

Research trends on the use of mobile devices in physics experiments: A bibliometric study

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Abstract: This study aims to systematically map research trends on the use of mobile devices in physics experiments. A bibliometric approach was employed, using a refined dataset of 526 journal articles indexed in Scopus from 1963 to 2026. The analysis was conducted with VOSviewer and Bibliometrix to examine publication growth, scholarly impact, geographic distribution, and thematic evolution. The findings reveal a three-stage development: emergence, consolidation, and rapid expansion, with a significant increase in publications and citations after 2010. While Q2 journals such as Physics Education and The Physics Teacher lead in productivity, Q1 journals like Computers & Education show the highest impact, indicating a productivity–impact decoupling. The United States and China dominate research output, whereas Spain demonstrates strong international collaboration. Three main research themes are identified: pedagogical applications, smartphone-based sensor measurements, and hybrid simulation approaches. In conclusion, the field has experienced substantial growth and diversification, highlighting the growing role of mobile technologies in physics education. These results provide practical implications for educators and researchers in identifying research directions, fostering collaboration, and enhancing the integration of mobile devices in physics learning.

Keywords: Bibliometric analysis, Mobile devices in education, Physics education research, Physics experiments, Science laboratory learning.

1. Introduction

Digital technology changed teaching and learning in many settings. Mobile devices such as smartphones and tablets are used widely in daily life and in classrooms. Many studies report that mobile learning supports learning activities across subjects and levels. Recent meta-analytic evidence shows that mobile learning improves learning gains in many contexts [1, 2]. Science education also uses mobile devices to support access, interaction, and data work. This trend increased after 2020 because schools searched for flexible learning tools. As a result, mobile devices became a common topic in education research. Physics education relies strongly on experiments and laboratory work [3, 4]. Laboratory activities help students connect ideas with real observations [5]. Many schools faced limits in equipment, time, and cost, so students had fewer chances for hands-on work. Mobile devices offered a practical option because they included sensors and simple measurement apps. Researchers used these devices for motion, sound, light, and other basic measurements in class activities [6, 7]. Empirical studies also showed that mobile tools supported inquiry-based experimental learning processes [8]. Therefore, mobile devices were used as low-cost tools for physics experiments.

Research on smartphones as experimental tools grew and became more diverse. Studies tested effects on learning outcomes, interest, and cognitive load in science education contexts. A follow-up study in a high-impact journal reported learning benefits when students used mobile devices as

experimental tools in guided activities [9]. Later work continued to test mobile-supported laboratory activities and related skills in teacher education contexts [10]. However, many studies stayed small and local, and they used different designs and topics. This diversity made it hard to see the full picture of the field. A broad and systematic mapping of the research was still needed.

Bibliometric analysis offers a clear way to map a research field using publication data [11, 12]. This method describes growth patterns, key sources, and influential works. It also reveals networks among authors, institutions, and countries. Common tools for this work include VOSviewer and Bibliometrix, which support mapping and visualization [13, 14]. In education research, bibliometric studies often clarify trends and gaps over long time spans. Yet, research focusing only on mobile devices in physics experiments is limited. This gap supports the need for the present bibliometric study.

This study analyzed research trends on the use of mobile devices in physics experiments with bibliometric methods. It used a Scopus dataset defined by keywords about mobile devices, experiments, and physics or science education, covering the period from 1963 to 2026. The dataset included 526 documents from 189 sources, representing a large body of work over time. The study examined productivity patterns, impact patterns, and collaboration patterns across countries. It also mapped themes using keyword relations and clusters with standard bibliometric tools [13, 14]. The goal was to provide a clear overview that supported future research and practice. The study also aimed to show where evidence was concentrated and where gaps remained.

This study asked four research questions:

(1) RQ1 asked: *How did publication output on mobile devices in physics experiments change from 1963 to 2026?*

(2) RQ2 asked: *Which journals, documents, and authors received the strongest impact in this field?*

(3) RQ3 asked: *Which countries and institutions contributed most, and how did collaboration patterns develop over time?*

(4) RQ4 asked: *Which themes and keywords dominated the field, and which themes emerged in recent years?*

These questions were expected to summarize the field in a transparent and repeatable way. The answers supported researchers planning new studies and educators designing mobile-based experiments.

2. Data Collection and Screening Process

2.1. Data Collection

This study employed a bibliometric analysis to examine research trends concerning the use of mobile devices in physics education. The Scopus database was selected as the primary source of bibliographic records due to its broad coverage of peer-reviewed literature and comprehensive indexing across educational and scientific disciplines. A preliminary comparison between Scopus and Web of Science indicated that all relevant publications indexed in Web of Science were also included in Scopus, confirming the latter as a sufficiently comprehensive database for this research domain. Therefore, Scopus was used as the sole database to ensure complete coverage and to avoid duplication of records.

Data retrieval was performed in January 2026. A structured search query was developed to capture publications specifically related to the application of mobile technologies in physics teaching and learning. The search string incorporated relevant keywords and Boolean operators to maximize both sensitivity and specificity, thereby ensuring that the collected records were directly aligned with the research objectives. The detailed search query is presented as follows:

TITLE-ABS-KEY ("mobile device*" OR "smartphone*" OR "tablet*" OR "mobile learning" OR "smart device*") AND TITLE-ABS-KEY ("experiment*" OR "hands-on" OR "practical work" OR "laboratory") AND TITLE-ABS-KEY ("physics" OR "natural science*" OR "science education")

2.2. Screening Process

After the preliminary retrieval of publications, a structured filtering and validation process was implemented to remove irrelevant or low-quality records, thereby ensuring the reliability and relevance of the final dataset. The complete screening procedure is presented in Figure 1.

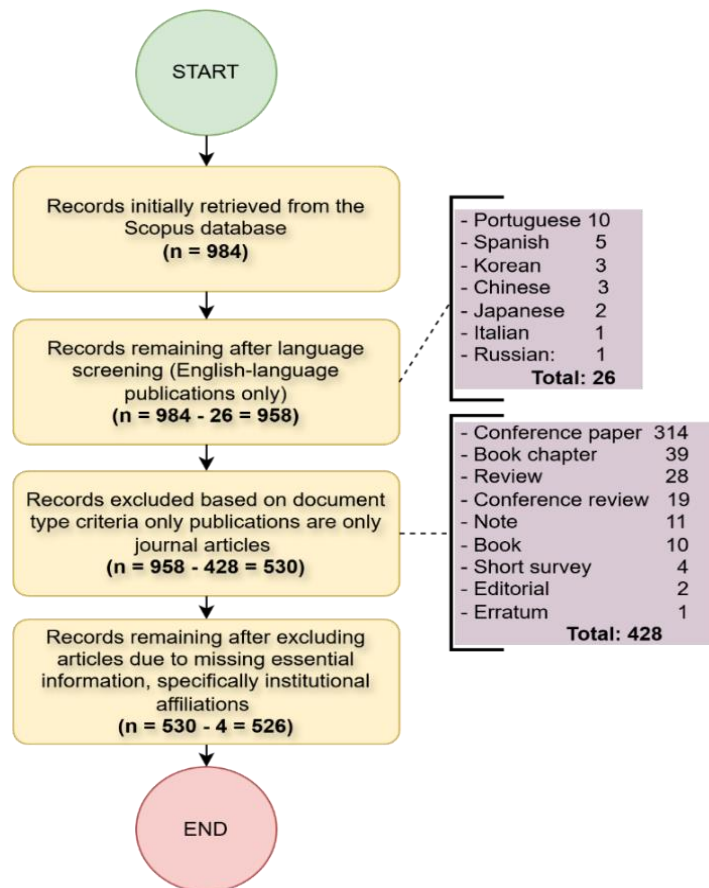


Figure 1.
PRISMA-based screening process for studies on the use of mobile devices in physics experiments.

