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Bibliometric analysis of the GentleWave system: trends, collaborations, and research gaps

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ABSTRACT

Objectives: The study aimed to conduct a bibliometric analysis of the GentleWave system (Sonendo, Inc.).
Methods: An electronic search was conducted in June 2024 using the Web of Science Collection database. Two reviewers independently screened publications, extracting data on authorship, publication details, study design, and citation metrics. Statistical analyses were performed in R to assess variable correlations, while the VOSviewer (Visualization of Similarities Viewer) software was used to map author and keyword networks.
Results: The search yielded 47 records, with 32 studies included. Publications spanned 2014 to 2024. The Journal of Endodontics published the highest number of studies (n = 15), and *the International Endodontic Journal* had the highest impact factor (5.4). The University of British Columbia and Sonendo, Inc. were the most frequent affiliations. Among the 32 articles, 28 were *in vitro* studies, primarily focusing on microbiology (n = 9). A total of 95 authors were identified, with Haapasalo and Shen being the most cited (n = 229). The articles accumulated 495 citations, demonstrating a strong positive correlation between the number of studies and citation counts (r = 0.98).
Conclusions: The analysis highlights a predominance of *in vitro* studies. Geographic concentration in the United States and Canada limits diversity, while the strong correlation between study numbers and citations suggests that increased publication volume enhances visibility.

Keywords: Bibliometrics; Endodontics; Multisonic; Root canal irrigants; Root canal therapy

INTRODUCTION

Biomechanical preparation of the root canal system is a critical step for the success of endodontic treatment. This process relies on the combined action of mechanical instrumentation and the physicochemical properties of irrigating solutions, along with their application protocols [1,2]. The primary objectives of irrigation include

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the removal of intracanal medicaments [3], eliminating the smear layer and debris [4,5], and enhancing disinfection. The latter is particularly crucial, as a substantial portion of the root canal walls remains unaffected by instrumentation alone [6,7].

To effectively promote disinfection and organic tissue dissolution, irrigation solutions must be adequately distributed within the root canal system [8]. Given the limitations of conventional syringe-and-needle irrigation [9,10], alternative irrigation protocols have been explored. Passive ultrasonic irrigation (PUI), for example, has been extensively investigated as a method for enhancing irrigant agitation [11,12]. Studies have demonstrated that PUI outperforms conventional irrigation in several aspects, including tissue dissolution [10], smear layer removal [13], and biofilm disintegration [14]. However, for PUI to be effective, canals must be enlarged to allow the insert to vibrate freely. Since it is typically performed with metal inserts, there is a potential risk of unnecessary wear on the dentin walls [12,15].

Recently, the GentleWave system (Sonendo, Inc., Laguna Hills, CA, USA) was developed to promote cleaning of the root canal system without the need for significant canal enlargement. The system comprises a console and a sterile, single-use handpiece designed for individual patients. It delivers a continuous stream of treatment fluid—3% sodium hypochlorite (NaOCl), 8% ethylenediaminetetraacetic acid (EDTA), and distilled water—from the handpiece tip into the pulp chamber. Simultaneously, excess fluid and debris are removed through a built-in suction mechanism integrated into the handpiece, which channels waste into a canister within the console. The GentleWave system utilizes a broad spectrum of sound waves, known as multisonic technology, to generate advanced fluid dynamics for agitating irrigating solutions. When the treatment fluid is introduced, it interacts with the stationary fluid in the pulp chamber, creating a strong shear force that leads to hydrodynamic cavitation. The treatment begins with 3% NaOCl, followed by a water rinse, and concludes with 8% EDTA. This flow induces a gentle vortical motion and generates a slight negative pressure within the root canal system, ensuring effective cleaning from the coronal to apical regions [14,16]. This system has shown promise in the disinfection of the root canal system [17,18], removal of intracanal medication [19], tissue dissolution [16], and retrieval of fractured instruments [20].

Bibliometric analyses offer a valuable approach to evaluating emerging trends, collaboration patterns, and the intellectual structure of a specific research domain within the existing literature [21]. Due to the benefits and conveniences, bibliometric analyses have become increasingly popular in endodontics. Recent studies have employed this approach to investigate topics such as regenerative endodontics [22], calcium silicate cements [23], guided endodontics [24], and photodynamic therapy [25]. To date, there has been no bibliometric analysis in the literature specifically assessing studies on the GentleWave system. Thus, this study aims to conduct a bibliometric analysis of the GentleWave system to identify potential gaps in the literature and generate new insights for future research.

