A bibliometric analysis of PER on quantum mechanics in secondary schools

Zac Patterson
Department of Teaching and Learning, The Ohio State University, 1945 N High St, Columbus, OH 43210-1172

Lin Ding
Department of Teaching and Learning, The Ohio State University, 1945 N High St, Columbus, OH 43210-1172

With the second quantum revolution and the growing need of a competent workforce in Quantum Information Science, formal instruction on contemporary physics topics such as quantum mechanics (QM) is a particularly important component of modern secondary science education. Additionally, a formal introduction to physics is incomplete without an exploration of the quantum realm and the findings of the first quantum revolution. Exposure to QM can radically alter an individual's view of the physical universe and can broadly engage secondary students. Exposure to QM in secondary schools has increased substantially in recent years yet is still an understudied area with a limited body of research on this topic. The aim of this paper is to analyze this body of research by bibliometric analysis, examining yearly output, citation index, author nationality, publishing venue, and keywords of relevant publications. The academic search engines SCOPUS and Web of Science were used to collect publications emphasizing the teaching and learning of QM at the secondary level. First, we present a quantitative analysis of the bibliometrics, followed by an assessment of publication trends in teaching and learning. Lastly, an analysis of research gaps and opportunities for further investigation is discussed.

2022 PERC Proceedings edited by Frank, Jones, and Ryan; Peer-reviewed, doi.org/10.1119/perc.2022.pr.Patterson

I. INTRODUCTION

Historically, secondary physics education has maintained a focus on content associated with classical physics topics (e.g., Newtonian mechanics). However, in recent decades secondary physics curricula around the globe have increasingly included contemporary physics topics such as quantum mechanics. This trend can be attributed to two realizations by secondary physics curriculum developers. The first being that a formal introduction to the field of physics is incomplete without the inclusion of content derived from the discoveries of the quantum revolution in physics that occurred during the early 20th century. The second is associated with the approach of a 2nd quantum revolution. Leaders worldwide identify the need of a quantum-smart workforce as the field of Quantum Information Science (QIS) expands throughout academia as well as industry and government agencies. We are currently witnessing an exponential growth in the development and implementation of quantum technologies as well as educational opportunities associated with QIS.

The trend of including contemporary physics content in secondary physics curricula, led by the efforts of European curriculum developers, sees no indication of slowing down [1]. There is, however, a limited body of physics education research (PER) addressing the teaching and learning of contemporary physics topics at the secondary level. A body of work predominantly focusing on the teaching and learning Quantum Mechanics (QM) has begun to accumulate with increasing depth and regularity in recent years. Currently there is a lack of coherent representation of the body of research associated with the teaching and learning of QM at the secondary level. A comprehensive analysis of present work will serve the PER community in efforts to expand upon research and fill gaps within the literature. To assist in this endeavor, we have performed a bibliometric analysis of PER addressing the teaching and learning of QM at the secondary level. To perform this analysis we identify research conducted on the teaching and learning of QM at the secondary level, quantify characteristics of this research, analyze trends, and identify gaps as well as opportunities for expansion. This is approached by pursuing the following research questions:

1. *How have publications on the teaching and learning of quantum mechanics in secondary schools developed over time in terms of number of publications and citations?*
2. *What sources are contributing to physics education research on quantum mechanics in secondary schools in terms of country and publishing venue?*
3. *What research trends can be witnessed throughout the collected body of work focusing on the teaching and learning of quantum mechanics in secondary schools?*

II. METHODS

A. Data Collection

A bibliometric analysis provides an overview of research output on a research focus. The research focus for this analysis is quantum mechanics education at the secondary level and the two databases used to retrieve articles of interest were SCOPUS (http://www.scopus.com, accessed on 8 March 2022) and Web of Science (https://www.webofscience.com/wos/woscc/basic-search, accessed on 8 March 2022). These two databases were selected based on the magnitude of available data they provide associated with physics and education. The search queries in Table I were used to obtain reliable and relevant data sets. We searched for articles associated with physics education or science education and filtered articles using two sets of keywords. The first set of keywords (*quantum physics, quantum mechanics,* and *quantum)* is used to identify articles associated with the physics content of interest, the second (*secondary education, high school, pre university*) to identify articles associated with the education level of interest. These key words were used to obtain articles of interest in conjunction with article titles, abstracts, and authors' keywords. Results were restricted to education research articles published in journals. There were no restrictions regarding article language or date of publication. The SCOPUS search included no refinements while the Web of Science search was restricted to articles published in journals and to the research area *Education - Education Research*.

TABLE I. Database search queries.