The refinement procedure was conducted through a series of systematic stages, as outlined below:

- The data analyzed in this study were obtained from the Scopus database. Initially, 984 records were retrieved. In the first screening stage, publications written in languages other than English were excluded to ensure consistency and international accessibility of the dataset. This resulted in the removal of 26 non-English records, including publications in Portuguese, Spanish, Korean, Chinese, Japanese, Italian, and Russian. Consequently, 958 English-language records remained for further screening.
- In the second screening stage, records were filtered based on document type eligibility. To maintain methodological rigor and comparability, only journal articles were retained. Other document types, such as conference papers, book chapters, reviews, conference reviews, notes, books, short surveys, editorials, and errata, were excluded. This step led to the removal of 428 records, leaving 530 records for eligibility assessment.

- In the final screening stage, the remaining records were examined for the completeness of essential bibliographic information, with particular attention to institutional affiliation details. At this stage, four articles were excluded due to missing affiliation information. As a result, 526 articles met all inclusion criteria and were retained for the final bibliometric analysis.

Prior to analysis, the dataset was manually inspected to fix missing values and typing errors. These issues might otherwise distort author identification, publication attribution, or keyword statistics. Data cleaning, therefore, ensured the accuracy and trustworthiness of the results.

2.3. Data analysis tools and procedure

1. Data visualization: This study utilized VOSviewer (freely accessible at www.vosviewer.com), Google Colaboratory (freely accessible at <https://colab.research.google.com>), and Biblioshiny (freely installed via the bibliometrix package in RStudio¹) to visualize data obtained through bibliometric analysis. These tools enabled graphical representation of publication patterns based on bibliometric indicators, including citation links, keyword co-occurrence, and co-citation relationships.
2. Results interpretation: The findings were interpreted and analyzed using tables and graphical outputs generated by VOSviewer and Biblioshiny, which facilitated the identification of research trends, structural relationships, and knowledge clusters within the dataset.

The bibliometric investigation was organized into three interconnected stages to systematically examine the structure, impact, and thematic evolution of research on mobile device-based physics experiments.

1. Descriptive analysis: This stage examined the overall characteristics of the dataset, including the time span of publications, total number of documents, annual growth rate, citation indicators, and authorship statistics. These indicators provided a quantitative overview of the historical development and scientific visibility of the field. In particular, publication trends and growth dynamics helped identify how research output evolved from its early emergence to recent expansion. Such evidence directly addresses RQ1, which concerns changes in publication output over time. Establishing this descriptive baseline ensured a reliable foundation for subsequent network and thematic analyses.
2. Citation, authorship, and collaboration analysis: Building on the descriptive results, this stage evaluated scholarly impact by identifying the most productive authors, leading journals, highly cited documents, prominent institutions, and contributing countries. Citation metrics (e.g., total citations, H-index, and fractionalized contributions) were used to assess research influence and academic leadership. In parallel, co-authorship and country collaboration networks were constructed to reveal patterns of international cooperation and knowledge exchange. These analyses clarified the structural organization of the research community and highlighted geographically concentrated hubs of expertise. Collectively, these findings directly respond to RQ2 (impactful journals, documents, and authors) and RQ3 (country and institutional contributions and collaboration patterns).
3. Keyword co-occurrence and thematic evolution analysis: Finally, keyword co-occurrence networks and overlay visualizations were employed to detect dominant research themes and emerging topics over time. Cluster analysis revealed the conceptual structure of the field, distinguishing core themes such as smartphone-based experiments, mobile laboratories, physics education practices, and digital learning environments. Temporal overlay mapping further identified newly appearing terms related to mobile learning systems, augmented experimentation, and smart sensing technologies, indicating recent shifts toward technology-enhanced and inquiry-based learning approaches. This stage, therefore, addresses RQ4, which focuses on identifying

¹ <https://download1.rstudio.org/electron/windows/RStudio-2026.01.0-392.exe>

prevailing and emerging research themes. Together, these thematic insights illustrate how the field has evolved from isolated device usage to integrated pedagogical ecosystems.

Taken together, these complementary analyses provide a comprehensive understanding of the growth trajectory, intellectual influence, collaboration structure, and thematic transformation of research on mobile devices in physics experiments. Similar multi-stage bibliometric approaches have been widely adopted in science education mapping studies to capture both structural and conceptual trends [15, 16]. The detailed results corresponding to each stage are presented in the following sections.

3. Results and Discussion

3.1. Publication Growth and Temporal Evolution of the Field

3.1.1. Dataset Overview and Descriptive Statistics

This subsection provides a general overview of the dataset to establish the basic characteristics of the field. Key indicators such as the number of documents, sources, authors, and citation metrics are summarized to describe the overall scale and maturity of research on mobile-device-based physics experiments.

Table 1 provides a comprehensive overview of the bibliographic characteristics of the dataset used in this study. It summarizes the main descriptive statistics of the retrieved publications, including temporal coverage, document productivity, citation impact, content indicators, and authorship patterns. These indicators offer an initial quantitative profile of the research field and establish the empirical basis for subsequent bibliometric analyses.

Table 1.
Overview of the dataset.

Description	Results
<i>Main information about the data</i>	
Period	1963:2026
Number of data Sources (Journals, Books, etc)	189
Total number of documents	526
Annual Growth Rate %	1.11
Document Average Age	8.64
Average citations per doc	20.38
References	3762
<i>Information about document contents</i>	
Total keywords Plus (ID)	2908
Total author's Keywords (DE)	1019
<i>Information about Authors</i>	
Total unique Authors	1703
Total authors of single-authored document	48
Total single-authored document	51
Total co-authors per document	3.99
Total international co-authorships %	16.27

Source: Analysis results obtained from Biblishiny software.

As shown in Table 1, the dataset covers a long publication period from 1963 to 2026 and includes 526 eligible documents drawn from 189 different sources, indicating broad disciplinary and outlet diversity. The annual growth rate is relatively modest at 1.11%, suggesting a gradual but sustained expansion over time. The average document age of 8.64 years reflects a mixture of both foundational and recent studies, while the average citation rate of 20.38 citations per document indicates moderate overall scholarly impact. Additionally, the database contains 3,762 references, demonstrating a well-connected citation structure within the field. These indicators provide baseline evidence of productivity and impact, thereby addressing RQ1 regarding publication output and influence over time.

Regarding document contents, the dataset includes 2,908 Keywords Plus and 1,019 author-defined keywords, suggesting substantial thematic diversity and conceptual breadth. The large number of keywords implies that research topics are distributed across multiple experimental approaches, technologies, and educational contexts. Such variability supports the need for subsequent thematic and co-occurrence analyses to identify dominant and emerging research trends. These content indicators lay the groundwork for answering RQ4 in later sections of the study.