METHODS

Databases and search strategies

An electronic search was conducted in June 2024 using the Web of Science Collection database (https://www.webofscience.com). The search strategy included terms related to the GentleWave system and the agitation method (multisonic). The complete search strategy employed was: ("gentlewave" OR "gentlewave system" OR "multisonic").

Eligibility criteria and study selection

Studies related to the GentleWave system were selected for this bibliometric analysis. Publications not pertinent to the topic and general literature reviews on endodontic irrigation were excluded. No filters were applied to restrict the years or language of publication. The search results were exported to the reference management software EndNote Web (Clarivate, London, UK).

The full texts were reviewed by two independent reviewers, and in cases of discrepancies, a third reviewer with expertise in the field was consulted to reach a consensus.

Data extraction

Data extraction was conducted by one reviewer, considering only the information present in the selected

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studies. The extracted data included authors, title, journal, year of publication, keywords, number of citations, country, institution, study design, impact factor (from Journal Citation Reports by Clarivate), and the Journal Citation Indicator (JCI from Clarivate). Regarding study design, the studies were classified according to their methodology into categories such as reviews, *in vitro*/*ex vivo*, and clinical studies.

Data analysis

The extracted data were compiled into a database and organized in a Microsoft Office Excel 2016 spreadsheet (Microsoft Corp., Redmond, WA, USA). The graphical representation of the data was conducted using the Visualization of Similarities Viewer software (VOSviewer, version 1.6.17.0; Centre for Science and Technology Studies of Leiden University, Leiden, the Netherlands) to assess the connections between authors and keywords. For keyword analysis, a threshold of a minimum of three occurrences was established. In the network analysis, the major clusters and their primary sources were identified based on their frequency of occurrence. Less frequent terms indicate lower emphasis or less-utilized sources. The lines connecting the terms represent collaborations among them.

Correlation matrix

The statistical analyses were carried out using the R programming language version 4.3.0 (The R Foundation for Statistical Computing, Vienna, Austria; https://www.r-project.org). The Shapiro-Wilk normality test was performed on each numerical variable in the dataset, including the Journal Impact Factor (JIF), JCI, number of studies, and number of citations. Based on the results of this test, appropriate correlation tests were selected. For variables that followed a normal distribution, the Pearson correlation test was applied, while for variables that did not follow a normal distribution, the Spearman correlation test was used. The significance level was set at $\alpha \leq 0.05$.

RESULTS

The data extracted from the selected studies are grouped in Supplementary Table 1.

Search and study selection

The initial database search yielded 47 records. Two non-article records were excluded. After reviewing the titles, abstracts, and full texts by two independent reviewers, 15 studies were excluded for not meeting the inclusion criteria. A total of 32 studies [14,16–20,26–51] were included in this bibliometric analysis (Figure 1).

Year of publication

The studies included spanned from 2014 to 2024. The year 2019 had the highest number of publications (n = 6), while both 2014 and 2024 had the lowest number of publications (n = 1). The earliest study was published by Haapasalo *et al.* [16], titled "*Tissue dissolution by a novel multisonic ultracleaning system and sodium hypochlorite*," while the most recent article was titled "*Efficacy of the GentleWave system in the removal of biofilm from the mesial roots of mandibular molars before and after minimal instrumentation: an ex vivo study*," published in 2024 by Kim *et al.* [50]. The description of the number of publications by year can be found in Figure 2.