Database	Search Query
SCOPUS	SRCTITLE((physics OR science) AND education) AND SRCTYPE(j) AND (TITLE-ABS-KEY("quantum physics") OR TITLE-ABS-KEY ("quantum mechanics") OR TITLE-ABS-KEY("quantum") AND TITLE-ABS-KEY("secondary education") OR TITLE-ABS-KEY("high school") OR TITLE-ABS-KEY("pre university"))
Web of Science	(TS = (physics) OR TS = (science) AND TS = (education)) AND (TI = ("quantum physics") OR TI = ("quantum mechanics") OR TI = ("quantum") OR AB = ("quantum physics") OR AB = ("quantum mechanics") OR AB = ("quantum") OR AK = ("quantum physics") OR AK = ("quantum mechanics") OR AK = ("quantum")) AND (TI = ("secondary education") OR TI = ("high school") OR TI = ("pre university") OR AB = ("secondary education") OR AB = ("high school") OR AB = ("pre university") OR AK = ("secondary education") OR AK = ("high school") OR AK = ("pre university"))

We first used the SCOPUS database to collect relevant articles for this study. This search produced 37 relevant items. Next, the Web of Science search query was implemented to supplement the results from the SCOPUS search. The Web of Science search revealed 8 additional publications relevant to the study. In total, we collected and analyzed 45 relevant documents.

III. DATA ANALYSIS & RESULTS

Upon retrieval of relevant articles for this bibliometric analysis we identified characteristics of interest from each article. For each article we identified the following: publication year, citation index, publisher, country of affiliated research institutions, author's keywords, research focus, QM instructional content, and data analysis methods. In the next section we provide figures and tables representing the data of interest. This is followed by an analysis of publication trends.

A. Quantitative Analysis of Bibliometrics

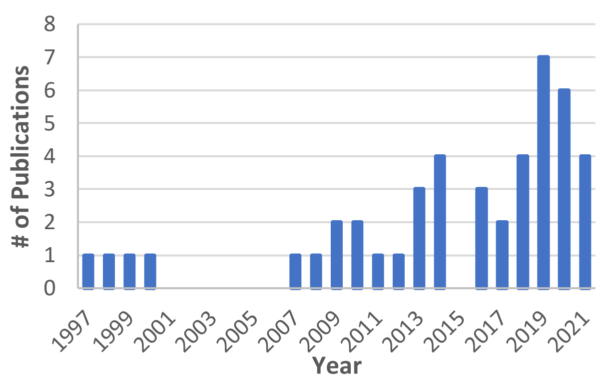

FIG. 1. Number of publications per year addressing the teaching and learning of quantum mechanics at the secondary level.

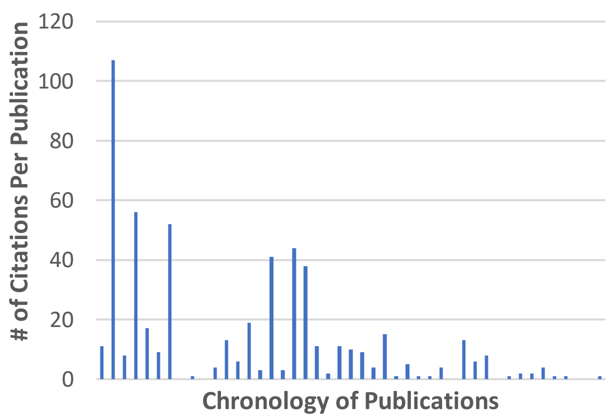

FIG. 2. Number of citations per publication.

TABLE II. Number of publications per publishing venue.

Publisher	# of Publications
Physics Education	19
Physical Review – PER	8
Science and Education	4
Int J of Science Education	3
Science Education	2
Chemistry Education Research & Practice	1
Didactic of Experimental and Social Science	1
Electronic Journal of E-Learning	1
Eurasia Journal of Math, Sci, and Tech Education	1
Eurasian Journal of Educational Research	1
Int J of Science and Math Ed	1
J of E-Learning and Knowledge Society	1
J of Research in Ed Sciences	1
Research in Sci & Tech Ed	1

TABLE III. Number of publications from country of affiliated research institution.

Country	# of Publications
Italy	8
Spain	6
Netherlands	5
Norway	4
Germany	4
USA	2
Chile	2
Taiwan	2
Denmark	2
Israel	2
Greece	2
England	2
Brazil	1
Argentina	1
Turkey	1
China	1
Australia	1
Sweden	1

B. Publication Trends

The articles reviewed for this study revealed multiple trends. Specifically, we were able to identify trends using the following information from each publication: author keywords, research focus, QM instructional content, and research methods.

