

Trends and themes of twenty years of physics education research: A bibliometric analysis of PRPER publications

Yajun Wei[✉],* Xiuli Wei[✉], and Ziqiang Chen[✉]

Institute of Physics Education Research, Guangzhou University, Guangzhou, 510006, China



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Physics education research (PER) has shown substantial growth in recent years, yet comprehensive reviews mapping the field's overall trajectory remain scarce. The leading journal, *Physical Review Physics Education Research* (PRPER), has been a cornerstone of the discipline since its launch in 2005. Marking its 20th anniversary, this study presents a comprehensive bibliometric analysis of PRPER publications from July 2005 to June 2025. Using data extracted from the Web of Science and Scopus, this study examines key indicators, including publication/citation trends, contributor demographics, prolific author characteristics, and collaborations, alongside the field's intellectual structures and their evolution. The results reveal sustained growth in publication volume and a concentration of authorship within U.S.-based institutions. The analysis finds that PRPER publications group well into seven major research clusters: Understanding and Supporting Student Learning; Identity and Equity; Conceptual Inventory; Physics Laboratory; Physics Problem Solving; Attitude and Epistemology; and Quantum Physics Education. Notably, Quantum Physics Education emerges in this analysis as one of the seven distinct major research clusters identified through bibliographic coupling. Timeline analysis reveals a shift in thematic emphasis from foundational work on conceptual assessment toward increasing focus on identity, equity, and quantum education. This bibliometric overview not only traces the intellectual trajectory of PRPER but also offers insights into the broader evolution of PER, highlighting existing gaps, such as the need to integrate equity research into quantum education, and suggesting future directions for the field.

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I. INTRODUCTION

Over the past decades, the field of physics education research (PER) has matured into a robust area of scholarly inquiry. *Physical Review Physics Education Research* (PRPER), formerly known as *Physical Review Special Topics—Physics Education Research* (PRST-PER), has played a particularly influential role. Since its founding in 2005 by the American Physical Society, PRPER has served as a home for empirical and theoretical work focused on understanding how physics is taught and learned in formal and informal settings. As one of the leading journals explicitly dedicated to PER, PRPER has not only reflected the field's evolution but helped shape its trajectory. Significantly, PRPER holds a unique position as the only PER-dedicated journal indexed in the Social Sciences Citation Index (SSCI) and possesses the highest impact factor among journals focused primarily on PER,

underscoring its central role and influence within the community. Celebrating its 20th anniversary in 2025, this study aims to conduct a comprehensive analysis of the research publications in PRPER to categorize past research themes, provide insights, identify gaps, and provide suggestions for future studies in the field of PER.

As research fields grow, it becomes increasingly valuable to conduct reflective analyses that assess their development, productivity, and structure. Bibliometric analysis offers a means to systematically evaluate a body of literature by examining patterns in authorship, citations, collaborations, and topic emergence [1–3]. Recent studies in educational research have employed bibliometric methods to produce journal retrospectives. For example, bibliometric methods have been employed for comprehensive journal retrospectives, such as the work of Chen *et al.*, which used topic modeling-based analysis exploring 50 years of the *British Journal of Educational Technology* (BJET) [4], and similar approaches have charted intellectual developments within leading science education publications like the *International Journal of Science Education* (IJSE) [5]. The 53-year analysis of the *Journal of Engineering Education* (JEE), the leading journal in the field of engineering education research, revealed key contributors, citation impacts, and intellectual shifts [6].

*Contact author: weiyajun@gzhu.edu.cn

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Similarly, this approach was used in the work of Modak *et al.*, which reviewed *Computers & Chemical Engineering*, a premier international journal in chemical engineering, in celebration of its 40-year contribution to the field [7]. Modak *et al.* focused on analyzing its publications with bibliometric indicators and exploring its publication and citation patterns. However, no such study has yet been conducted for PRPER, despite its centrality to the physics education research community.

Furthermore, the value of periodic synthesis and reflection is well recognized within the PER community itself. Recent years have seen the publication of several valuable review articles that consolidate findings and map future directions within specific subdomains or aspects of physics education research. For instance, reviews have examined trends in researcher demographics and participation [8], the role and nature of interactions within established pedagogical structures like physics tutorials [9], the effectiveness and implementation of specific instructional approaches like active learning [10], recommendations for physics teachers [11], and provided comprehensive syntheses of core PER methodologies and findings [12]. While these targeted reviews and syntheses are crucial for advancing specific research areas or understanding particular facets of the field by synthesizing evidence and identifying gaps, a comprehensive, longitudinal bibliometric analysis of the field's premier journal provides a complementary, timely, and macroscopic perspective. Such an analysis, focused on PRPER, can reveal overarching trends, interconnections between diverse topics, and shifts in the field's intellectual landscape that might be missed by reviews with a narrower or different scope, thus addressing a distinct need for systematic self-assessment and broad perspective within the PER community.

This study seeks to fill the gap by providing a comprehensive bibliometric overview of PRPER's first twenty years. Drawing on bibliometric data from Web of Science and Scopus, we identify key trends in publication output, influential articles, institutional and geographic contributions, collaboration patterns, and thematic shifts in research focus. We address the following research questions (RQ):

- RQ1: What are the publication and citation patterns of PRPER over the past 20 years?
- RQ2: Which institutions and countries have contributed most significantly to PRPER?
- RQ3: Which articles published in PRPER are the most frequently cited?
- RQ4: What is the nature of author and country-level collaboration in PRPER?
- RQ5: What are the characteristics of the most prolific authors?
- RQ6: What are the major research topics featured in PRPER, and how have they evolved over time?
- RQ7: What are the main research themes based on bibliometric coupling clusters?

By addressing these questions, we aim to offer both a retrospective summary of PRPER's contributions and a forward-looking map of potential research directions in physics education.

II. METHOD

A. Overview of bibliometric analysis

This study employs bibliometric analysis, a set of quantitative methods used to evaluate scholarly outputs based on publication metadata and citation relationships. Bibliometrics is the application of mathematical and statistical methods to books and other means of communication [3]. Initially employed to explore citation relationships among academic journals, bibliometric methods have gained increasing prominence for assessing scholarly output and comparing publication trends across journals—especially with the rise of large-scale bibliographic databases and advances in digital data processing [13–14].

Bibliometric analysis offers significant value to the scientific community due to its ability to detect emerging research trends, evaluate journal and article performance, and analyze patterns of collaboration and knowledge production [15]. It is also a powerful tool for mapping the intellectual structure of a research field based on existing literature [16], allowing researchers to obtain a comprehensive overview of a field, identify research gaps, generate new research ideas, and situate their contributions within the scholarly landscape. Given that these capabilities align closely with our research goals, bibliometric analysis is particularly well suited to this study.

Bibliometric analysis typically consists of two main components: performance analysis and science mapping [17]. Performance analysis focuses on evaluating the contributions of authors, institutions, countries, and journals within a given field. It employs descriptive metrics such as total publications, citation counts, average citations, and indices like the h-index and i-index. In contrast, science mapping examines the relationships among various research elements, including authors, keywords, and cited Ref. [1]. This aspect of bibliometric analysis encompasses techniques such as citation analysis, revealing the relational structure of a research field through network visualizations of coauthorship, co-citation, and keyword co-occurrence.

In this study, we apply both performance analysis and science mapping to the corpus of articles published in PRPER before July 2025. By examining performance indicators, we assess who contributes to the journal and how their work is received. Through network analysis, we explore how ideas are connected, which topics have gained prominence, and what new areas are emerging.

B. Data collection and performance analysis

We retrieved all PRPER regular research articles and review papers indexed in the Web of Science (WoS) Core

Collection, one of the most widely used databases for bibliometric research [18]. The complete bibliographic information, including article titles, authors, affiliations, Keywords Plus, abstracts, and cited references, was downloaded and organized for analysis. The search was restricted to the journal *Physical Review Physics Education Research* and its predecessor *Physical Review Special Topics–Physics Education Research*, covering the full publication history of the journal between July 2005 and June 2025, a 20-year span. This Web of Science search yielded a corpus of 1291 publications (articles and reviews); editorials and corrections were excluded.

While the primary corpus of publications was identified using WoS, we used Scopus for all citation-based performance indicators. This decision was made after validation checks revealed significant and systematic underreporting of citation counts for some PRPER articles within the WoS database. In contrast, Scopus provided more complete and stable citation data for this journal, making it a more reliable source for these specific metrics. The Scopus search for the same journal and time period identified 1276 PRPER items, reflecting minor coverage differences between the two databases. This small discrepancy (1.16%) in coverage does not affect the patterns reported and is acceptable in bibliometric analysis. Citation counts were taken from Scopus using the cutoff dates indicated in the relevant tables. Institutional affiliation data were manually disambiguated by separating multicampus university systems into individual campuses to avoid redundancy and double counting.

The performance metrics presented in this study were compiled from the Scopus database. Our analysis involved two data collection procedures. The dataset for analyzing the most productive institutions and countries (RQ2) and most cited articles (RQ3) was manually compiled on June 30, 2025, by recording the summary statistics displayed on the Scopus web interface. During our verification process, we identified a data-reporting artifact within this interface that resulted in anomalous citation counts for recent publications. To correct for this and ensure the highest accuracy for our trend analysis, the specific data for citation patterns of PRPER publications presented in Table I (RQ1) were subsequently collected via a direct data export from the Scopus database on July 8, 2025. VOSviewer, a Java-based application for visualizing bibliometric networks, was used for subsequent analyses, including author and country collaboration networks (RQ4). To address RQ5, which focuses on characterizing the most prolific contributors to PRPER, we identified the 15 authors with the greatest number of publications in the journal and collected publicly available information—such as institutional webpages, ORCID profiles, conference biographies, and journal author notes—to determine their educational backgrounds and current departmental affiliations.

TABLE I. Publication and citation structure of *PRPER* papers published between July 2005 and June 2025. Citation counts are based on Scopus data as of July 8, 2025.