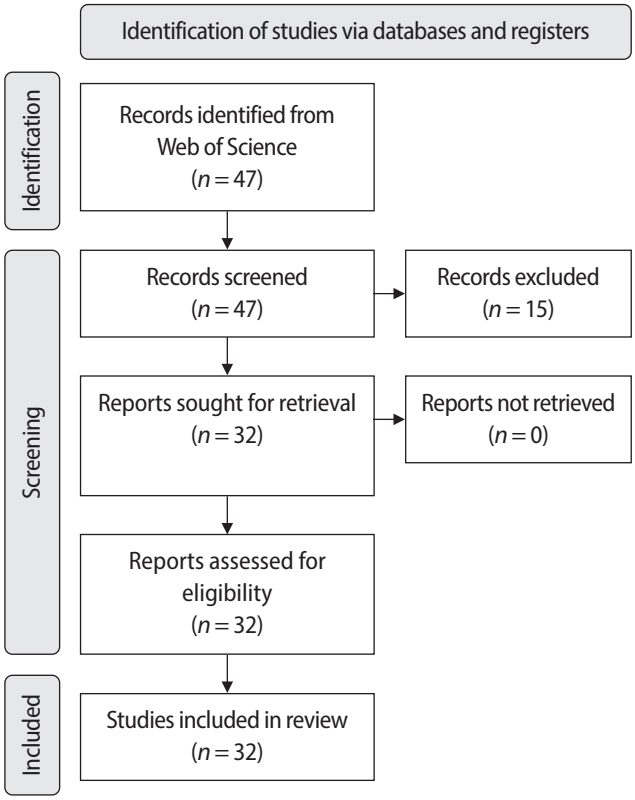

Figure 1. Flowchart of the study selection protocol.

Journals, Journal Impact Factor, and Journal Citation Indicator

The articles were published in 11 journals. *The Journal of Endodontics* (JOE) had the highest number of studies related to the GentleWave system (n = 15), followed by *the International Endodontic Journal* (IEJ, n = 4). According to the Journal Citation Reports, the IEJ has the highest impact factor (5.4), followed by Scientific Reports (3.8) and the JOE (3.5). Additionally, the IEJ exhibited the highest JCI (1.9), followed by the JOE (1.86) and *Clinical Oral Investigations* (1.33). Data on the JCI and JIF were not available for *Restorative Dentistry and Endodontics*.

A description of the journals, their JIFs, JCIs, number of studies, and citations of articles published on the GentleWave system can be found in Table 1.

Affiliations

The following affiliations were the most frequent: University of British Columbia (10 studies and 229 citations), Sonendo, Inc. (six studies and 208 citations), University of Minnesota (five studies and 28 citations), Huazhong University of Science and Technology (four studies and 73 citations), New York University (three studies and 61 citations), São Paulo State University (three studies and 15 citations), University of Maryland

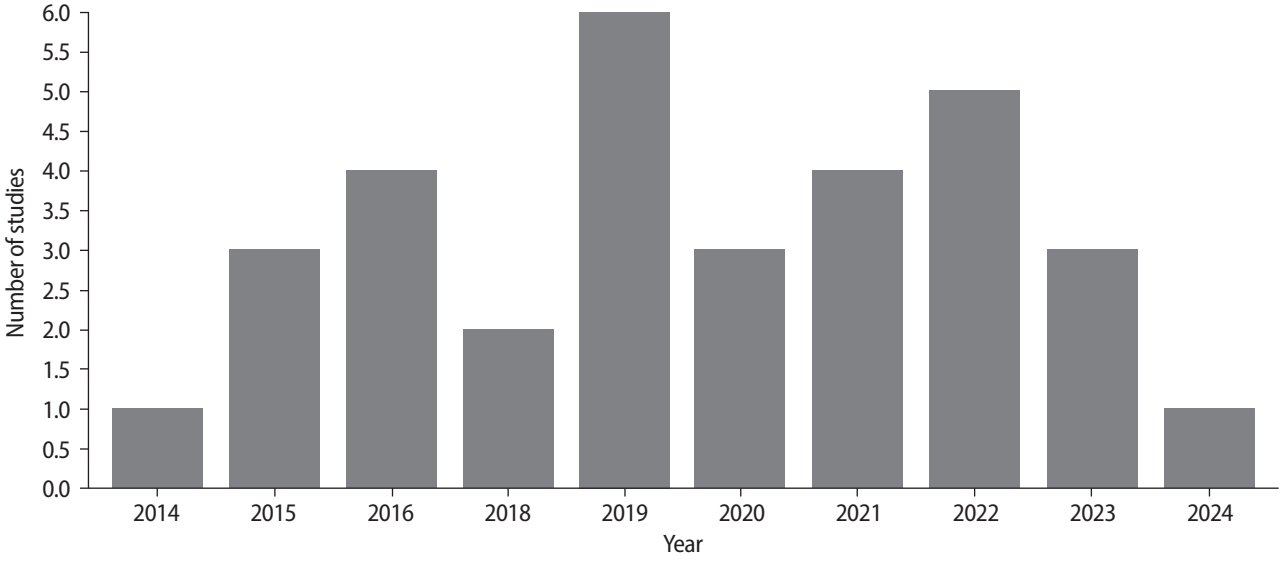

Figure 2. Distribution of the number of studies published over the years.