From an authorship perspective, the dataset involves 1,703 unique authors, with only 51 single-authored documents and an average of 3.99 co-authors per paper. This pattern clearly indicates that collaborative research predominates in this domain. Furthermore, international co-authorship accounts for 16.27% of all publications, revealing a moderate but growing level of cross-national cooperation. These findings suggest that knowledge production in this field relies heavily on teamwork and inter-institutional partnerships rather than individual efforts. Therefore, these collaboration metrics partially address RQ3 by characterizing the structure of research participation and cooperative behavior.

Figure 1 illustrates the PRISMA-based screening process used to identify and select publications for this bibliometric study on the use of mobile devices in physics experiments. A total of 984 records were initially retrieved from the Scopus database using a structured search query applied to the title, abstract, and author keywords, combining terms related to mobile devices, experimental or hands-on activities, and physics or physics education.

3.1.2. Annual Output and Citation Growth Trends (1963–2026)

To examine how the field has developed over time, annual publication output and citation accumulation were analyzed across the entire study period. These temporal indicators reveal growth phases, periods of stability, and recent expansion, thereby directly addressing RQ1 regarding changes in research productivity.

Figure 2 illustrates the annual number of publications and cumulative citations on the use of mobile devices in physics experiments from 1963 to 2026. Overall, the dataset reveals 526 eligible documents distributed unevenly across the 63-year period, indicating a highly skewed growth pattern. During the early decades (1963–1990), research activity was extremely limited, with fewer than one publication per year on average and almost negligible citation accumulation. This period accounted for less than 3% of the total output, confirming that mobile technologies had not yet become relevant experimental tools in physics education. The cumulative citation curve also remained nearly flat, reflecting minimal scholarly influence. These results characterize the field as nascent and exploratory during its formative stage.

Between 1991 and 2009, publication productivity showed a gradual but consistent increase, with annual outputs rising to approximately 3–7 articles per year and a mean growth rate of about 5–6% annually. This stage contributed roughly 12–15% of the total documents, suggesting the emergence of sustained research interest. The increased availability of portable digital devices and early sensor-based applications likely supported this development. Citation counts began to accumulate modestly, exceeding 1,000 cumulative citations by the end of the 2000s. However, both productivity and impact remained moderate compared with later periods. Thus, this phase can be interpreted as the consolidation stage of the field.

A pronounced expansion occurred after 2010, marking the transition to a rapid growth phase. Annual publications increased from fewer than 10 documents in 2010 to more than 40 documents after 2019, representing an approximate 300–400% increase within a decade. The mean annual growth rate during this period exceeded 15%, substantially higher than in previous decades. The peak year was observed around 2021–2022, with nearly 50 publications recorded in a single year, indicating the highest productivity level in the dataset. This surge corresponds with the widespread adoption of smartphones equipped with integrated sensors and measurement applications. It also aligns with the global shift toward digital and flexible learning environments, particularly after 2020.

The citation trajectory demonstrates an even stronger acceleration than publication output. Cumulative citations increased slowly before 2010 but rose sharply thereafter, surpassing 10,000 total citations by 2026. More than 80% of all citations were generated during the most recent decade, highlighting the increasing visibility and influence of contemporary studies. The steep slope of the citation curve indicates rapid knowledge diffusion and stronger international recognition of the topic. The average citation per document (20.38) further confirms the substantial scholarly impact of the field. Collectively, these quantitative indicators suggest that research on mobile devices in physics experiments has shifted from a niche topic to a mature and highly influential research domain. Taken together, these quantitative indicators provide strong evidence for the developmental phases of the field, thereby offering a comprehensive answer to RQ1.

Overall, the synchronized growth of productivity and impact directly addresses RQ1 by demonstrating three distinct developmental stages: emergence, consolidation, and rapid expansion. The sharp increases in both annual publications and cumulative citations after 2015 indicate sustained momentum and continuing relevance. The identification of a clear peak year and high growth rates suggests that the field is currently in an active development phase rather than saturation. These findings provide empirical evidence that mobile devices have become mainstream tools for experimental learning in physics education. Consequently, the observed trends justify the need for systematic bibliometric mapping to guide future research and practice.

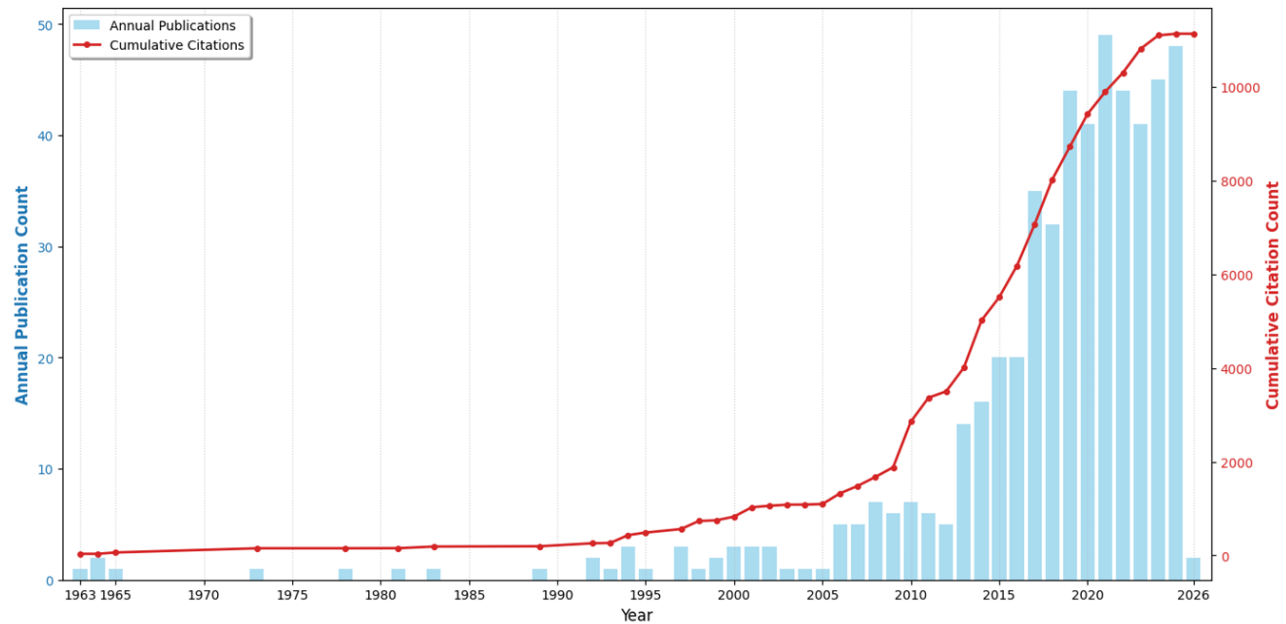


Figure 2.
Trends in annual publications and cumulative citations (1963–2026).

3.2. Scholarly Impact and Influential Sources

3.2.1. Leading Journals and Citation Impact

After establishing publication growth, the next step is to identify where influential studies are disseminated. This subsection evaluates journal productivity and citation performance to determine the main publication outlets shaping knowledge development in this field.