Year	Number of publications	Cumulative total publications	Total citations	Citations per publication	H
2005	5	5	750	150.00	4
2006	14	19	1558	111.29	13
2007	18	37	1544	85.78	18
2008	20	57	1066	53.30	19
2009	17	74	957	56.29	13
2010	33	107	1549	46.94	23
2011	30	137	981	32.70	21
2012	45	182	2072	46.04	28
2013	46	228	1606	34.91	25
2014	53	281	1641	30.96	26
2015	55	336	1800	32.73	26
2016	88	424	3493	39.69	35
2017	77	501	2126	27.61	29
2018	81	582	1982	24.47	27
2019	89	671	2244	25.21	27
2020	115	786	2072	18.02	25
2021	102	888	1424	13.96	21
2022	102	990	1035	10.15	18
2023	119	1109	884	7.43	13
2024	112	1221	238	2.13	7
2025	55	1276	20	0.36	2

C. Keyword analysis

Keywords provide insights into the intellectual or scientific content of a study and are often used to trace the development and advancement of a specific scientific field [19,20]. To investigate how topics in PRPER papers have evolved (RQ6), we extracted keyword terms from the Web of Science Keywords Plus field and used VOSviewer to construct a co-occurrence network. These index terms are automatically generated by WoS based on the titles of cited articles and reflect core thematic elements within the dataset [21]. This method involves examining the frequency with which pairs of keywords appear together within a set of documents, thereby uncovering relationships between research topics and identifying prevailing themes within a field [22,23]. To explore topic evolution, we divided the dataset into four periods: 2005–2010, 2011–2015, 2016–2020, and 2021–2025. The dominant topics in each period were identified by calculating the number of occurrences of keywords. VOSviewer 1.6.20 basic was used to perform the analysis.

D. Thematic structure and trend analysis

To identify major research themes within the PRPER literature (RQ7), we employed bibliographic coupling analysis to construct and visualize a network of publications using VOSviewer [24]. In this network, each node (circle) represents a published document, and a “link” is

drawn between two documents if they share at least one reference—an approach known as bibliographic coupling [25]. The greater the number of shared references, the stronger the link. In this context, a pair of documents is considered more densely coupled than another pair if the first pair shares a greater number of common references. This strong coupling often indicates greater conceptual overlap between the two documents. This method enables researchers to uncover the intellectual structure of a field based on how current publications are grounded in shared prior work.

VOSviewer assigns each document a “links” value (number of coupled documents) and a “total link strength” (the sum of shared references across all links). A high total link strength suggests that a document’s reference list significantly overlaps with those of many others, indicating strong structural embeddedness within a particular topic area [2].

To detect thematic groupings within this network, we used VOSviewer’s built-in clustering tool, which applies the Leiden algorithm—a widely used modularity optimization method [26,27]. This algorithm partitions the network into clusters by maximizing a modularity score. Modularity quantifies how densely connected the nodes within a cluster are, compared to how connected they would be in a random network. Therefore, rather than using a fixed cutoff for internal density, the algorithm iteratively assigns documents to clusters in a way that yields the highest possible overall modularity for the entire network. The resulting cluster borders reflect these optimized divisions, grouping papers that are far more interconnected with each other through shared references than they are with papers in other clusters, making each cluster a structurally coherent region within the overall bibliographic space. The VOSviewer default setting of a minimum cluster size of 1 was used in our analysis [28].

After cluster generation, two experts in physics education research—each holding a Ph.D. and with over a decade of experience—reviewed the titles of all documents in each cluster and read the three most highly coupled papers (by total link strength) within each group. Based on this content-driven review, they collaboratively assigned descriptive thematic labels to each cluster. This human-in-the-loop process ensures that the resulting clusters are both algorithmically grounded and interpretively meaningful.

III. RESULTS

A. Publication and citation patterns of PRPER

Table I summarizes the publication and citation structure of PRPER papers published between July 2005 and June 2025. For example, in 2006, 14 papers were published and received a total of 1558 citations by the cutoff date. The “Citations per publication” value for that year was therefore calculated as 1558 divided by 14, yielding an average of

111.29 citations per paper. The corresponding h-index of 13 indicates that 13 out of the 14 papers had each been cited at least 13 times by the cutoff date. This example illustrates how the metrics in the table were derived and how they reflect both productivity and sustained scholarly influence over time.

PRPER’s growth in both output and influence is evident in its publication and citation trajectory. As shown in Table I, the number of articles published annually increased from 5 in its inaugural year to a high of 119 articles in 2023. This steady rise reflects the journal’s increasing visibility and its role in establishing physics education research as a mature scholarly field.

Citation patterns reveal that foundational articles published in the first decade continue to be highly cited. Papers from 2005 and 2006 have average citation counts of 150.00 and 111.29, respectively, suggesting that these early works laid the groundwork for much subsequent research. Papers published in 2016 were the most cited, with a total of 3493 citations. Furthermore, this group of 88 publications has the highest h-index of 35, meaning that 35 of them were each cited at least 35 times.

Table II presents the 20 most cited papers published in PRPER between 2005 and 2025, identified using citation counts retrieved from the Scopus database as of June 30, 2025. Leading the list is the article “New instrument for measuring student beliefs about physics and learning physics: The Colorado Learning Attitudes about Science Survey” by Adams *et al.* [29], with a total of 531 citations and an average of 26.55 citations per year. This article introduced the CLASS instrument, which has since become a standard tool for measuring student attitudes and beliefs in physics education research. The second most cited article is by Finkelstein *et al.* [30], which examines the effect of using computer-based simulations to substitute physical laboratories. Also ranking highly is Henderson and Dancy’s [31] study of barriers to adopting research-based instructional strategies, cited 420 times. These top articles demonstrate the journal’s influence in both assessment instrument development and studies of instructional change.

To assess whether these foundational papers continue to influence the field, we plotted the annual citation counts for the ten most-cited articles (see Fig. 1). Although citation rates have moderated from initial peaks for most publications, all ten papers continue to receive consistent citations in recent years between 2021 and 2024, confirming their ongoing relevance. The drop in 2025 is partly caused by the fact that only half of the year’s citations are captured.

Several more recent publications have also achieved notable impact, such as the review of upper-level quantum mechanics difficulties by Sing and Marshman [42], and the investigation into gender disparities in physics self-efficacy by Marshman *et al.* [40]. Overall, the top-cited articles span a range of themes—student beliefs, curriculum

TABLE II. Top-cited PRPER papers published between July 2005 and June 2025. Citation counts are based on Scopus data as of June 30, 2025. DT = Document type, TC = Total citations.

Title	Authors (year)	DT	TC	Citations per year
New instrument for measuring student beliefs about physics and learning physics: The Colorado Learning Attitudes about Science Survey [29]	Adams <i>et al.</i> (2006)	Article	531	26.55
When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment [30]	Finkelstein <i>et al.</i> (2005)	Article	431	20.52
Barriers to the use of research-based instructional strategies: The influence of both individual and situational characteristics [31]	Henderson and Dancy (2007)	Article	420	22.11
Evaluating an electricity and magnetism assessment tool: Brief electricity and magnetism assessment [32]	Ding <i>et al.</i> (2006)	Article	307	15.35
Synthesis of discipline-based education research in physics [12]	Docktor and Mestre (2014)	Article	287	23.92
Use of research-based instructional strategies in introductory physics: Where do faculty leave the innovation-decision process? [33]	Henderson <i>et al.</i> (2012)	Article	271	19.36
Elements of a cognitive model of physics problem solving: Epistemic games [34]	Tuminaro and Redish (2007)	Article	211	11.11
Scientific abilities and their assessment [35]	Etkina <i>et al.</i> (2006)	Article	205	10.25
Approaches to data analysis of multiple-choice questions [36]	Ding and Beichner (2009)	Article	192	11.29
Insights into teaching quantum mechanics in secondary and lower undergraduate education [37]	Krijtenburg-Lewerissa <i>et al.</i> (2017)	Article	177	19.67
Fitting in or opting out: A review of key social-psychological factors influencing a sense of belonging for women in physics [38]	Lewis <i>et al.</i> (2016)	Article	173	17.30
Beneath the numbers: A review of gender disparities in undergraduate education across science, technology, engineering, and math disciplines [39]	Eddy and Brownell (2016)	Review	172	17.20
Female students with A's have similar physics self-efficacy as male students with C's in introductory courses: A cause for alarm? [40]	Marshman <i>et al.</i> (2018)	Article	167	20.88
Gender gap on concept inventories in physics: What is consistent, what is inconsistent, and what factors influence the gap? [41]	Madsen <i>et al.</i> (2013)	Article	159	12.23
Review of student difficulties in upper-level quantum mechanics [42]	Singh and Marshman (2015)	Review	159	14.45
Gender discrimination in physics and astronomy: Graduate student experiences of sexism and gender microaggressions [43]	Barthelemy <i>et al.</i> (2016)	Article	154	15.40
Gender, experience, and self-efficacy in introductory physics [44]	Nissen and Shemwell (2016)	Article	140	14.00
Not all interactive engagement is the same: Variations in physics professors' implementation of Peer Instruction [45]	Turpen and Finkelstein (2009)	Article	137	8.06
Educational pathways of Black women physicists: Stories of experiencing and overcoming obstacles in life [46]	Rosa and Mensah (2016)	Article	135	13.50
Modeling instruction: Positive attitudinal shifts in introductory physics measured with CLASS [47]	Brewe <i>et al.</i> (2009)	Article	134	7.88

implementation, conceptual assessment, and equity—highlighting PRPER's broad scope and central role in shaping physics education research.

B. Country-level contribution analysis

Nationally, as shown in Table III, the United States is the dominant contributor to PRPER, with authors affiliated with U.S. institutions appearing on 952 articles—more than all other countries combined. The U.S. also holds the highest h-index (71) and total citation count (25 276).