Table 1. Journals, Journal Impact Factor[a], Journal Citation Indicator[a], and citation counts of studies published on the GentleWave system[b]

Source title	Journal Impact Factor	Journal Citation Indicator	Number of studies	Number of citations
Journal of Endodontics	3.5	1.86	15	376
International Endodontic Journal	5.4	1.9	4	15
Journal of Pharmacy and Bioallied Sciences	0.7	0.2	1	0
Scientific Reports	3.8	1.05	2	8
Restorative Dentistry And Endodontics	-	-	2	10
Applied Sciences-Basel	2.5	0.56	1	0
Odontology	1.9	0.95	2	18
Medicina-Lithuania	2.4	0.67	1	10
Materials	3.1	0.58	1	10
Australian Endodontic Journal	1.3	0.62	1	9
Clinical Oral Investigations	3.1	1.33	2	39

[a]Clarivate, London, UK. [b]Sonendo, Inc., Laguna Hills, CA, USA.

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(three studies and 12 citations), and University of Toronto (three studies and 65 citations).

Study design and themes

Among the 32 studies included, 28 were *in vitro*/*ex vivo* studies. Other study designs included clinical studies (n = 3), and one narrative literature review. No systematic reviews, meta-analyses, or bibliometric analyses on the GentleWave system were found. Microbiology emerged as the most prevalent research theme (n = 9), followed by root canal debridement (n = 4), apical pressure (n = 3), retreatment (n = 3), healing rate (n = 2), calcium hydroxide removal (n = 2), dentin structure analysis (n = 2), obturation (n = 1), tissue dissolution (n = 1), removal of calcification (n = 1), removal of separated instruments (n = 1), postoperative pain (n = 1), apical extrusion (n =1), and others (literature review, n =1).

Authors

A total of 95 authors were identified from 10 countries: the United States, Canada, Brazil, China, Saudi Arabia, South Korea, India, Japan, Mexico, and Spain. Most authors are from the United States (n = 22), followed by Canada (n = 13) and Brazil (n = 6) (Table 2). The three most cited authors are Haapasalo, M (n = 229); Shen, Y (n = 229); and Khakpour, M (n = 172). The authors with the highest citations and their number of published studies are presented in Table 3.

Keywords

A total of 207 keywords were identified, with 33 keywords appearing at least three times across the selected studies. The most frequently occurring keywords were "GentleWave system" (n = 20) and "Irrigation" (n = 19). The frequency distribution and co-occurrence patterns of these keywords are illustrated in Figure 3.

Studies

The 32 selected articles collectively accumulated 495 citations. The article published by Haapasalo *et al.* [16] in the JOE was the most cited in the literature (51 citations). The journals with the highest number of citations were JOE, *Clinical Oral Investigations*, and *Odontology*, with 376, 39, and 18 citations, respectively (Table 2). Complete citation data for all included are available in Supplementary Table 1.

Correlation matrix

According to the correlation matrix analysis, there is a strong positive correlation between the number of studies and the number of citations (0.98). A moderate positive correlation was observed between the number of citations and the JCI (0.57), and a low positive correlation with the JIF (0.24). The number of studies showed a positive correlation coefficient of 0.65 with the JCI and 0.34 with the JIF. Additionally, a strong positive correlation was found between the JIF and the JCI (0.85) (Figure 4).

DISCUSSION

Bibliometric reviews play a crucial role in contemporary academic research by providing a systematic and quan-

Table 2. Countries and number of studies and citations on the GentleWave system[a)]

Country	Number of studies	Citations
United States	22	365
Canada	13	294
China	6	93
Brazil	6	65
Saudi Arabia	3	8
South Korea	2	20
Spain	1	5
Mexico	1	0
Japan	1	31
India	1	0

[a)]Sonendo, Inc., Laguna Hills, CA, USA.

Table 3. The authors with the highest number of studies and citations in GentleWave system[a)]

Author	Number of studies	Citations
Haapasalo, M	10	229
Shen, Y	10	229
Khakpour, M	4	172
Wang, Z	5	139
Curtis, A	3	114
Patel, P	3	114
Vandrangi, P	3	78
Ma, J	4	73
Basrani, B	3	65
Friedman, S	2	65

[a)]Sonendo, Inc., Laguna Hills, CA, USA.