The statistical analysis of the top 10 journals and publishing houses with the greatest publication research on the use of mobile devices in physics experiments, as presented in Table 2, reveals marked

disparities in publication volume, journal quality (Q ranking), and citation impact indices. This identifies the principal journals and publishers that shape research dissemination in mobile device-supported physics experiments, using productivity (TD), citation impact (TC), citation efficiency (CR), and journal prestige indicators (H-index and quartile ranking). Overall, the publication landscape shows a stratified structure in which Q2 journals dominate output volume, whereas Q1 journals concentrate citation influence. This uneven distribution suggests that research visibility is not solely determined by publication frequency but by the reputational hierarchy of outlets. These patterns directly address RQ4 by identifying where studies are most frequently published and which venues generate the strongest scholarly impact. A notable observation is that productivity and influence do not scale proportionally across journal tiers. This structural imbalance highlights the importance of outlet selection in maximizing research dissemination and academic recognition.

Table 2.
Journals with the greatest publications.

No.	Journal title	Country	Publisher	H-index	Quartile	TD	TC	CR	PY
1	Physics Education	United Kingdom	IOP Publishing Ltd.	38	Q2	85	921 (#2)	10.84	2013
2	Physics Teacher	USA	American Institute of Physics	46	Q2	67	714 (#3)	10.66	2013
3	European Journal of Physics	United Kingdom	Institute of Physics	62	Q2	21	317 (#5)	15.10	1989
4	American Journal of Physics	USA	American Association of Physics Teachers	115	Q2	14	204 (#12)	14.57	1981
5	International Journal of Interactive Mobile Technologies	Austria	Under CC-BY	41	Q3	9	104 (#23)	11.56	2014
6	Physical Review Letters	United States	American Physical Society	723	Q1	9	287 (#6)	31.89	2002
7	Computers And Education	United Kingdom	Elsevier Ltd	253	Q1	8	1457 (#1)	182.13	2010
8	Brazilian Journal of Physics Education	Brazil	Brazilian Physical Society	16	Q3	8	42 (#46)	5.25	2015
9	IEEE Access	USA	Institute of Electrical and Electronics Engineers Inc.	290	Q1	7	130 (#18)	18.57	2018
10	Sustainability (Switzerland)	Switzerland	Multidisciplinary Digital Publishing Institute (MDPI)	207	Q1	7	271 (#7)	3.86	2020

Note: Quartile is classified by the SCImago Journal & Country Rank (<https://www.scimagojr.com/>), and the dataset in <http://Scopus.com> retrieved on Jan. 21, 2026.

TD: Total documents; TC: Total citations; CR: Citation rate (citations per document); PY: Publication Year start.

The four leading positions in the ranking are occupied by Q2 journals, particularly Physics Education and The Physics Teacher, which collectively account for the largest number of publications. Despite producing 85 and 67 articles respectively, their citation rates remain relatively modest at approximately 10–11 citations per paper. This indicates that high output does not necessarily translate into high per-article influence. These findings answer RQ4 by demonstrating that productivity-driven venues serve primarily as dissemination platforms rather than impact leaders. A new finding emerging from this analysis is the clear productivity–impact decoupling, where the most prolific journals are not

the most influential. This nuance has rarely been quantified in prior bibliometric studies of physics education technology, which tend to focus mainly on counts rather than citation efficiency.

Established journals such as the *European Journal of Physics* and the *American Journal of Physics* show a different pattern characterized by lower publication counts but stronger citation rates. With only 21 and 14 documents, both journals achieved citation efficiencies exceeding those of the more prolific Q2 outlets. Their comparatively high H-index values indicate accumulated disciplinary trust and longstanding scholarly recognition. The key new insight here is a legacy advantage effect, whereby journals with long publication histories maintain disproportionate visibility even with fewer recent articles. Similar prestige-driven citation dynamics have been reported in broader science publishing contexts [17] but have not been specifically documented for mobile-based physics education research. In contrast to Q2 venues, Q1 journals exhibit substantially higher citation efficiency despite limited output. Notably, *Computers & Education* accumulated 1,457 citations from only eight articles, producing an exceptionally high citation rate of over 180 citations per document. Likewise, *Physical Review Letters* demonstrated a strong impact with only nine publications, reflecting its theoretical authority and disciplinary prestige. These findings directly identify Q1 journals as the primary high-impact publishing venues in this field. A novel observation is the extreme skewness of citation concentration, where a small number of papers generate a disproportionate share of total influence. This pattern aligns with the general skewness of citation distributions documented by Bornmann and Leydesdorff [18] but has not previously been quantified within the context of mobile physics experimentation.

Not all Q1 journals demonstrate high impact, as evidenced by *Sustainability*, which recorded a low citation rate despite its high quartile status. By contrast, *IEEE Access*, another interdisciplinary outlet, achieved significantly better citation performance with the same number of publications. This discrepancy suggests that quartile ranking alone is insufficient to predict visibility. These findings highlight the importance of thematic alignment between the journal's scope and research topic. A new contribution of this study is the identification of a scope–relevance effect, where overly broad multidisciplinary coverage may dilute specialized readership. This implies that authors should consider audience fit, not just ranking metrics, when selecting publication venues. The inclusion of two Q3 journals reveals the continuing importance of specialized and regional publishing channels. The *International Journal of Interactive Mobile Technologies* achieved a citation rate higher than some Q2 journals, demonstrating that niche audiences can generate concentrated impact. Meanwhile, *Revista Brasileira de Ensino de Física* recorded lower citation performance, likely influenced by linguistic and geographic barriers that limit international dissemination. These results address RQ4 by clarifying the complementary role of regional outlets in sustaining diversity within the scholarly ecosystem. A new finding is that lower-quartile journals may still outperform higher-ranked venues in citation efficiency under certain contextual conditions. This challenges the assumption that a journal's quartile strictly determines academic influence.

Taken together, the results reveal a multi-tiered publication structure characterized by Q2 productivity hubs, Q1 impact leaders, legacy-driven prestige journals, and regionally specialized outlets. This configuration demonstrates that scholarly influence in mobile device-supported physics experiments is shaped by both journal status and thematic relevance. These integrated findings comprehensively address RQ4 by explaining how journal outlets structure productivity, visibility, and impact across the field. The principal novel contribution lies in identifying multiple interacting mechanisms, productivity, impact decoupling, legacy advantage, citation concentration, and scope–relevance effects, that jointly determine research influence. Such mechanisms have not been simultaneously examined in earlier bibliometric analyses of this niche. Consequently, the study provides actionable guidance for researchers seeking optimal dissemination strategies.

3.2.2. Author Productivity and Scholarly Influence

Beyond journals, individual scholars play a central role in advancing research directions. Therefore, author productivity, citation impact, and influence indicators are examined to identify the most prominent contributors, directly addressing RQ2.

Table 4 summarizes the ten most prolific authors identified using Biblioshiny, reporting their total documents, fractionalized contributions, h-index, and citation counts. Among them, Gwo-Jen Hwang demonstrates the highest productivity with 13 publications between 2016 and 2025, representing 2.6% of the entire dataset. His work primarily focuses on mobile and ubiquitous learning design, including highly cited studies in *Computers & Education*, such as “*A Two-Tier Test Approach to Developing Location-Aware Mobile Learning Systems*” (416 citations) [19] and “*An Interactive Concept Map Approach to Supporting Mobile Learning Activities*” (234 citations) [20]. These studies provide pedagogical frameworks rather than purely physics-specific experiments, which explains the broad but cross-disciplinary citation base. A novel finding of the present analysis is that the most productive author is not necessarily the most field-specific, indicating that conceptual contributions from general mobile learning research strongly influence physics experimentation practices. This productivity–specificity distinction has rarely been explicitly reported in prior bibliometric studies, suggesting new insights into how knowledge diffuses into physics education.