Figure 2 visualizes the international coauthorship network over time. Each node represents a country, with node size indicating the total number of authored or coauthored publications (only countries with more than ten such publications are shown for clarity). Node color reflects the average publication year, following the color gradient legend from blue (earlier years) to red (more recent years). This visual encoding allows inference of temporal participation trends. For example, countries such as Thailand and South Africa have node colors toward the left of the gradient, indicating earlier contributions, while countries

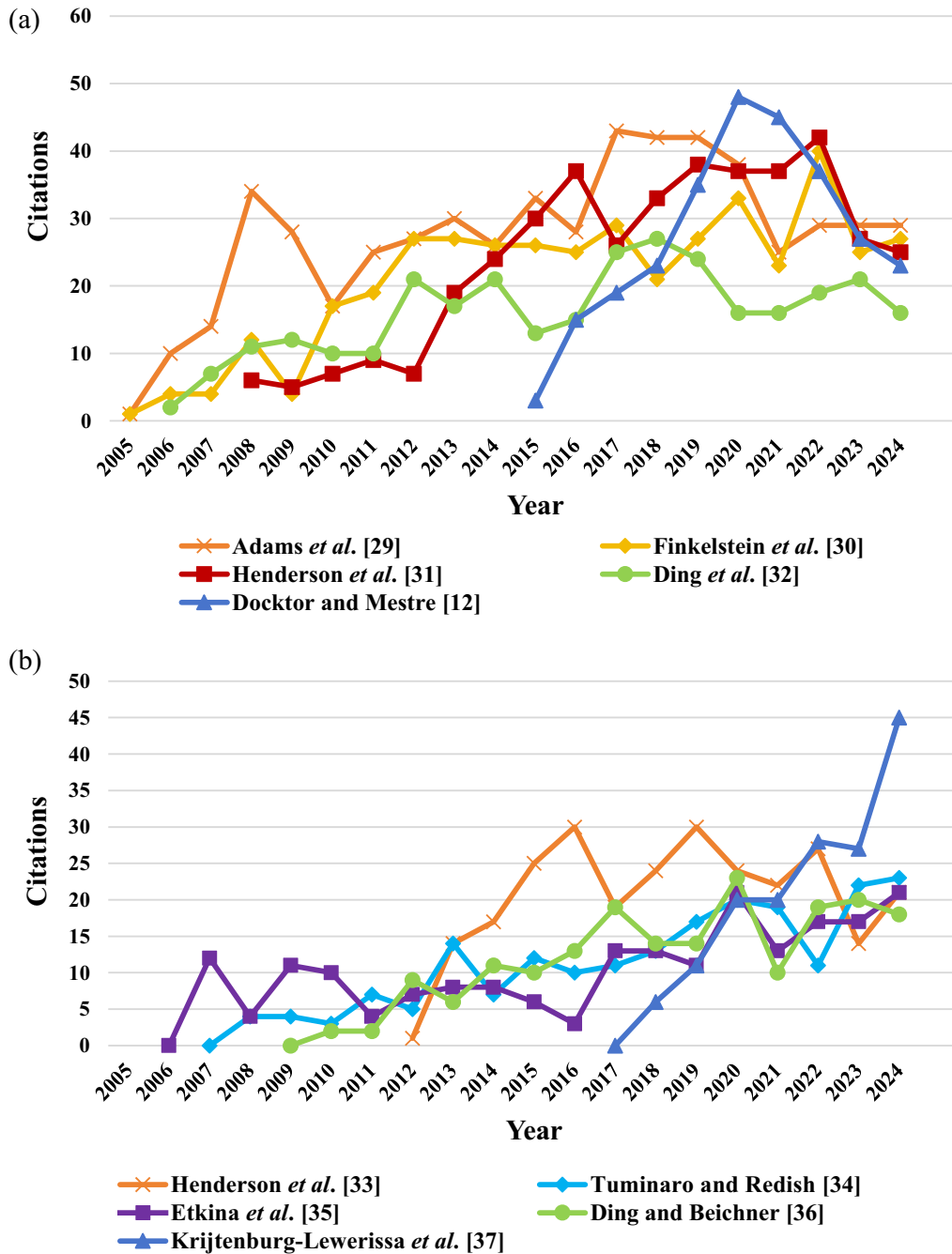


FIG. 1. Annual citation trajectories of the ten most-cited PRPER articles (based on Scopus data, cutoff: June 30, 2025). (a) Citation counts of the top five publications. (b) Citation counts of the top 6–10 publications.

like Germany, China, and Switzerland have node colors toward the right, reflecting more recent engagement. Countries such as the U.S. and Sweden fall near the middle of the gradient, which could suggest either a concentration of contributions in the journal's middle years or a full-span engagement across two decades. A manual check confirms that these countries have been published consistently throughout the journal's history.

Links between nodes represent international coauthorships, with link thickness indicating collaboration strength,

quantified as the total number of coauthored publications between countries. The strong and thick links between countries such as Germany and the U.S., China and the U.S., and Norway and the U.S. indicate robust international collaborations centered on U.S.-based researchers.

Overall, the figure illustrates that several countries—notably Germany, China, and Norway—have shown increasing involvement in PRPER, often through collaboration with U.S.-based authors. Among the top 15 contributing countries by publication count over the past

TABLE III. Most contributing countries or territories of *PRPER* papers between July 2005 and June 2025.

Country	Total publications	Total citations	Citations per publication	h-index
United States	952	25 276	26.55	71
Germany	67	1077	16.07	18
China	47	658	14.00	13
Canada	41	958	23.37	20
United Kingdom	36	692	19.22	17
Norway	33	471	14.27	13
Israel	29	349	12.03	11
Italy	27	444	16.44	14
Croatia	27	796	29.48	15
Sweden	24	414	17.25	13
Austria	21	271	12.90	9
Finland	20	694	34.70	11
Belgium	20	416	20.80	11
Australia	19	254	13.37	9
Ireland	18	592	32.89	15

twenty years, all are developed countries except China, indicating a continued underrepresentation of the developing world in *PRPER*.

C. Institutional-level analysis

Institutionally, as illustrated in Table IV, a relatively small group of institutions has made outsized contributions to *PRPER*. The University of Colorado Boulder leads with

145 publications and over 6000 citations. Other major contributors include the University of Pittsburgh, Michigan State University, and The Ohio State University, each with between 65 and 80 publications. The majority of the top institutional contributors, in terms of the total number of publications, are American research universities. Among the top 15 institutional contributors, the National Institute of Standards and Technology is the only non-university institution, and the University of Oslo is the only non-U.S. institution.

As *PRPER* is an educational research journal covering all levels of physics education—and given the increasing number of research-trained K-12 teachers (i.e., Ph.D. holders)—we examined the extent of contributions from K-12 institutions. We searched for the terms “high school,” “middle school,” or “academy” in the affiliation fields on *PRPER*’s official website. The search was carried out in early July 2025. This yielded 21 publications with K-12 affiliations. Many of these reflect productive collaborations between university researchers and K-12 educators, indicating promising connections between research and classroom practice. However, many of these were authored by individuals whose primary affiliation was with a research university and who listed a K-12 school as a secondary affiliation or by university researchers collaborating with a K-12 coauthor. Only one paper appeared to be primarily contributed by a K-12 practitioner [48]. In contrast, a 2019 survey by the American Institute of Physics (AIP) reported that approximately 8% of U.S. high school physics teachers held a Ph.D., a figure that has shown an upward trend in recent years [49].

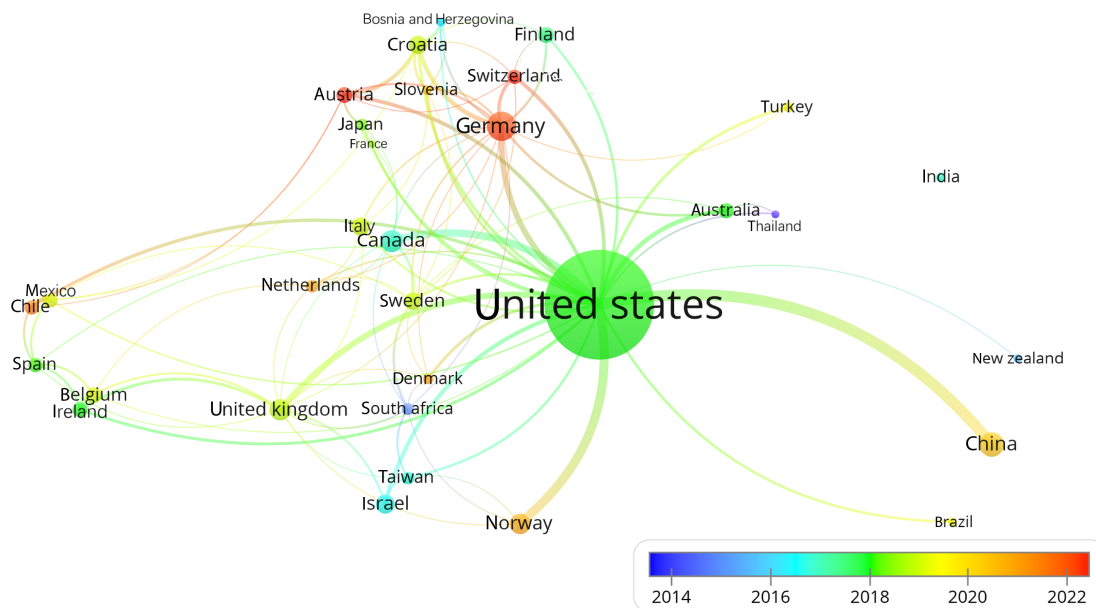


FIG. 2. Coauthorship network among authors’ affiliated countries or territories. Each node represents a country or territory; node size indicates the total number of publications associated with that country. Node color reflects the average publication year, following the color gradient legend. Links between nodes represent international collaboration, with link thickness indicating the strength of collaboration, defined as the total number of coauthored publications.

TABLE IV. Most contributing institutions of *PRPER* papers between July 2005 and June 2025.

Institution	Total publications	Total citations	Citations per publication	h-index
University of Colorado Boulder	145	6036	41.63	44
University of Pittsburgh	78	2595	33.27	32
Michigan State University	71	1248	17.58	21
The Ohio State University	68	1373	20.19	22
National Institute of Standards and Technology	53	1188	22.42	22
Florida International University	44	1669	37.93	27
University of Maryland, College Park	44	1380	31.36	22
University of Maine	43	991	23.05	19
Kansas State University	36	1178	32.72	21
University of Illinois Urbana-Champaign	34	1035	30.44	17
Cornell University	33	576	17.45	13
West Virginia University	33	562	17.03	14
Western Michigan University	32	1463	45.72	16
University of Washington	32	685	21.41	14
University of Oslo	28	450	16.07	13

D. Author-level profile and representation

To visualize the social structure and identify key collaborative patterns within the PER community publishing in *PRPER*, we constructed an author coauthorship network using VOSviewer, as presented in Fig. 3. Each node represents an author, with node size indicating the number of authored or coauthored *PRPER* publications, and link thickness representing coauthorship frequency. For visual clarity, only authors with more than eight authored or coauthored articles are shown. Node color reflects the average publication year of each author's contributions, following a gradient from blue (earlier years) to red (more recent years).