1. Keyword frequency and research focus

Through a frequency analysis of author's keywords, we were able to identify the most relevant keyword associations with these publications. The articles included a total of 74 keywords. Of these, 23% were associated with specific QM content (e.g., wave-particle duality, photoelectric effect, spin concept). The next most common keyword associations were *quantum mechanics* (18%), *education/learning* (16%), and *secondary education* (8%). The high frequency of keywords associated with specific QM content indicates that many of the articles isolate the teaching and learning of a narrow component of QM for analysis.

Article abstracts and research questions were used to identify research focus trends throughout the body of work. Through an iterative data exploration process splits in research foci were identified in two common areas: 1) orientation (research- vs practitioner-oriented) and 2) teaching and learning (instructor- vs student-focused). Trends over time were then analyzed to identify evolving research foci.

To identify the research orientation (research- vs practitioner-oriented) we determined whether the goal of the publication is to assist in further research development (research-oriented) or enhance instruction (practitioner-oriented). We view work with a research-oriented focus as an attempt to expand knowledge or establish academic understanding, whereas work with a practitioner-oriented focus aims to propose new instructional strategies, lesson design, or pedagogical approaches that enhance the learning process.

We identified 24 of the articles of focus as research-oriented, 21 as practitioner-oriented. There were no significant trends over time regarding research orientation. The median year of publication of this data set is 2017. Exactly half of research-oriented articles were published before this date and half after, with 10 practitioner-oriented articles being published before this date and 11 after. Overall, there seems to be a balanced divide between the two categories of orientation as well as orientation focus over time.

The second research focus area (teaching and learning) involved categorizing the articles as instructor-based (teaching centered) or student-based (learning centered). We identify instructor-based research foci as research analyzing instructors and/or teaching or involving instructional design. We identify student-based research foci as research analyzing students or learning.

Over half of the articles were instructor-focused (29), while 11 were student-focused, and 5 articles exhibited a combined focus. With 76% of the articles focusing on instruction (at least partially) it is evident that research on QM at the secondary level has predominantly focused on teacher-facing content. No trends of importance were identified over time.

2. Instructional content and methods of analysis

Throughout our analysis it became evident that many of the articles of focus isolate specific QM instructional content for their reported study while others address the collective field of QM. To determine the most common QM content of focus we identified the instructional content involved in each study and performed a content frequency analysis.

The content frequency analysis revealed that all but four articles isolated specific QM content for the purpose of the study. Among these articles the most common content areas of focus were wave-particle duality and Heisenberg's Uncertainty Principle. These two areas were a focus in 11 and 10 of the articles, respectively. Apart from these, no other specific QM content area served as the content focus in more than 4 articles. This seems to suggest that wave-particle duality and Heisenberg's Uncertainty Principle are the only items that have generated significant attention in studies associated with QM at the secondary level. All other areas of QM study (e.g., superposition, photoelectric effect, quantization, entanglement) have yet to generate substantial research focus in teaching and learning at the secondary level.

When conducting the content frequency analysis, we found it intriguing that the two most common QM content areas of focus (wave-particle duality and Heisenberg's Uncertainty Principle) were each only isolated in a study twice prior to 2017. The first 22 publications by year did not exhibit any regularity regarding these two content areas. However, the 23 publications from year 2017 on contained 17 combined mentions of these two content focus areas. This seems to indicate an increased focus on research associated with the teaching and learning of wave-particle duality and Heisenberg's Uncertainty Principle since the year 2017.

An analysis of research methods was also conducted. For this analysis we determined whether the authors employed methods that were qualitative, quantitative, or a mixed methods approach. It was revealed that qualitative methods are by far the most prevalent data analysis methods used by researchers studying the teaching and learning of QM at the secondary level. 23 out of the 45 articles of focus used only qualitative methods, while 7 studies used only quantitative methods, and 8 used a combination of the two (mixed methods). Additionally, 7 articles used no data analysis methods at all. These articles predominantly maintained a focus on proposing new teaching methods (e.g., instructional tools, pedagogical strategies, lesson designs) in which no data analyses were conducted.

It comes as no surprise that qualitative methods were the dominant form of data analysis in these articles. Qualitative work is more common than quantitative and mixed methods in science education research [2] as well as the whole of education research [3]. Additionally, the research goals of many articles within this study involved analyzing student perspectives and interpretations of QM. The most common methods of analyses were thematic analysis and questionnaires.