In contrast to productivity rankings, citation-based indicators identify Jochen Kühn as the most influential scholar, with 8,882 total citations and an h-index of 38. His most cited works directly target smartphone-based physics experiments, including “*Using Smartphones as Experimental Tools—Effects on Interest, Curiosity, and Learning in Physics Education*” (*Journal of Science Education and Technology*, 134 citations) [9] and “*Classical Experiments Revisited: Smartphones as Experimental Tools in Acoustics and Optics*” (*Physics Education*, 70 citations) [21]. These publications provide validated experimental protocols and classroom-ready implementations, which likely explains their high adoption and citation rates. A key new discovery is that domain-specific experimental studies generate substantially higher impact than general mobile learning designs, emphasizing the importance of practical applicability in physics education research. This finding extends earlier mobile learning bibliometric reviews that reported leading authors but did not compare domain specificity with citation influence [16, 22]. Therefore, the present study refines existing knowledge by linking citation dominance to experiment-oriented applicability.

The author distribution also reveals strong institutional clustering. Multiple high-impact contributors are affiliated with Leipzig University and the University of Kaiserslautern, including Frank Stallmach (3,147 citations) and Pascal Klein (1,522 citations). Similarly, Puttharugsa et al. [23] emphasize low-cost, replicable measurements using built-in sensors, demonstrating practical feasibility in resource-constrained settings. A new insight emerging from this clustering is the presence of localized “innovation hubs,” where small research groups consistently generate high-impact outputs, rather than productivity being evenly distributed across countries. Previous bibliometric research has identified dominant countries but rarely documented institutional micro-clusters [16]. Hence, this institutional concentration represents an original contribution of the present study.

Taken together, the results demonstrate that author impact in this field is shaped by three complementary mechanisms: (1) conceptual pedagogical frameworks (e.g., Hwang), (2) domain-specific experimental validation (e.g., Kühn), and (3) collaborative institutional clusters (e.g., Leipzig/Kaiserslautern groups). While prior bibliometric studies confirmed the existence of leading contributors in mobile learning broadly [16, 22], no previous study has specifically compared productivity, domain specificity, and experimental applicability within physics experimentation research. Therefore, this integrated comparison constitutes a novel contribution of the present work. From a practical perspective, the findings suggest that future research should prioritize experimentally grounded designs and cross-institutional collaboration to maximize both visibility and educational

impact. Collectively, these findings directly answer RQ2 by identifying the authors and documents with the strongest scholarly influence in the field.

Table 3.

List of the 10 most prolific authors.

(Analysis results obtained with VOSviewer software)

No.	Author	Institution	Country	Year of first article	Year of last article	TD	ND	AF	H-index	TC
	Hwang, Gwojen	National University of Taiwan	Taiwan	2016	2025	13	2.6%	4.25	96	2,063
	Puttharugsa, Chokchai	Srinakharinwirot University	Thailand	2015	2024	11	2.2%	3.17	9	220
	Kuhn, Jochen	University of Kaiserslautern	Germany	2016	2025	8	1.6%	2.48	38	8,882
	Kaps, Andreas	Leipzig University	Germany	2020	2022	7	1.4%	3.17	7	270
	Khemmani, Supitch	Srinakharinwirot University	Thailand	2016	2022	7	1.4%	1.75	6	130
	Stallmac, Frank	Leipzig University	Germany	2016	2025	7	1.4%	3.17	28	3,147
	Martí, Arturo c.	University of the Republic	Uruguay	2016	2025	6	1.2%	1.95	23	1,453
	Müller, Andreas	University of Geneva	Switzerland	2016	2025	6	1.2%	1.82	25	2,654
	Onorato, Pasquale	University of Trento	Italy	2016	2025	6	1.2%	1.95	20	1,245
	Klein, Pascal	University of Kaiserslautern	Germany	2016	2025	5	1.0%	1.15	22	1,522

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

3.3. Geographic and Institutional Contributions and Collaboration Networks

3.3.1. Country Productivity and Citation Performance

To understand the global distribution of research activity, publication, and citation outputs were analyzed at the country level. This assessment highlights which nations contribute most actively and exert the strongest academic influence in the field.

Table 4.

The 10 leading countries on the Use of Mobile Devices in Physics Experiments.

No.	Country	TD	TC	CR
1	USA	182	2360 (#1)	42.10 (#6)
2	China	174	1094 (#2)	23.80 (#11)
3	Germany	76	325 (#5)	14.10 (#21)
4	Italy	65	454 (#3)	20.60 (#13)
5	Spain	62	137 (#11)	8.60 (#28)
6	Indonesia	49	24 (#26)	1.60 (#44)
7	Japan	44	159 (#8)	11.40 (#23)
8	Brazil	36	340 (#4)	24.30 (#10)
9	France	30	38 (#24)	4.20 (#37)
10	Thailand	29	123 (#12)	15.40 (#20)

Note: TD: Total documents; ND: Number of document (%); AF: Articles Fractionalized; TC: Total citations

Table 4 summarizes the ten leading countries contributing to research on the use of mobile devices in physics experiments, measured by total documents (TD), total citations (TC), and citation rate (CR). The United States of America ranked first in overall productivity with 182 publications, accounting for approximately 34.6% of the total dataset, and also achieved the highest citation impact with 2,360

citations and a citation rate of 42.10 citations per document. China followed closely with 174 documents, representing comparable productivity; however, its citation rate (23.80) was nearly half that of the United States, suggesting lower average influence per study. Together, these two countries produced more than two-thirds of the publications, indicating a strong concentration of research output in major research economies. This dominance highlights the critical role of large-scale funding systems, infrastructure, and technology access in supporting mobile-based experimental research. Overall, the results reveal clear disparities in both productivity and impact across countries. These results directly answer RQ3 by identifying the countries that contribute most significantly to both productivity and impact.

A second tier of contributors included Germany, Italy, and Spain, each producing between 60 and 76 documents. Among these, Italy showed particularly strong citation performance with 454 citations and a citation rate of 20.60, exceeding Germany's 14.10 and Spain's 8.60. This difference suggests that although publication counts were similar, the scholarly influence of Italian studies was relatively higher. Germany maintained a moderate impact with 325 citations, reflecting consistent but not leading visibility. Spain, despite comparable productivity, recorded fewer citations overall, indicating limited dissemination or narrower research networks. These findings suggest that impact does not scale linearly with output and may depend more on collaboration quality and publication venues.

Emerging contributors were observed in Indonesia, Japan, Brazil, France, and Thailand, each contributing between 29 and 49 publications. Notably, Brazil demonstrated a relatively high citation rate of 24.30, ranking among the top three in impact despite a smaller document count, indicating a strong average influence per article. In contrast, Indonesia produced 49 documents but accumulated only 24 citations, yielding the lowest citation rate (1.60), which may reflect limited international reach or recent entry into the field. Japan and Thailand showed moderate citation performance, while France recorded comparatively low visibility despite its established research base. These variations illustrate heterogeneous development patterns across regions. Collectively, the distribution suggests that while research leadership remains concentrated in North America and East Asia, emerging economies are increasingly participating in mobile-based physics education research. Similar geographic concentration patterns have been reported in previous bibliometric studies of mobile learning [16, 22]. Therefore, although research participation is expanding globally, scholarly influence remains unevenly distributed across regions. Consequently, the observed productivity and impact patterns, along with differences in visibility and collaboration, further address RQ3 by clarifying how national contributions are structured within the field.