The network structure in Fig. 3 includes a large, densely connected central cluster, along with a few smaller, coherent clusters and several isolated nodes of considerable size. The central cluster features highly collaborative and prolific authors such as Chandralekha Singh, Heather J. Lewandowski, N. G. Holmes, Charles Henderson, and Eric Brewe—indicating a major hub of collaborative activity. Smaller collaborative groups are also apparent—for example, clusters centered around Lei Bao and around Maja Planinic and Martin Hopf. The structure observed in Fig. 3 aligns with and updates the trends previously documented by Anderson *et al.* [50], who analyzed the evolution of the PER coauthorship network through 2014. Their study revealed an increased collaboration. Our analysis, which extends this timeline by a full decade, shows the continued consolidation of this network, with an increase in the number and strength of collaborative links between established authors.

Some nodes with considerable size appear isolated or only loosely connected to the rest of the network. These authors have nonetheless made substantial individual contributions to the PER community. Examples include Gerd Kortemeyer, Zhongzhou Chen, and Italo Testa. Yet this

visualization alone does not necessarily imply that these authors lack coauthors; rather, it may reflect that their collaborators have authored fewer than eight *PRPER* publications and are thus excluded from the visualization for clarity. Authors such as Jochen Kuhn and Alexandra Werth appear as more recent and rising contributors, as suggested by the red coloring of their nodes positioned toward the right end of the color gradient.

We identified the 15 most prolific authors in *PRPER*, with individual publication counts ranging from 20 to 77. Table V summarizes their undergraduate and doctoral training as well as their current academic affiliations. All are affiliated with research-intensive universities, and the majority hold faculty positions in physics departments—some with joint appointments or affiliations in schools of education or discipline-based education research (DBER) units. Most of these authors earned bachelor's degrees in physics, while two have undergraduate backgrounds in mathematics or engineering. Nearly all completed doctoral degrees in physics, and two hold Ph.D.s specifically in physics education research.

Notably, none of the 15 most prolific contributors followed a pathway in which they earned a physics undergraduate degree and then transitioned into a general education doctoral program (e.g., curriculum and instruction or EdD programs within a faculty of education). Instead, all received Ph.D.s in physics. Even the two who specialize in physics education research—which is an interdisciplinary field combining physics and education—earned their Ph.D.s within discipline-based programs (e.g., physics education research). This reflects a model in which advanced content expertise in physics is considered foundational for scholarly productivity in this field. This pattern may highlight the strongly discipline-rooted nature of physics education research.

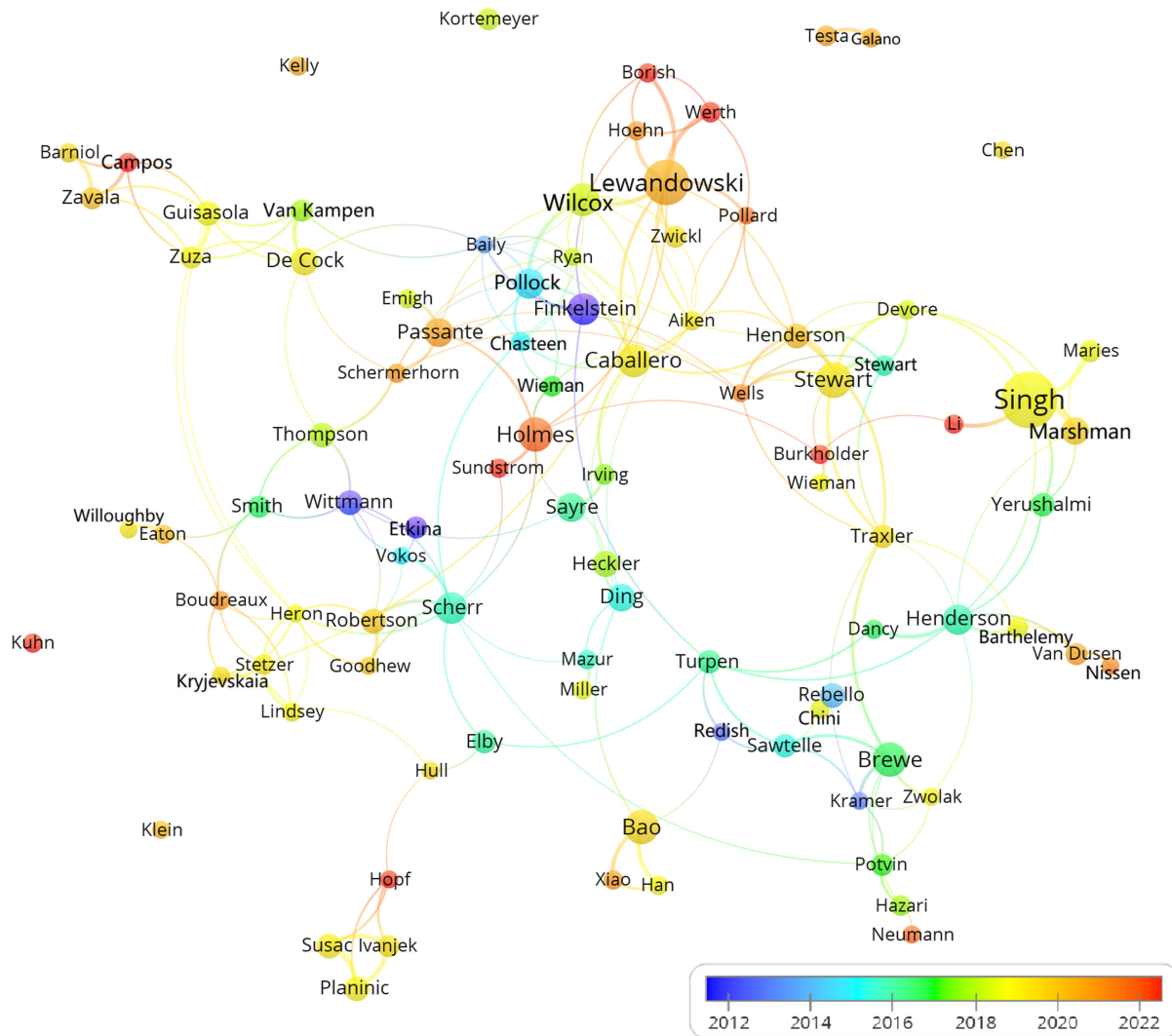


FIG. 3. Author collaboration network of PRPER papers. Each node represents an individual author, with node size corresponding to the number of PRPER publications co-authored by that author. Node color reflects the average publication year of each author, using a gradient from blue (earlier years) to red (more recent years). To ensure visual clarity, this visualization was set to include only nodes (authors) with a minimum of eight coauthored publications, and name labels show only family names.

E. Keyword analysis

To examine the terminology and topical emphasis of articles published in *Physical Review Physics Education Research* (PRPER), we analyzed keywords from four time periods, each spanning approximately five years: 2005–2010, 2011–2015, 2016–2020, and 2021–2025. Co-occurrence mapping, generated using VOSviewer, reveals keyword frequency and pairing patterns. The results are presented in Figs. 4–7. In these figures, each node represents a keyword, with node size indicating the frequency of that keyword. A link between two keywords represents their co-occurrence—i.e., their appearance together in a publication. The thickness of the link reflects the frequency of co-occurrence.

In the journal’s early years (2005–2010, Fig. 4), keywords such as “physics,” “mechanics,” “knowledge,”

“students,” and “performance” suggest a strong focus on core disciplinary content and cognitive learning outcomes. Additional terms like “categorization” and “expectations” point to interest in students’ conceptual development and learning goals. In this context, “categorization” refers to how students group physics problems based on underlying principles rather than surface features, a classic indicator of their conceptual understanding and the organization of knowledge in the mind. Overall, this period reflects a phase of foundational work centered on disciplinary understanding and student cognition in physics contexts.

The second period (2011–2015, Fig. 5) shows the continued dominance of “physics,” “students,” and “knowledge,” but with a notable rise in terms like “beliefs,” “instruction,” and “college physics.” The appearance of “education” and “achievement” suggests an expanding

TABLE V. Profiles of the 15 most prolific authors in PRPER, based on the number of authored or co-authored publications from July 2005 to June 2025.

Name	Number of publications	BSc/BA	Ph.D.	Department affiliation
C. Singh	77	Physics	Physics	Department of Physics; Discipline-based Science Education Research Center
H. J. Lewandowski	50	Physics	Physics	Department of Physics
J. Stewart	31	...	Physics	Department of Physics and Astronomy
N. G. Holmes	29	Physics	Physics	Department of Physics
E. Brewe	29	Physics	Physics education research	Physics & Science Education
L. Bao	29	Electrical engineering	Physics	Department of Physics; Department of Education
N. D. Finkelstein	28	Mathematics	Applied physics	Department of Physics
B. R. Wilcox	27	Physics and astronomy	Physics	Department of Physics
M. D. Caballero	27	Physics	Philosophy in physics	Department of Computational Mathematics, Science, and Engineering
R. E. Scherr	26	Physics	Physics	School of STEM
C. Henderson	24	Mathematics and physics	Physics education	Department of Physics
S. J. Pollock	23	Physics	Physics	Department of Physics
G. Passante	21	Physics	Physics and astronomy	Department of Physics
E. C. Sayre	20	Physics	Physics	Department of Physics
M. De Cock	20	Physics	Theoretical physics	Department of Physics and Astronomy

concern with instructional contexts and learning outcomes. Compared to the previous period, keyword use begins to reflect a broader educational lens, even as traditional disciplinary anchors remain prominent.

During the 2016–2020 period (Fig. 6), there is a visible increase in interdisciplinary terms. Keywords such as “mathematics,” “difficulty,” “education,” and “science” appear alongside consistent core terms like “performance,” “beliefs,” and “knowledge.” The network points to growing interest in how students navigate physics in relation to adjacent domains and educational structures.