4. DISCUSSION

In response to our first research question, it is evident that research on the teaching and learning of QM at the secondary level is expanding. As Figure I indicates, there has been a noticeable increase in the number of publications by year in the past decade. It is reasonable to expect these numbers to continue to rise along with trends in physics education research related to QM instruction in secondary schools such as an increased emphasis on conceptual understanding and NOS topics, as well as the expected increase in the integration of quantum technologies throughout society. Citations for the publications in this study are still very low compared to other areas of PER. With the exception of three studies published prior to 2010 no publication in this study has amassed more than 50 citations (Fig. 2). This may indicate that this subfield of research is still in its infancy, growing in breadth but lacking a core of agreeable studies to serve as the backbone for future research. As this body of work continues to grow it can be expected that citation indexes will continue to grow as well.

Our second research question investigates affiliated institutions contributing to this body of work (Table III) and what venues have published this work (Table II). The vast majority of publications on this topic are the work of researchers representing European institutions. Work of European origin has clearly paved the way for this area of research. Authors representing European institutions are responsible for producing 75% of the articles in this study. This overwhelming European majority can be explained by the content of secondary physics curricula in European countries. Compared to the rest of the world European physics curricula more commonly include QM content and at greater quantities than other country's secondary physics curricula [1]. As the PER community continues to emphasize conceptual understanding, as more open-source resources on QM instruction are made available, and as countries continue to pass legislature with a focus on preparing a quantum workforce (e.g., The National Quantum Initiative Act – USA) it is reasonable to expect increased production in the future from non-European institutions.

Physics Education was by far the most common publishing venue for this category of work (Table II), 42% of the articles in this study were published through this venue. The second most common venue being *Physical Review – PER*, accounting for 18% of publications, followed by a dozen publishers with less than five total publications.

The third research question we posed investigated research trends throughout this body of work. We isolated three trends to explore: research orientation, teaching and learning focus, and research methods. We found that the research orientation of these articles was nearly equally split between research-oriented and practitioner-oriented publications, with 24 and 21 publications, respectively. This indicates that work on this topic has essentially equally addressed the research community's interests as well as practitioner interests.

The teaching and learning focus and research methods of these articles was not so balanced. 76% of the articles had a teaching research focus and 31 articles used qualitative methods (23 using only qualitative methods). The uneven distribution of these trends is not alarming; however, this may indicate the need for learning focused quantitative research to help expand and strengthen this field of study.

A. Research Gaps and Opportunities

The articles gathered for this study cover a wide range of topics and answer a variety of research questions. This is not to say that there are not gaps within the research or plenty of opportunity for further investigation. Two important lines of inquiry that we did not find within the research involve bridging instruction from classical physics to QM and when to introduce QM into the curriculum for optimal conceptual comprehension.

It is identified that studying QM requires a conceptual framework that diverges from classical mechanics [4][5][6] but how to lead into QM study and compare quantum phenomena with classical mechanics was hardly addressed by this body of work. Cleary students will attempt to initially use classical frameworks to analyze QM (unsuccessfully) and the field would benefit from a thorough investigation on how to best promote a quantum framework of understanding and how this framework fits into students pre-existing knowledge structures. Failure to address this component of QM in secondary schools is likely indicative of the lack of learning focused research orientation. It is our claim that an increase in research focused on learning QM at the secondary level would inevitably help with the development of instructional frameworks associated with student learning progressions and instructional strategies that best promote conceptual divergence to an appropriate framework of QM.

Additionally, more student-focused articles would likely benefit the field by providing insight into students' conceptual development, learning challenges, and epistemological resources. A thorough investigation of student cognition during QM instruction would certainly aid in the development of teaching resources and appropriate pedagogical approaches that best address QM at the secondary level and increase the efficiency and effectiveness of lessons addressing this topic.

Lastly, an increase in quantitative methods of data analysis could serve as a great opportunity to expand this field of research. Large scale statistical analyses have the potential to add depth to generalizations about the challenges and successful interventions related to the teaching and learning of QM at the secondary level.

[1] H.K.E. Stadermann, E. van den Berg, and M.J. Goedhart, Analysis of secondary school quantum physics curricula of 15 different countries: different perspectives on a challenging topic. Phys. Rev. – PER. **15**, 1 (2019)

[2] L. Suter, Multiple methods: Research methods in education projects at NSF. Int. J of Research & Method in Education. **28**, 2 (2005)

[3] K.M. Jackson, A review of research methods trends in educational leadership journals. ICPEL Educational Leadership Review. **20**, 1 (2019)

[4] R. Muller and H. Wiesner, Teaching quantum mechanics on an introductory level, Amer. J. Phys. **70**, 3 (2002)

[5] C. Baily and N.D. Finkelstein, Teaching and understanding of quantum interpretations in modern physics courses, Phys. Rev. – PER. **6**, 1 (2010).

[6] C. Baily and N.D. Finkelstein, Teaching quantum interpretations: revisiting the goals and practices of introductory quantum physics courses, Phys. Rev. – PER. **11**, 2 (2015)