3.3.2. Corresponding Author Distribution and International Collaboration

In addition to productivity, collaboration patterns provide insight into how research communities are structured. This subsection examines corresponding author affiliations and international co-authorship to reveal cross-border cooperation trends.

Table 5 reports the top 10 corresponding author countries in the Scopus dataset, separating output into single-country publications (SCP) and multi-country publications (MCP). China ranked first with 56 articles (11.2%), followed by the USA with 46 (9.2%), then Italy (23; 4.6%) and Germany (22; 4.4%). In most countries, SCP was larger than MCP (e.g., China: 50 SCP vs. 6 MCP; MCP% = 10.7), suggesting that corresponding-author leadership was often organized within national research teams. This pattern is consistent with bibliometric evidence in broader mobile learning research, where high-output countries (e.g., USA/China) tend to dominate productivity counts, while collaboration varies across regions and subfields [24–26]. These results answer RQ3 by identifying leading countries and showing how cross-country collaboration appears in the corresponding-author structure.

Table 5.
The 10 leading Corresponding Authors' Countries.

No.	Country	Articles	Articles %	SCP	MCP	MCP %
1	China	56	11.2	50	6	10.7
2	USA	46	9.2	40	6	13
3	Italy	23	4.6	20	3	13
4	Germany	22	4.4	16	6	27.3
5	Indonesia	16	3.2	13	3	18.8
6	Brazil	15	3	14	1	6.7
7	Japan	14	2.8	13	1	7.1
8	Spain	14	2.8	7	7	50
9	India	9	1.8	9	0	0
10	Switzerland	8	1.6	8	0	0

Note: SCP: Single-Country Publications; MCP: Multiple-Country Publications

A clearer insight emerges when focusing on MCP%, because it is commonly used as a proxy for the extent of international collaboration in Scopus-based bibliometric studies. In Table 5, Spain shows the highest MCP% (50%), with 7 SCP and 7 MCP, even though its total output is moderate (14 articles; 2.8%). Germany also shows relatively strong international collaboration (6 MCP; MCP% = 27.3) compared with its total volume (22 articles). By contrast, India (9 articles) and Switzerland (8 articles) recorded MCP% = 0, meaning all corresponding-author papers were single-country outputs. A new finding in your dataset is that Spain emerges as the most internationally collaborative corresponding-author hub among the top 10, which is not always visible when only “total documents” are reported. This matters because higher MCP% often reflects stronger cross-border research networks that can accelerate method sharing (e.g., apps/sensors, experimental designs) and broaden adoption across education systems. This result answers RQ3 by specifying which countries lead collaboration rather than only productivity.

The dominance of SCP in several high-output countries can be explained by the local practicality of mobile-device physics experiments. Many smartphone-based experiments (motion, sound, light, magnetism) can be implemented with low-cost equipment and local classroom access, so research teams may not require international partners to produce publishable outcomes. At the same time, the countries with higher MCP% (e.g., Spain, Germany, Indonesia) may reflect projects where teams seek cross-country validation, shared datasets, or comparative classroom implementations. This interpretation aligns with bibliometric guidance that collaboration indicators (SCP/MCP) help reveal the “structure” of a field beyond raw counts [15, 27]. A new finding here is the contrast between “productivity leaders” (China/USA) and “collaboration leaders” (Spain/Germany) within the same topic space, which suggests that influence in the field may come from different pathways: volume versus networked collaboration. Practically, this implies that future work aiming for broader generalizability may benefit from targeting the collaboration-oriented clusters indicated by high MCP%. This result answers RQ3 because it clarifies how collaboration developed across the most active countries.

Finally, the table suggests a two-tier country landscape in corresponding-author leadership: (i) high-volume producers (China, USA) with moderate MCP% (~10–13%), and (ii) mid-volume producers with either high MCP% (Spain, Germany, Indonesia) or very low MCP% (India, Switzerland). Similar “volume vs. collaboration” splits have been discussed in recent bibliometric reviews of mobile learning, where the most productive countries are not always the most internationally connected [24, 25]. A new contribution of your results is that this split is documented specifically for mobile devices in physics experiments using the corresponding-author perspective, which is more sensitive to leadership patterns than simple co-authorship counts. The significance is methodological and practical: it helps readers see where the field is expanding through national classroom pipelines versus cross-border experimental education networks. This result answers RQ3 by directly mapping both contribution and collaboration patterns.

3.3.3. Institutional Contributions and Research Hubs

Research leadership can also be observed at the institutional level. Thus, institutional outputs are analyzed to identify universities that function as active centers or hubs of mobile-based physics experimentation research.

To better understand how research leadership is organized at the institutional level, Table 6 examined the affiliations of corresponding authors to identify the most productive universities in mobile-device-based physics experiments. The results indicate that productivity is shared across several institutions rather than concentrated in a single dominant center. The most active affiliation is National Taiwan University of Science and Technology, with 12 articles, followed by University of Science and Technology of China and Università di Trento, each contributing 8 publications. Other institutions, including Srinakharinwirot University and Leipzig University, also show consistent outputs. Because the differences in publication counts are small, the field appears moderately decentralized. These patterns directly answer RQ3, as they identify which institutions contribute most to knowledge production.

Table 6.

The 10 leading institutions in the use of mobile devices in physics experiments.

No.	Affiliation	Country	Articles
1	National Taiwan University of Science and Technology	Taiwan	12
2	University of Science and Technology of China	China	8
3	University of Trento	Italia	8
4	Srinakharinwirot University	Thailand	7
5	Leipzig University	Germany	7
6	Hiroshima University	Japan	6
7	National Taiwan Normal University	Taiwan	6
8	National Yunlin University of Science and Technology	Taiwan	6
9	Valencia Polytechnic University	Spain	6
10	National Central University	Taiwan	5

A clear regional structure can also be observed. Several leading affiliations are located in Taiwan, including National Taiwan Normal University, National Yunlin University of Science and Technology, and National Central University. This concentration suggests the presence of a strong Asian cluster. Similar geographic tendencies have been reported in broader mobile learning and digital education research, where Asian and European institutions often play key roles in publication output and innovation [28, 29]. However, those studies typically examined general e-learning or online education rather than physics experimentation specifically. The current findings, therefore, extend earlier evidence by showing that Taiwan is not only active in mobile learning overall but also particularly visible in experimental physics education. This indicates that regional expertise and local research networks may strongly influence topic specialization.

At the same time, certain universities appear repeatedly across author, citation, and productivity analyses, which points to the existence of institutional “hubs.” For example, research teams associated with Leipzig University and the University of Kaiserslautern contribute multiple publications and are linked to several highly cited authors. Bibliometric research explains that such institutional hubs often emerge when groups share laboratories, tools, and co-authorship networks, leading to cumulative expertise and higher output [30]. While prior studies have mainly discussed hubs at the country level, fewer investigations have mapped them clearly at the university level within physics education. Identifying these hubs in the present study, therefore, adds a new perspective, as it highlights where methodological know-how and experimental practices are likely concentrated. This has practical value because future collaborations may benefit from connecting with these established centers.