In the most recent period (2021–2025, Fig. 7), the keyword “science” surpasses “physics” in frequency, suggesting a shift from disciplinary specificity to a broader

interdisciplinary framing. Terms like “experiences,” “women,” and “achievement” gain prominence, indicating heightened focus on equity, identity, and inclusion. While foundational terms such as “students,” “knowledge,” and “performance” remain, they are now embedded in richer educational and social contexts, reflecting the field’s maturation and diversification. Research in this phase appears to connect disciplinary learning with educational

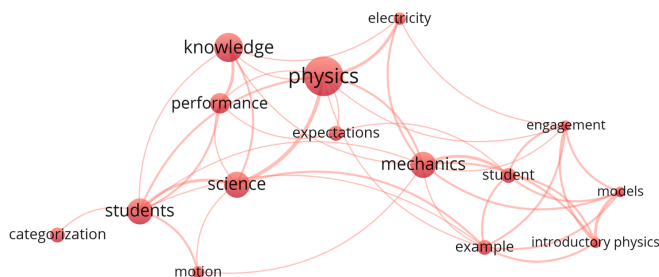


FIG. 4. Keywords in PRPER publications from 2005 to 2010. The size of each node is proportional to the keyword’s frequency, and the links between nodes represent their co-occurrence in the same articles, with thickness representing the frequency of co-occurrence.

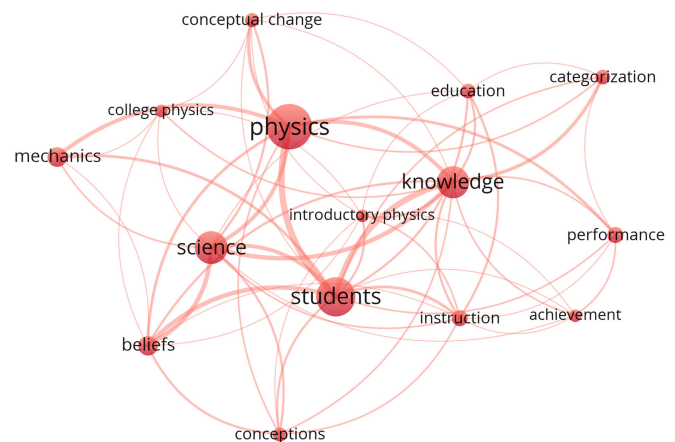


FIG. 5. Keywords of PRPER papers published between 2011 and 2015. The size of each node is proportional to the keyword’s frequency, and the links between nodes represent their co-occurrence in the same articles, with thickness representing the frequency of co-occurrence.

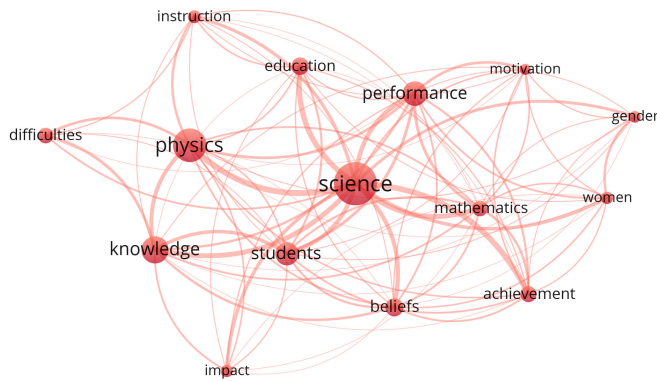


FIG. 6. Keywords of PRPER papers published between 2016 and 2020. The size of each node is proportional to the keyword's frequency, and the links between nodes represent their co-occurrence in the same articles, with thickness representing the frequency of co-occurrence.

psychology, as suggested by the considerable node sizes of terms like “self-efficacy” and “identity” and their links with keywords such as “physics” and “science” in the co-occurrence network.

Over two decades, the frequency and co-occurrence of keywords in PRPER reveal a progression from a “discipline-centered focus on physics learning” to a more “interdisciplinary and socially aware” discourse. Notably, the rise of keywords such as “science,” “mathematics,” and “education,” alongside increased attention to “student experiences” and “gender,” signals a broadening of scope beyond physics content alone. This shift reflects the journal's role in expanding the boundaries of physics education research to encompass a more integrated view of learning, identity, and instructional environments. Another trend is the inversion in prominence between “physics” and “science.” By comparing the relative node

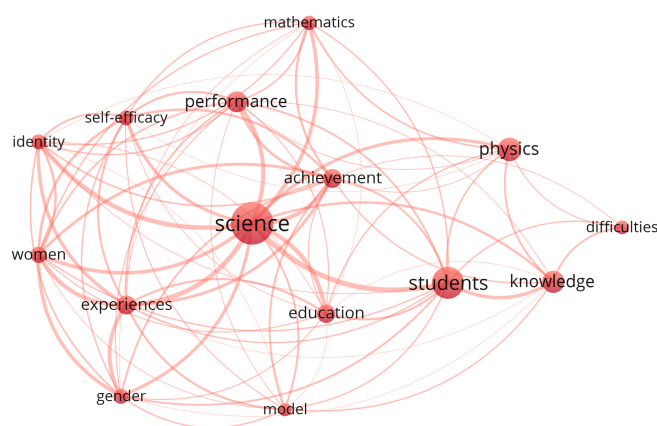


FIG. 7. Keywords of PRPER papers published between 2021 and 2025. The size of each node is proportional to the keyword's frequency, and the links between nodes represent their co-occurrence in the same articles, with thickness representing the frequency of co-occurrence.

sizes of “physics” and “science” in Figs. 4–7, one can easily see a consistent decline in the frequency ratio between physics and science. In the most recent period, science appears to have become the central organizing theme, situating physics research within the broader context of science education. This evolution, coupled with the rise of keywords related to identity, equity, and student experience, demonstrates the field's expanding scope to embrace a more holistic and integrated understanding of learning in diverse educational environments.

This observed shift of physics-to-science ratio is likely amplified by the nature of the Keywords Plus algorithm used by Web of Science, which derives terms from the titles of an article's cited Ref. [21]. Therefore, the falling “physics”-to-“science” ratio may also indicate a shift in the scholarly conversations they are engaging with. As PRPER authors increasingly cite and build upon work from the broader science education, psychology, and equity-focused communities, the algorithm captures this intellectual integration.

F. Thematic structure

VOSviewer first computes the bibliographic coupling strength as the raw number of shared cited references between paper pairs. It then normalizes this raw count using an “association strength” formula, which accounts for the total number of references in each of the compared documents. This normalization prevents papers with very long reference lists from dominating the network. The specific formula is $S(i, j) = \frac{c(i, j)}{r(i) \cdot r(j)}$, where $c(i, j)$ is the number of shared references, and $r(i)$ and $r(j)$ are the total number of references in documents i and j , respectively [24]. VOSviewer then builds a weighted network including only links above its internal minimum strength. Using default clustering settings (resolution = 1.0, no minimum cluster size), the algorithm assigned 1289 of the 1291 publications into 7 clusters; the remaining two papers were not clustered, having insufficient coupling strength to enter any group. The clustering process, as discussed previously, aims to maximize the network's modularity. The “resolution” parameter (set to a default value of 1.0) influences the granularity of the outcome; a higher resolution value tends to produce more, smaller clusters, while a lower value results in fewer, larger clusters. The emergence of precisely seven clusters is not a predetermined number but rather the outcome of the Leiden algorithm finding the optimal modularity partitioning of this specific network dataset at the default resolution of 1.0.

Bibliometric coupling connects articles based on shared references, meaning papers that cite similar prior work tend to belong to the same thematic area, as visualized in Fig. 8. Each cluster is discussed below in terms of its defining themes, size, and most coupled contributions (i.e., those with the highest total link strength).

1. Cluster 1: Understanding and Supporting Student Learning

The largest and most foundational cluster in this analysis brings together work that seeks to understand how students learn physics and how instruction can better support that learning. The core of this theme involves identifying student difficulties, mapping their reasoning processes, and building frameworks and tools to support learning progression.

A pivotal contribution is the article by Robertson *et al.*, published in 2023 [51], with a total link strength of 1671, offering a practical guide for researchers to identify students' conceptual resources for understanding physics. Another highly coupled study, by Gupta *et al.* [52], with a total link strength of 1648, explores how personal epistemologies and emotions intertwine in students' thinking. These studies reflect the cluster's deep commitment to both documenting and supporting the cognitive and emotional dimensions of student learning in physics. It is a theme at the heart of PER, guiding instructional design and research agendas alike.

Algorithmically, the publication with the highest link strength in this cluster is the comprehensive synthesis of PER by Docktor and Mestre [12], but we exclude it as an exemplar publication in Table VI for this cluster as such reviews synthesize across many areas of PER and thus are not representative of a single theme, though we acknowledge their importance for the field.

2. Cluster 2: Identity, Equity, and Belonging

Cluster 2 brings visibility to the critical roles that identity, social context, and equity play in students' experiences of learning physics. A distinctive strength of this cluster is its empirical and theoretical commitment to understanding gender and racial equity, sense of belonging, and the cultural dynamics of classrooms.

One of the most coupled articles is Li and Singh's article in 2023 [54], which has the strongest total link strength (3192) and demonstrates that sense of belonging significantly predicts introductory physics students' academic performance. Li and Singh's article in 2022 [55], with a total link strength of 3016, further shows how inclusive learning environments improve student learning and motivational beliefs. The article by Traxler *et al.*, published in 2016 [56], with a total link strength of 2601, critiques binary gender models in PER and advocates for a complex, inclusive future.

These contributions collectively call attention to the structural and cultural conditions that shape who thrives in physics classrooms. This cluster's prominence affirms the growing attention PER gives to equity-oriented and identity-informed research.

3. Cluster 3: Conceptual Inventory

This cluster focuses on the development, validation, and advanced analysis of conceptual inventories, particularly those assessing force and motion concepts. It serves as the measurement backbone of many PER studies.

