for enhancing the international visibility of research from these regions through increased global collaboration. Institutions such as Tecnológico de Monterrey in Mexico and Universitas Negeri Padang in Indonesia are significant contributors to the volume of publications. However, their citation rates indicate moderate impact, suggesting that while these institutions are productive, further steps could be taken to improve the global influence of their research.
3. Influential scholars and collaborative networks: Scholars such as C. Aramo and L. Caccianiga have emerged as key figures in the field, actively contributing to dense and well-connected research clusters. The co-authorship network analysis suggests that these collaborative groups, particularly among European researchers, are associated with higher citation rates and broader research visibility, indicating a positive impact on the quality and influence of the work produced. In contrast, more isolated research groups, such as those involving L. Neri and J. Noguez, tend to have fewer collaborative ties, which may limit the dissemination and impact of their research. These patterns highlight the importance of frequent and diverse collaboration, which can enhance methodological rigor, enable interdisciplinary perspectives, and increase the overall reach and relevance of online physics education research.
4. Keyword co-occurrence and emerging research themes: The keyword co-occurrence analysis reveals several dominant themes in the field. The terms "physics," "education," and "e-learning" are central, reflecting the field's focus on integrating digital tools into physics education. Emerging trends include the use of "augmented reality," "learning analytics," and "virtual laboratory," highlighting the innovative approaches being developed to enhance student engagement and learning outcomes. The impact of COVID-19 on research is also evident, with terms like "pandemic" and "distance learning" appearing prominently in recent studies. This shift toward online teaching during the pandemic has accelerated research into effective digital teaching methods, particularly in STEM fields like physics.

To advance the field, we propose the following implications for future research:

1. Global collaboration and visibility: While countries such as the United States and the United Kingdom lead in research contributions, emerging regions like Southeast Asia and Latin America show growing potential. To further enhance the global impact of research from these regions, promoting international collaboration and increasing visibility through high-impact publications is crucial (Okamura, 2023). This can lead to region-specific solutions that address the unique challenges faced in online physics education. Additionally, fostering collaboration within emerging regions could help develop localized innovations suited to their specific contexts.
2. Key contributors and collaborative networks: The analysis highlights influential scholars and institutions driving innovation in the field. However, there are also isolated research groups with fewer collaborations, thereby limiting the broader impact of their work. To address this, future efforts should aim to bridge the gap between centralized and isolated research groups, fostering more interdisciplinary collaboration and idea-sharing. This would enhance the exchange of methodologies and encourage diverse contributions to the global research landscape (Paraskevopoulos et al., 2021).
3. Document types and research impact: Different document types exhibit varying levels of impact, with journal articles showing higher citation rates than conference papers and book chapters. Future research seeking broader influence should prioritize publishing in high-impact journals, while review articles offer a valuable way to synthesize knowledge and guide new research directions. Specific topics such as virtual reality, learning analytics, and virtual laboratories are ripe for review articles, which can consolidate existing knowledge and provide a roadmap for future technological advancements (Li & Liang, 2025).
4. Keyword trends and emerging research themes: The keyword co-occurrence analysis reveals that virtual laboratories, augmented reality, and learning analytics are central themes in online physics education. Future research should not only expand these areas but also explore their interdisciplinary applications. For example, integrating technologies from fields like medical simulations could introduce more immersive and engaging learning experiences for physics students. These themes should also be explored in the context of accessibility, ensuring that such technologies are available to students across diverse socioeconomic backgrounds (Vidak et al., 2024).
5. Technological innovation and student engagement: The increasing integration of digital tools into physics education highlights the need for refining technologies like virtual reality, adaptive learning platforms, and learning analytics (Vidak et al., 2022). These tools have the potential to revolutionize student engagement in online learning environments. Future research should explore how these technologies can be used to create personalized learning experiences, address academic challenges, and enhance student participation.
6. Socio-emotional impacts and longitudinal studies: Socio-emotional factors, such as motivation, well-being, and stress, remain underexplored in online physics education (Balta & Mohammad, 2017). Future research should focus

on understanding these aspects through longitudinal mixed-methods studies that combine quantitative measures (e.g., validated surveys on student motivation, anxiety, or engagement) with qualitative approaches (e.g., in-depth interviews or reflective journals) to capture changes over time. Studies could also incorporate experience sampling methods to assess real-time emotional states during online learning sessions. Additionally, comparing outcomes across different instructional modalities (e.g., synchronous vs asynchronous, simulation-based vs traditional video lectures) could shed light on how various design elements impact socio-emotional well-being. This line of inquiry would provide deeper insights into how students' emotional states evolve in response to online learning environments, particularly in cognitively demanding subjects like physics. Addressing these factors is essential to designing holistic and supportive online learning strategies that foster both academic achievement and emotional resilience.

5. Conclusion

This bibliometric study provides a comprehensive overview of the evolution and current landscape of online physics education research. The analysis of 1,118 publications from 1990 to 2024 reveals several key insights. First, research output has significantly increased over the past decade, with notable contributions from countries such as the United States and the United Kingdom. However, emerging regions like Southeast Asia and Latin America are showing growing participation, highlighting the potential for more inclusive global collaboration. The identification of leading authors and institutions also emphasizes the role of strong collaborative networks in shaping the field. Keyword co-occurrence analysis indicates that topics such as virtual laboratories, augmented reality, and learning analytics are at the forefront of current research. These technologies offer promising avenues for enhancing student engagement and learning outcomes in physics education. However, challenges remain in ensuring equitable access and addressing the socio-emotional dimensions of online learning. Future research should focus on evaluating the long-term effectiveness of these emerging technologies, exploring strategies to improve accessibility, and understanding the emotional and motivational experiences of diverse learner populations.

6. Statements and Declarations

Competing Interest

The authors declare that they have no conflict of interest.

Data Availability Statement

The data supporting the findings of this study are sourced from the Scopus database. However, access to these data is restricted due to licensing agreements, and they are not publicly available. The authors can provide the data upon reasonable request.

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