Another notable characteristic is the presence of productive institutions in countries with varied economic contexts, such as Thailand. This broad participation may be related to the low-cost nature of

smartphone-based experiments. Many activities rely only on built-in sensors and free applications rather than expensive laboratory equipment. Because the financial barrier is lower, universities with limited resources can still conduct meaningful classroom-based research. Recent reviews of mobile technologies in education argue that affordability and portability increase access and adoption across diverse settings [31]. The current dataset provides quantitative support for this idea within physics experimentation, suggesting that mobile devices may help democratize research opportunities. Such accessibility likely explains why institutional productivity is not limited to a small number of well-funded universities.

Taken together, several consistent trends emerge. Productivity is distributed across multiple institutions, East Asia forms a strong regional cluster, certain universities function as research hubs, and low-cost technologies support wider participation. Some of these observations align with broader digital education bibliometrics, but the detailed mapping of institution-level leadership in smartphone-based physics experiments appears to be less documented in earlier work. By combining affiliation counts with contextual interpretation, the present analysis clarifies how institutional structures shape the development of this field. In this way, the findings provide a comprehensive answer to RQ3, explaining both which institutions contribute most and how participation spreads across regions.

3.3.4. Country Collaboration Network Analysis (Bibliographic Coupling)

To further explore structural relationships among countries, a bibliographic coupling network was constructed. This visualization reveals intellectual proximity and collaboration intensity, offering deeper insight into the evolution of international research networks and directly addressing RQ3.

To better understand how countries are intellectually connected in this field, a bibliographic coupling network was constructed using VOSviewer at the country level. Figure 3 shows this visualization, where each node represents a country, the size of the node indicates publication output, and the thickness of the links reflects the strength of shared references between countries. Countries citing similar sources or working on related topics tend to appear closer and are grouped into clusters. This method helps reveal not only productivity but also shared research foundations and collaboration structures. Therefore, the map provides direct evidence for RQ3, which asks how countries contribute and how collaboration patterns develop over time.

Several central hubs clearly dominate the network. The United States of America appears as the largest and most connected node, indicating both high productivity and strong intellectual ties with many partners. Germany and China also occupy central positions with multiple thick links. These three countries connect different clusters and function as bridges across regions. Similar central roles of the USA and China have been observed in broader educational technology bibliometrics [16, 24], which reported that these systems often lead global knowledge production. However, the present map shows that this dominance is not only quantitative but also structural, since these countries share references with many others and thus shape the intellectual base of the field. This suggests that research standards, methods, and themes may spread outward from these hubs. Distinct regional clusters are also visible. One cluster groups Taiwan, Indonesia, India, and Brazil, which are closely linked to each other but somewhat peripheral to the main USA and Germany core. Another cluster connects Italy, Chile, and the Czech Republic. A third group links France, Sweden, and Switzerland. These clusters indicate that countries tend to collaborate with geographically or culturally related partners. Comparable regional grouping effects were noted in global higher-education technology mapping [32]. The current findings confirm that this regional logic also applies to smartphone-based physics experimentation.

An interesting observation is that some mid-sized producers show strong bridging roles despite lower publication counts. For example, Italy and Spain connect multiple clusters and maintain links with both American and Asian partners. This bridging position suggests that these countries contribute to knowledge exchange between otherwise separated communities. Such intermediary roles are less visible when only total publications are reported. The identification of these “connector countries”

only education-, mobile-, and physics-related concepts. Therefore, the results directly address RQ4, which seeks to identify dominant and emerging themes.

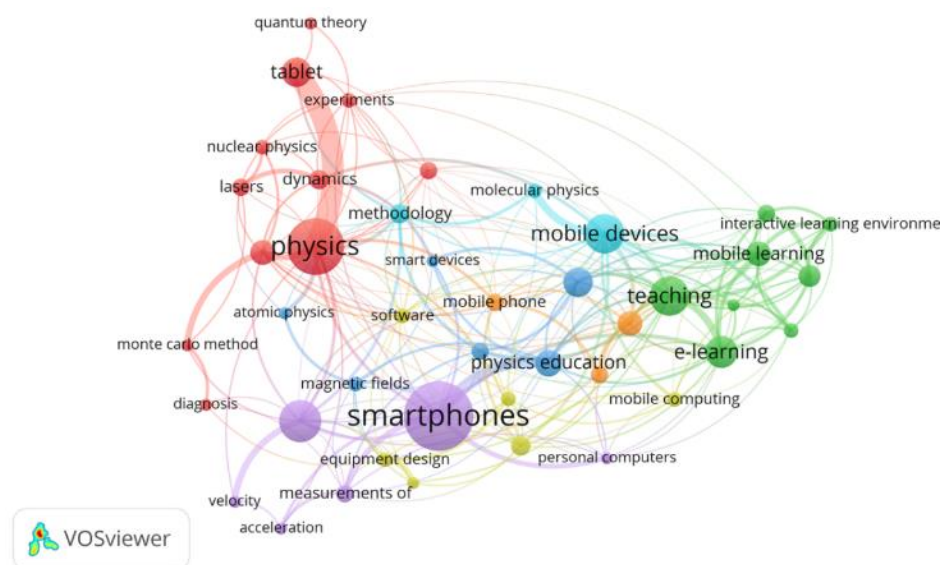


Figure 4.
Keyword co-occurrence network of mobile-device-based physics experiments.

The largest and most central nodes are “smartphones,” “physics,” “mobile devices,” “teaching,” and “e-learning.” Their large sizes and dense connections indicate that these topics dominate the field. In particular, *smartphones* act as the core technological term, while *teaching* and *e-learning* represent the pedagogical focus. This structure shows that research mainly concerns applying smartphones to improve physics learning rather than developing new hardware. Recent reviews of educational technology research similarly report that mobile learning studies increasingly emphasize classroom implementation and instructional design rather than device engineering [35–37]. The present network confirms that this pedagogical orientation is also central within physics experimentation.

Cluster analysis reveals several clearly differentiated themes. One cluster groups education and learning terms, including *teaching*, *education*, *e-learning*, *mobile learning*, *learning systems*, and *learning achievement*. These terms are tightly connected and positioned on the right side of the map, indicating a strong instructional focus. This suggests that many studies evaluate student outcomes, engagement, or performance when mobile devices are used in laboratory settings. Such outcome-oriented research has become common after 2020, when digital and remote learning expanded globally [38, 39]. Thus, the dominance of this cluster indicates that the field has matured toward evidence-based pedagogy.

A second cluster centers on physics content and measurements, with terms such as *acceleration*, *velocity*, *magnetic fields*, and *measurements*. These keywords are closely linked with *smartphones*, showing that built-in sensors are frequently used to measure motion and physical quantities. This pattern reflects the practical advantage of smartphones in mechanics experiments, where accelerometers and gyroscopes are readily available. A recent review of digital tools in STEM education noted that motion-related experiments are among the most feasible and widely adopted activities [40, 41]. The current findings provide bibliometric confirmation that such experiments form the core of physics mobile labs. Importantly, this cluster demonstrates that the field remains grounded in authentic scientific measurements rather than purely virtual activities.