Among the most coupled publications is the article by Stewart *et al.*, published in 2018 [57], which has the strongest total link strength (2602) and uses multidimensional item response theory to explore the structure of the Force Concept Inventory (FCI). The article by Hewagallage *et al.*, published in 2022 [58], with a total link strength of 2303, examines how high school preparation and college achievement relate to conceptual understanding. The article by Wells *et al.*, published in 2019 [59], with a total link strength of 2283, employs modified module analysis to reveal patterns in student misconceptions on the FCI.

These papers reflect the empirical rigor and theoretical insight that underpin conceptual inventory research, which remains essential for assessing and comparing learning outcomes in physics education.

4. Cluster 4: Physics Laboratory

Cluster 4 contributes to understanding how students develop conceptual knowledge and scientific reasoning and thinking in experimental contexts. A key contribution is May's article in 2023 [60], which has the strongest total link strength (1400) and provides a historical analysis of innovation and research in physics instructional laboratories, identifying recurring themes and future directions. The article by Vignal *et al.*, published in 2023 [61], with a total link strength of 1241, presents the Survey of Physics Reasoning on Uncertainty Concepts in Experiments (SPRUCE), assessing students' scientific reasoning of measurement uncertainty in introductory labs. Buggé's article in 2023 [62] examines how lab report revision in a high school setting improves scientific abilities.

This cluster stands out for its contributions to understanding laboratory instruction and reasoning practices, both of which are central to the development of scientific habits of mind in physics students.

5. Cluster 5: Physics Problem Solving

Research in cluster 5 investigates the complex cognitive and affective dimensions of students' problem-solving processes. It addresses how students frame, approach, and persist through challenging problems in physics.

One influential article by Good *et al.* [63], which has the strongest total link strength (2719), examines how traditional versus evidence-based active-engagement instruction impacts students' attitudes and approaches to problem solving. Maries's article in 2017 [64], with a total link strength of 2117, explores challenges in designing

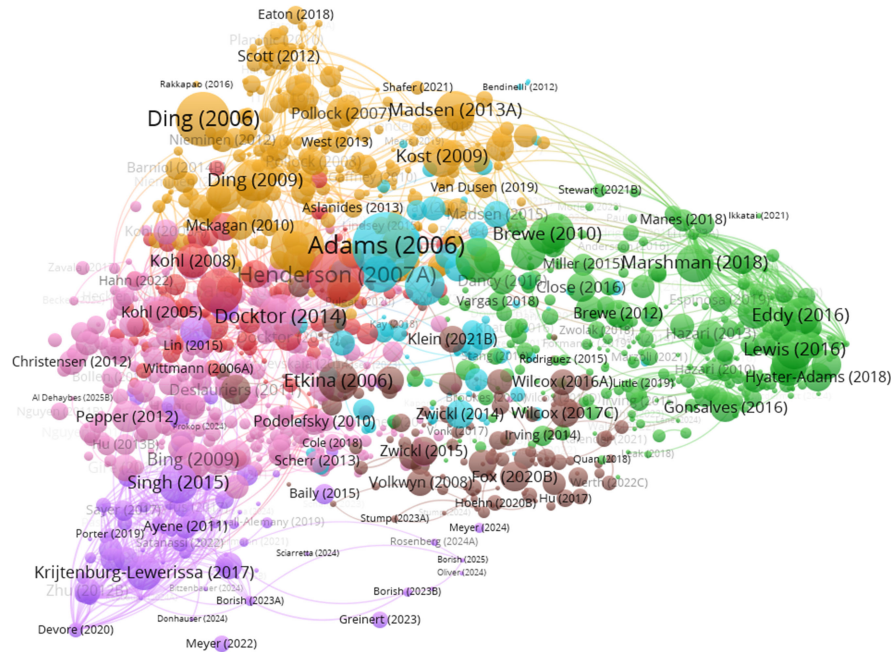


FIG. 8. Bibliometric coupling of PRPER documents between July 2005 and June 2025. Each node represents a published paper. Nodes are positioned based on their coupling strength, with more closely related papers appearing nearer to each other. The distinct colors represent the seven major thematic clusters identified by the Leiden algorithm. Each color-coded region represents a cluster, which is a group of documents that are more strongly bibliographically coupled (i.e., share more references) with each other than with documents in other clusters.

scaffolding to improve representational consistency in a Gauss's law problem. The article by Tuminaro *et al.*, published in 2007 [34], with a total link strength of 1929, studies epistemic games as elements of a cognitive model of physics problem solving.

This cluster underscores the central role of problem solving in PER and highlights the instructional strategies that support students in becoming more effective and reflective problem solvers.

6. Cluster 6: Attitude and Epistemology

Cluster 6 brings together work on students' beliefs about physics, their expectations for learning, and the epistemological frameworks they hold. These beliefs profoundly affect how students engage with instruction and how they persist through challenges.

Among the core contributions is the article by Robinson *et al.*, published in 2021 [65], which has the strongest total link strength (2200) and investigates whether expertlike attitudes correlate with higher learning gains for women, alongside attitudinal shifts and gender gap narrowing. The article by Hull *et al.*, published in 2016 [66], with a total link strength of 1751, examines unexpected attitudinal growth in a course with reformed curricula. Elby's article in 2020 [67], with a total link strength of 1670, rethinks the relationship between instructors and physics education researchers.

This theme plays a foundational role in understanding students' motivational orientations and the implicit messages communicated by physics instruction.

7. Cluster 7: Quantum Physics Education

Although the smallest in size, cluster 7 addresses a highly specialized and conceptually rich area of physics education: the teaching and learning of quantum physics. A structurally central article by Marshman and Singh [68], which has the strongest total link strength (2408), provides a framework for understanding patterns of student difficulties in quantum mechanics. Dini and Hammer's article in 2017 [69], with a total link strength of 2335, presents a case study of a successful learner's epistemological framings of quantum mechanics. The article by Keebaugh *et al.*, published in 2024 [70], with a total link strength of 2142, explores challenges in sensemaking and reasoning within degenerate perturbation theory in quantum mechanics. This cluster reveals the challenges and innovations associated with teaching one of the most abstract domains in physics, and it is gaining importance as quantum content increasingly enters the undergraduate curriculum.

It is interesting to note that the Identity and Equity cluster (green) is visually distant from the Quantum Physics Education cluster (violet), indicating limited bibliographic coupling despite potential conceptual intersections. The spatial arrangement of clusters and nodes in the VOSviewer

TABLE VI. An overview of bibliometric clusters of PRPER publications between July 2005 and June 2025 (n = number of publications in the cluster; TLS = Total link strength).

Cluster	Theme	Most linked publications		
		Authors	Title	TLS
1 Pink $n = 328$	Understanding and Supporting Student Learning	Robertson <i>et al.</i> (2023)	Identifying student conceptual resources for understanding physics: a practical guide for researchers [51]	1671
		Gupta <i>et al.</i> (2018)	Exploring the entanglement of personal epistemologies and emotions in students' thinking [52]	1648
		Bailey <i>et al.</i> (2017)	Meeting students halfway: Increasing self-efficacy and promoting knowledge change in astronomy [53]	1500
2 Green $n = 295$	Identity, Equity, and Belonging	Li and Singh (2023)	Sense of belonging is an important predictor of introductory physics students' academic performance [54]	3192
		Li and Singh (2022)	Inclusive learning environments can improve student learning and motivational beliefs [55]	3016
		Traxler <i>et al.</i> (2016)	Enriching gender in physics education research: A binary past and a complex future [56]	2601
3 Orange $n = 247$	Conceptual Inventory	Stewart <i>et al.</i> (2018)	Multidimensional item response theory and the Force Concept Inventory [57]	2602
		Hewagallage <i>et al.</i> (2022)	Examining the relation of high school preparation and college achievement to conceptual understanding [58]	2303
		Wells <i>et al.</i> (2019)	Exploring the structure of misconceptions in the Force Concept Inventory with modified module analysis [59]	2283
4 Brown $n = 145$	Physics Laboratory	May (2023)	Historical analysis of innovation and research in physics instructional laboratories: Recurring themes and future directions [60]	1400
		Vignal <i>et al.</i> (2023)	Survey of physics reasoning on uncertainty concepts in experiments: An assessment of measurement uncertainty for introductory physics labs [61]	1241
		Buggé (2023)	Improving scientific abilities through lab report revision in a high school investigative science learning environment classroom [62]	1173
5 Red $n = 103$	Physics Problem Solving	Good <i>et al.</i> (2019)	Impact of traditional or evidence-based active-engagement instruction on introductory female and male students' attitudes and approaches to physics problem solving [63]	2719
		Maries <i>et al.</i> (2017)	Challenges in designing appropriate scaffolding to improve students' representational consistency: The case of a Gauss's law problem [64]	2117
		Tuminaro and Redish (2007)	Elements of a cognitive model of physics problem solving: Epistemic games [34]	1929
6 Blue $n = 86$	Attitude and Epistemology	Robinson <i>et al.</i> (2021)	Positive attitudinal shifts and a narrowing gender gap: Do expertlike attitudes correlate to higher learning gains for women in the physics classroom? [65]	2200
		Hull <i>et al.</i> (2016)	Unexpected attitudinal growth in a course combining reformed curricula [66]	1751
		Elby and Yerdelen-Damar (2020)	Rethinking the relationship between instructors and physics education researchers [67]	1670
7 Purple $n = 85$	Quantum Physics Education	Marshman and Singh (2015)	Framework for understanding the patterns of student difficulties in quantum mechanics [68]	2408
		Dini and Hammer (2017)	Case study of a successful learner's epistemological framings of quantum mechanics [69]	2335
		Keebaugh <i>et al.</i> (2024)	Challenges in sensemaking and reasoning in the context of degenerate perturbation theory in quantum mechanics [70]	2142

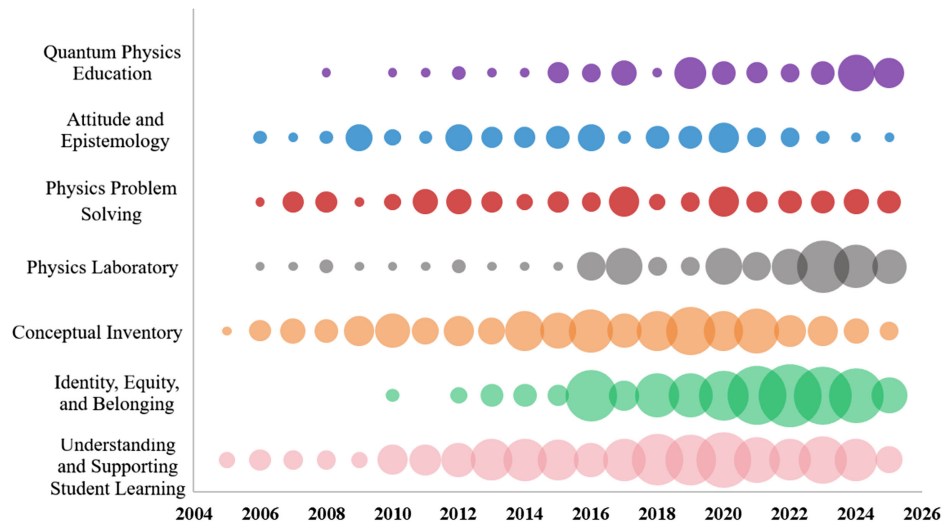


FIG. 9. Thematic influence over time. Circle size = Total number of publications in the cluster during that year. Note that the counts for 2005 and 2025 represent partial years (July–December and January–June, respectively) due to the data collection timeframe.

map is meaningful: the software uses a force-directed layout algorithm—known as the VOS mapping technique—to position nodes on a two-dimensional plane. In this approach, nodes are modeled as objects that repel each other, while the links (representing relatedness) act as springs that pull connected nodes together. The final layout is the equilibrium state of this system, where strongly related nodes are naturally pulled closer. In this layout, the distance between any two nodes reflects the strength of their relatedness; nodes with strong bibliographic coupling are positioned closer together, while those with weaker or no coupling are placed farther apart, thereby visually representing the intellectual structure of the field [28]. Although identity-related themes such as equity and belonging are well represented in PRPER, few articles explicitly address these constructs in the context of quantum physics education [71].

G. Temporal trends in thematic development

This section explores how the prominence of different research themes in PRPER has evolved over time. Using the publication year of each article and its assigned cluster, we tracked annual publication counts across the seven clusters identified in the bibliometric coupling analysis. To visually represent the influence of each cluster over time, we created a timeline figure where each research theme is shown on a horizontal track, with one circle per year (Fig. 9). The size of each circle corresponds to the total number of publications in that cluster for that year. This figure provides a visual proxy for the output of each theme over time.

The results reveal clear phases of thematic development. In the early years of PRPER (2005–2015), clusters focused on conceptual understanding, learning support, physics problem solving, and attitude research dominated the

structural core of the literature. In the more recent phase (2016–2025), physics problem solving, as well as Understanding and Supporting Student Learning, continues to play a significant role, while research attention to attitudes and epistemology peaked in 2020 and then declined from 2021 onward, and its share of PRPER publications also decreased relative to other themes in the same period. During these years, research on physics laboratories, identity, equity, and quantum physics education shows a marked increase in publication counts. These changes reflect an expanding scope in PER, evolving from a focus on foundational cognitive research to include affective, social, and systemic dimensions.

IV. DISCUSSION

This bibliometric study offers a comprehensive overview of the development and intellectual structure of physics education research (PER) as represented in Physical Review Physics Education Research (PRPER) over its first two decades (2005–2025). In this section, we discuss the key findings derived primarily from publication or citation trends, keyword analysis, and bibliographic coupling analysis. We examine the implications of the observed trends, particularly the thematic structure revealed through bibliographic coupling, address methodological considerations, and propose future directions for researchers in PER.

A. Intellectual structure and cluster coherence

The bibliographic coupling analysis, visualized using VOSviewer, identified seven distinct clusters of intellectually related research within the PRPER corpus. Bibliographic coupling links documents that cite similar prior work, thus grouping articles that share a common intellectual heritage

and are likely addressing related research questions or building upon the same foundational literature [24,25]. These seven clusters represent major thematic areas that have shaped the journal's content, encompassing diverse topics from foundational student learning and conceptual understanding to specific subfields like quantum mechanics education and cross-cutting issues like identity, equity, and belonging.

These clusters collectively reflect the multifaceted nature of physics education research and its evolution. While the VOSviewer algorithm [26] groups documents into distinct clusters based on the density of shared references, it is important to interpret these as representing interconnected thematic zones rather than entirely separate silos. Some overlap or shared boundaries are natural, indicating research areas that draw upon common theoretical or empirical bases [2]. The manual review and labeling process, based on the most coupled papers (highest total link strength) within each cluster, aimed to capture the core essence of each thematic area, resulting in an interpretable map of PRPER's intellectual landscape. The analysis highlights both the established pillars of PER (like understanding student learning and conceptual inventory) and the dynamic emergence of newer foci (like equity and quantum education).

Our findings complement previous efforts to categorize physics education research by offering a citation-based map of how research areas in PRPER have co-developed over time. For example, Odden *et al.* proposed a topic model of PER built from semantic text embeddings of article titles and abstracts, paired with deductive coding using a framework grounded in the *International Handbook of Physics Education Research* [72]. Their approach provides a normative classification of research topics—that is, a classification based on a predefined, expert-derived framework—and reveals the semantic similarity between publications across journals. In contrast, our analysis maps the intellectual structure of PRPER through bibliographic coupling, which highlights how articles are connected through shared citations rather than textual content.

While text embedding approaches emphasize what publications say, bibliographic coupling emphasizes what prior work they build upon. The resulting clusters reveal different but complementary views of the field: one organized by conceptual discourse, the other by intellectual lineage. Notably, some of the clusters we identified—such as those focused on identity, equity, and quantum education—emerged organically through shared references rather than predefined categories, reflecting how these themes are being actively developed and linked within the PRPER corpus itself.

Together, these approaches suggest that PER is not only diversifying semantically but also structurally: topics once peripheral are becoming more integrated into the field's shared knowledge base.

B. The emergence of quantum physics education as a distinct theme

A particularly noteworthy finding from the bibliographic coupling analysis is the emergence of cluster 7: Quantum Physics Education (QPE) as one of the seven distinct major themes. While other clusters represent broader pedagogical concerns (e.g., problem solving and epistemology) or fundamental learning processes, this cluster is uniquely defined by a specific physics subdiscipline. Its distinctiveness signals the maturation of QPE into a significant and coherent subfield within PER, with its own set of research questions, conceptual challenges, and shared foundational literature reflected in the coupling patterns.

Research within this cluster often grapples with specific challenges like student difficulties with abstract concepts (e.g., superposition and measurement), the role of mathematical formalism, and the development of effective representational tools and instructional strategies [67,73]. The strong bibliographic coupling within this cluster suggests a dedicated community of researchers actively building upon a shared knowledge base to address these unique educational challenges.

The rise of QPE's prominence within PRPER is likely driven by a confluence of factors, encompassing both the internal evolution of the PER field and significant external influences. Primarily, the trend reflects the natural trajectory of PER itself, as pointed out by an anonymous referee of this contribution. After several decades of foundational work focused on the core topics of classical physics, quantum mechanics represented one of the last remaining unexplored frontiers in physics education. This naturally drew the attention of researchers looking for novel areas of investigation and new, challenging conceptual problems to address.

This internal momentum was concurrently amplified by several external factors. First, the field of quantum mechanics itself is entering its landmark centenary period, marking 100 years since foundational developments around 1925–1926 by Heisenberg and Schrödinger, potentially renewing interest in its foundations and pedagogy [74,75]. Second, there is a growing recognition of the need to introduce quantum concepts earlier and more effectively in the physics curriculum, moving beyond specialized upper-level courses, driven partly by the conceptual richness and counterintuitive nature of the subject [37,40]. Third, the burgeoning field of quantum technologies (quantum computing, sensing, and communication)—often termed the “second quantum revolution”—underscores the societal and economic relevance of quantum literacy, creating external pressure for improved educational approaches [76].

Furthermore, the formation of this cluster may be influenced by the editorial call of the 2021 Focused Collection on Quantum Physics Education published in PRPER [77]. However, it is important to note that

editorial calls do not necessarily result in structurally coherent clusters. Other well-established subfields—such as classical mechanics, electricity and magnetism, or optics—have long been central in physics education but do not appear as separate thematic clusters in this analysis. The fact that QPE does emerge as a distinct cluster suggests it has developed a shared intellectual core, characterized by strong internal bibliographic coupling. While bibliographic coupling alone does not establish conceptual identity, the cohesion of this cluster may reflect the early formation of a focused research community around QPE. Future work could examine whether these papers also share common methodologies, theoretical frameworks, or self-referential citation practices—hallmarks of a mature research identity.

It is notable that while Quantum Physics Education emerges as a distinct cluster, other core physics topics like classical mechanics or electricity and magnetism do not. This does not imply a lack of research in these areas; on the contrary, they form the bedrock of much of the work in the “Understanding and Supporting Student Learning” and “Conceptual Inventory” clusters. Their absence as separate clusters may be a feature of how the field has developed. Research on these foundational topics is often integrated and shares a common intellectual heritage, citing a broad and overlapping set of foundational PER literature. In contrast, QPE research appears to have developed a more distinct and self-referential literature base, allowing it to cohere into a separate cluster in a bibliographic coupling analysis. This finding highlights how this method reveals communities of practice defined by shared citations, rather than simply content topics.

C. Physics laboratory instruction

Cluster 4 brings together research focused specifically on the physics instructional laboratory. This distinct environment, long considered a cornerstone of physics education, forms the core of this thematic cluster, differentiating it from research primarily focused on classroom-based conceptual learning or theoretical problem solving. Notably, while instructional labs have always been discussed within PER literature, the identification of laboratory instruction as a major, distinct intellectual cluster through subjective analysis represents a novel finding compared to prior broad syntheses [12,78], where lab-related research was often subsumed under broader categories like instruction or assessment. The papers grouped here share a common foundation in literature discussing the goals, design, implementation, and assessment of laboratory work [79,80]. Research within this cluster investigates various facets of the lab experience, including its effectiveness in achieving different learning objectives—ranging from reinforcing theoretical concepts to developing experimental skills, data analysis capabilities, and understanding the nature of science [35,81].