Another cluster includes simulation and computational methods, such as *computer simulation*, *simulation*, and *software*. These terms connect both to physics and mobile technologies, indicating hybrid

approaches that combine physical data collection with digital modeling. The presence of these links suggests that researchers increasingly integrate real experiments with computational analysis. This blended design aligns with contemporary trends toward multimodal and data-supported learning environments [42, 43]. Compared with earlier periods that relied mainly on standalone measurements, this integration signals methodological innovation. Hence, simulation may represent a growing direction in the field. A smaller cluster contains device and application infrastructure, including *mobile applications*, *mobile computing*, *equipment design*, and *devices*. These terms describe technical support rather than direct pedagogy. Their smaller size indicates that hardware development plays a secondary role compared with teaching applications. This balance suggests that the field prioritizes usability and classroom integration over engineering complexity. Notably, earlier bibliometric studies of mobile learning often emphasized app design, whereas the present map shows a stronger emphasis on experimental practice. This difference highlights a distinctive feature of physics education research.

Overall, the network reveals three dominant thematic pillars: (1) pedagogical implementation, (2) smartphone-based measurements in core physics topics, and (3) hybrid simulation approaches. At the same time, emerging links around *mobile applications* and *laboratories* suggest continued innovation in portable and flexible lab designs. While earlier educational technology research described general mobile learning trends, the present analysis provides more detailed evidence specific to experimental physics contexts. Taken together, these findings clearly identify both established and developing themes, thereby offering a comprehensive answer to RQ4.

4. Discussion

This bibliometric study offers a systematic mapping of research developments, collaboration structures, and thematic directions in mobile-device-based physics education. The analysis highlights several major patterns and provides insights that may inform future investigations and practices in this field.

1. **Publication Growth and Temporal Development:** The findings indicate that research on mobile devices in physics experiments has expanded steadily over time, with a clear acceleration in the last decade. In the early years, publications were sporadic and mainly exploratory, focusing on testing the feasibility of smartphone sensors for basic measurements. However, after 2015, and particularly after 2020, the annual output increased markedly. This rapid growth likely reflects the widespread ownership of smartphones and the decreasing cost of digital technologies, which make mobile-based experiments more accessible to schools and universities. The shift toward online and hybrid learning during the COVID-19 period may also have stimulated the search for portable and flexible laboratory tools. Similar growth trends have been reported in broader reviews of mobile learning and educational technology, where research output increased significantly during the same period [44, 45]. These converging patterns suggest that mobile experimentation is not an isolated niche but part of a larger digital transformation in science education.
2. **Scholarly Impact and Knowledge Leadership:** The impact analysis reveals that influence is concentrated among a limited number of journals and authors. Specialized outlets in physics and science education appear to serve as the main platforms for disseminating smartphone-based experimental practices. At the same time, several authors consistently publish multiple studies and receive high citation counts, indicating the presence of stable research leaders. Such concentration is common in developing research areas, where early pioneers establish methodological standards and shape research agendas. Comparable patterns have been observed in bibliometric studies of STEM education and educational technology, where a small group of core contributors accounts for a large share of citations [15, 46]. The current results confirm that mobile-device-based physics experiments are moving toward a more structured and organized research community. An important implication is that collaboration with these leading scholars and journals may accelerate knowledge dissemination and methodological refinement.

3. **Geographic Distribution and Collaboration Patterns:** The geographic and institutional analyses show uneven but increasingly international participation. A few countries and universities dominate both publication counts and citation impact, suggesting strong research capacity and established laboratory infrastructures. At the same time, collaboration networks demonstrate growing cross-border connections, with several countries forming tightly linked clusters. This expansion of international cooperation likely facilitates the exchange of teaching practices, software tools, and experimental designs. Similar developments have been reported in global analyses of science education research, where collaboration networks tend to broaden as fields mature [47]. Notably, mobile-based experiments rely on low-cost and widely available devices, which may lower entry barriers for institutions with limited resources. This accessibility could explain the gradual inclusion of more diverse regions in recent years. Such democratization of participation appears to be a distinctive strength of this research area.
4. **Thematic Evolution and Emerging Topics:** The thematic analysis shows a clear transition in research focus over time. Early studies primarily emphasized technical validation, such as testing sensor accuracy or demonstrating measurement feasibility. More recent studies increasingly address instructional design, student engagement, and learning outcomes. Keywords related to laboratories, inquiry, teaching, and learning have become more prominent, indicating a stronger pedagogical orientation. This evolution from technology-centered to learner-centered perspectives aligns with recent reviews of digital tools in education, which report a similar shift toward evaluating educational effectiveness rather than mere technical functionality [28, 48]. However, the present study provides more specific evidence within physics experimentation, where smartphones are integrated directly into hands-on measurement tasks. The combination of real-time sensing, data logging, and classroom implementation represents an emerging hybrid model that blends physical and digital experimentation. To our knowledge, few prior studies have mapped this transition at a large scale, highlighting the novelty of the current synthesis.
5. **Implications for Research and Practice:** Taken together, these findings suggest that mobile-device-based experimentation has evolved into a mature and practically relevant research domain. The steady growth in publications, the emergence of influential contributors, expanding international collaboration, and the shift toward pedagogical themes indicate increasing stability and educational value. For researchers, identifying key journals, authors, and networks may support more targeted collaboration and dissemination strategies. For educators, the results highlight the potential of smartphones as affordable tools that can extend laboratory experiences beyond traditional settings. Future studies may benefit from combining bibliometric mapping with empirical classroom evidence to better understand long-term learning outcomes and instructional effectiveness. Such integration would further strengthen the connection between research trends and educational practice.

5. Conclusion

This study provides a systematic bibliometric overview of research on the use of mobile devices in physics experiments from 1963 to 2026. By examining publication trends, scholarly influence, collaboration structures, and thematic patterns, the analysis clarifies how this field has developed and gradually matured. The results show sustained growth in research output, increasing citation impact, and broader international participation. A core group of journals, authors, and institutions appears to play a leading role in shaping research directions, while collaboration networks continue to expand across countries. The thematic analysis further indicates a clear transition from early technical validation of smartphone sensors toward pedagogically oriented applications, including inquiry-based laboratories and student-centered learning activities. This shift highlights the growing integration of mobile technologies into authentic experimental practice rather than purely technical demonstrations. Overall, the study offers a comprehensive mapping of the intellectual, geographic, and conceptual

landscape of mobile-device-based physics experimentation and provides a useful reference for researchers and educators seeking to understand the structure and evolution of this domain.

6. Future Work

Although this study presents a broad overview of research development, several directions remain open for further investigation. First, future studies could combine bibliometric findings with systematic reviews or meta-analyses to evaluate the actual effectiveness of mobile-based experiments on student learning outcomes. Second, expanding data sources beyond a single database may provide more inclusive coverage of regional or non-English publications. Third, more attention could be given to emerging technologies, such as sensor analytics, augmented reality, artificial intelligence, and real-time data processing, which may further enhance experimental learning environments. Finally, empirical classroom research is needed to examine how mobile devices can be integrated into different educational contexts and how such integration influences teaching practices and learner engagement. Addressing these areas may deepen understanding of both the practical and pedagogical value of mobile technologies in physics education.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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