The most coupled papers identified in Table VI exemplify the focus on laboratory practice and pedagogy. May’s historical analysis in 2023 underscores the recurring themes and ongoing debates surrounding innovation and reform within instructional labs, highlighting the enduring challenges and evolving priorities in this area [60]. Studies examining specific skills developed in the lab context are also prominent, such as research on student reasoning about measurement uncertainty [61,82] or the development of scientific abilities through revising lab reports [62]. The coherence of this cluster signifies the unique set of pedagogical questions.

D. Contribution to the PER literature

This study’s findings contribute to a growing body of reflective work within PER. Much valuable synthesis work in the field delves deeply into specific domains, pedagogical approaches, or demographic aspects. For instance, reviews like Kanim and Cid [8] provide critical insights into researcher demographics, Pawlak *et al.* [9] meticulously analyze interactions within physics tutorials, and Meltzer and Thornton [10] synthesize findings on active learning. These focused reviews are essential for advancing understanding within particular subfields. Our macroscopic analysis complements these efforts by providing the broader context. By analyzing the entire PRPER corpus via bibliographic coupling, we reveal the relative prominence, intellectual interconnectedness, and temporal trajectory of diverse themes, situating these specific research areas within the wider ecosystem of this key journal.

Beyond these focused reviews, broader syntheses have also shaped the field. Notably, two prior works offer comprehensive perspectives: the narrative synthesis by Docktor and Mestre [12] and the topic modeling analysis of abstracts by Yun [78]. Our findings for the period up to roughly 2014 align closely with the foundational areas mapped by Docktor and Mestre, while our identified themes up to 2019 show strong parallels with those identified by Yun, particularly concerning conceptual understanding, problem solving, and epistemology. This consistency lends confidence to the mapping of the field’s earlier state presented here.

However, the landscape of PER, as reflected in PRPER, has evolved rapidly, particularly in the last five years—a period subsequent to the scope of these prior comprehensive reviews. Our analysis extends to the present and, with a substantially larger dataset, a 73% increase in PRPER papers since Yun’s 2019 data cutoff, captures this recent dynamism. Furthermore, our methodology differs significantly: employing bibliographic coupling network analysis on full publication records allows us to map the intellectual structure based on shared scholarly foundations within PRPER, specifically, revealing connections and coherences (like the distinct clusters for “Physics laboratory” and

“Quantum Physics Education”) potentially obscured by other methods or broader journal scopes.

Therefore, this study uniquely contributes to the literature by providing (i) the first comprehensive structural map of PRPER’s specific knowledge base using large-scale bibliographic coupling; (ii) quantitative identification of influential actors and collaborations shaping research within this premier journal; (iii) an updated longitudinal perspective (2005–2025) capturing recent rapid evolution across a significantly larger dataset than previous trend analyses; and (iv) a macroscopic, network-based view that complements existing thematic, methodological, and demographic reviews in the PER field.

E. Methodological reflections and limitations

This study employed bibliographic coupling analysis using VOSviewer to map the intellectual structure of PRPER. This method effectively identifies thematic connections based on shared reference lists, highlighting communities of research built upon common foundations [23]. However, certain methodological considerations and limitations should be acknowledged.

First, like any citation-based analysis, bibliographic coupling relies on historical publication and citation patterns. Newly emerging research themes or niche topics that have not yet established a substantial body of work citing common references might be underrepresented or not form distinct clusters [2]. The analysis reflects established connections more readily than nascent ones.

Second, the cluster formation depends on both the specific algorithm implemented in VOSviewer (the Leiden algorithm) and the parameters selected by the researchers. We adhered to common practices in bibliometric network analysis and carefully selected parameters aimed to generate interpretable and substantive clusters, thereby enhancing confidence that the presented map reliably reflects the underlying intellectual structure of PRPER. Nonetheless, it is important to acknowledge that clustering outcomes are inherently sensitive to specific algorithmic choices and parameter settings; consequently, alternative analytical decisions could potentially yield variations in the resulting cluster structure [26,27]. Furthermore, the cluster labeling process involved manual interpretation by experts. While this enhances semantic meaning compared to purely algorithmic labels, it inevitably introduces an element of subjectivity into the final thematic descriptions.

Third, bibliographic coupling can be influenced by publication date and reference list length. It is important to acknowledge that bibliographic coupling has inherent biases. Because the method links papers by overlapping reference lists, it favors more recent publications that can draw upon a larger pool of prior work, and it also advantages authors who include unusually long reference lists, not always limited to directly relevant sources. As a result, some papers that are conceptually central may

appear less connected in the coupling network. Complementary approaches, such as text embedding or topic modeling based on article titles and abstracts, do not depend on reference list length and can capture thematic relationships that bibliographic coupling overlooks. Future work that integrates citation-based and text-based analyses could therefore provide a more balanced view of the intellectual structure of PER.

Additionally, while the algorithm assigns each paper to a single cluster based on the strength of its bibliographic coupling, this process has limitations—especially for comprehensive review articles that span multiple themes. For instance, a review such as Docktor and Mestre [12], which was designed to synthesize findings across diverse areas of PER, is algorithmically grouped into the “Understanding and Supporting Student Learning” cluster. This likely reflects the fact that its reference list shares the most overlap with papers in that (largest) cluster. In this sense, the cluster assignment is not entirely unreasonable, as it reflects the strongest bibliographic connection in terms of shared references. Nevertheless, we acknowledge that such assignments may obscure the broader thematic scope of integrative papers. This highlights a general limitation of citation-based clustering methods: while objective and reproducible, they may underrepresent the interdisciplinary or cross-cutting nature of certain works.

Finally, the analysis is intentionally limited to publications from PRPER. This journal-specific focus provides a deep view of this key venue but necessarily overlooks related research published in other important journals (e.g., *American Journal of Physics*, *The Physics Teacher*, *Research in Science Education*) or conference proceedings. Therefore, the findings represent the structure within PRPER and should be interpreted as a significant, but not exhaustive, view of the entire PER field.

F. Research gaps, implications, and future directions

The findings and trends identified in this analysis carry several direct implications for researchers, editors, and the broader PER community, and they highlight clear opportunities for future work. We structure these around three key areas: thematic content, global and contextual diversity, and researcher-practitioner engagement.

First, our analysis of keywords and thematic contents reveals several underrepresented areas within PRPER’s dominant clusters. Topics such as computational physics education, physics in informal learning environments (e.g., museums, outreach), and deeper interdisciplinary integration with fields like biology or engineering appear less frequently, suggesting that expanding research in these domains could enrich the field.

Second, the intellectual structure revealed by our network analysis points to a compelling opportunity for synthesis. The Identity and Equity cluster and the Quantum Physics Education cluster, two of the most rapidly growing themes,

are structurally distant on our map, indicating limited bibliographic coupling. This data-driven finding suggests that the research communities focused on these critical topics have so far developed in parallel. This gap highlights a clear and important future direction: work that intentionally bridges these themes—for instance, by investigating equity and belonging in upper-level quantum courses—is needed to integrate socioaffective dimensions into advanced physics education.

Third, the need for broader representation is evident. While our timeline analysis reveals encouraging growth in equity-focused research, our performance analysis confirms a strong dominance by U.S.-based institutions. This underscores a significant need for more comparative and global studies. Actively soliciting and featuring submissions from geographically diverse and underresourced educational contexts would enhance the global relevance and inclusivity of PRPER's contributions, while also testing the generalizability of findings primarily derived from a U.S. context. This aligns with the vision laid out by the journal's recently appointed Editor-in-Chief, Eric Brewe, who, in his recent editorial, emphasized the importance of increasing global inclusivity [83].

Finally, our analysis of author and institution characteristics suggests a very limited contribution from the K-12 practitioner community. We found that contributions primarily authored from a K-12 school setting are virtually absent, despite a growing number of Ph.D.-trained K-12 physics teachers. This indicates an opportunity to foster stronger collaborations and create pathways for research-trained K-12 teachers to contribute to the scholarly literature. Bridging this gap could potentially enhance both the impact and practical relevance of physics education research at this level.

Overall, this structured map of PRPER's evolving discourse can help researchers navigate the field's intellectual terrain, while also encouraging the community to reflect on its priorities. As PER continues to respond to societal shifts and advances in pedagogy, maintaining a balance between conceptual rigor, methodological innovation, and social relevance—all visible across the identified clusters—will be essential for its continued vitality.

V. CONCLUSIONS

Commemorating *Physical Review Physics Education Research*'s 20th anniversary, this study presented the first comprehensive bibliometric analysis of the journal's publications from its inception in July 2005 through

June 2025. Employing a multifaceted approach, we analyzed publication and citation trends, institutional and national contributions, collaboration networks, keyword frequency and co-occurrence patterns, and, centrally, the intellectual structure revealed through bibliographic coupling analysis.

The results paint a picture of a vibrant and growing journal central to the PER field. Key findings include a sustained increase in publication volume over the two decades, demonstrating the journal's expanding output and reach. Analysis revealed the enduring impact of foundational articles, particularly those published in the early years, alongside dominant contributions from U.S.-based institutions and authors operating within identifiable collaboration networks. The thematic structure analysis finds that PRPER publications group well into seven major research clusters: Understanding and Supporting Student Learning; Identity and Equity; Conceptual Inventory; Physics Laboratory; Physics Problem Solving; Attitude and Epistemology; and Quantum Physics Education. Furthermore, our analysis of author backgrounds reveals that the field's most prolific contributors in PRPER are predominantly researchers with Ph.D.s in physics instead of education who are now housed within physics departments, providing a demographic insight into the identity of the PER community publishing in its flagship journal.

Trend analysis confirms a dynamic evolution in the field's focus. While foundational themes like student understanding and problem solving remain stable pillars, recent years have seen a marked increase in research activity related to identity, equity, and quantum physics education, while attention to some other areas, like attitudes and epistemology, has declined. This comprehensive, data-driven overview provides not only a retrospective map of PRPER's influential first two decades but also offers a valuable resource for understanding the field's trajectory and navigating future research directions within the PER community.

The authors declare no competing interests.

This study does not involve human participants.

DATA AVAILABILITY

The data that support the findings of this article are openly available [84].

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