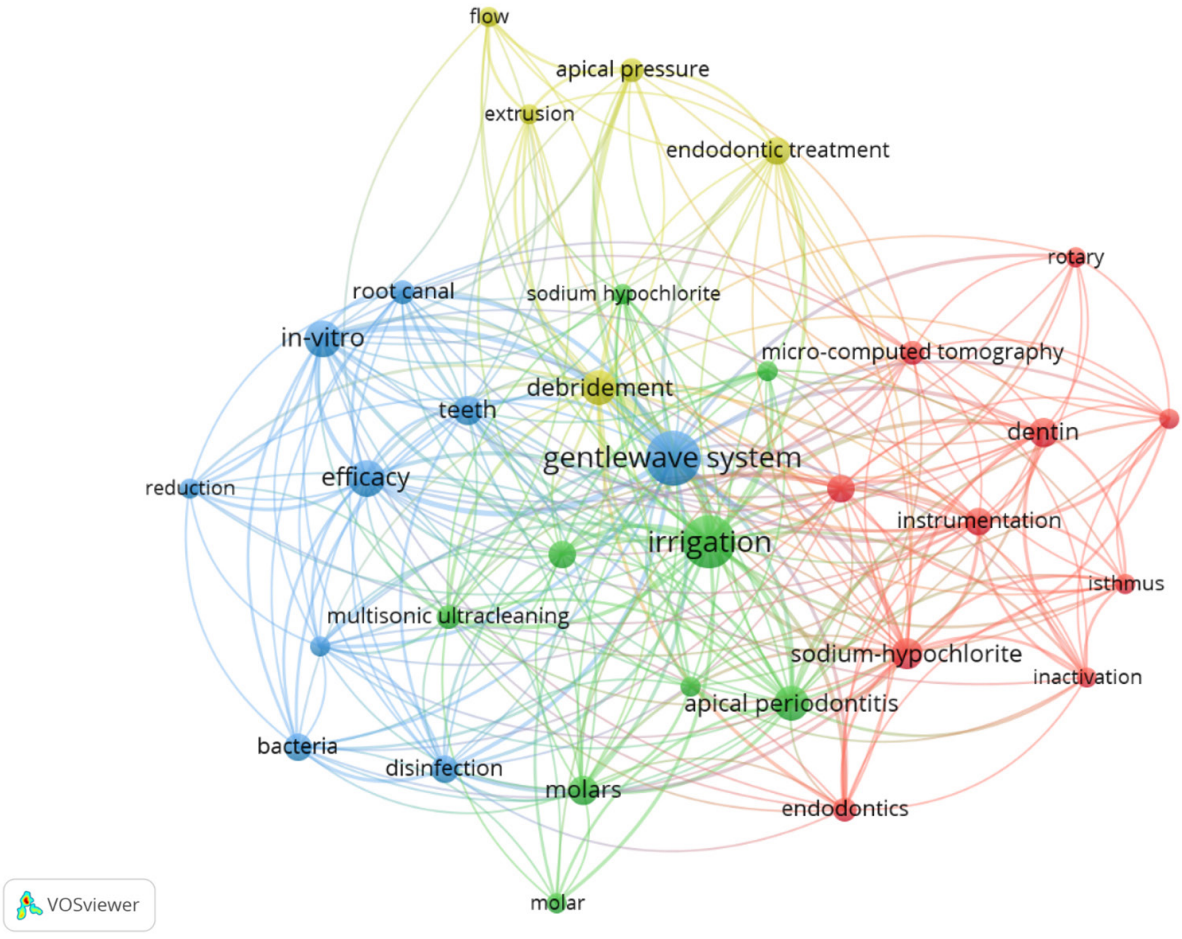

Figure 3. Frequency and interaction between keywords. Larger circles indicate the most used keywords. Lines between circles indicate relationships between keywords. Different colors indicate different clusters according to year. VOSviewer (Visualization of Similarities Viewer software): Centre for Science and Technology Studies of Leiden University, Leiden, the Netherlands.

titative analysis of scientific production. Emerging fields of study, such as the rise of new technologies, offer a comprehensive view of the current state of knowledge [52]. The GentleWave system is a new device designed to promote minimally invasive root canal treatment by facilitating the cleaning of anatomically complex areas through the propagation of acoustic energy and powerful agitation of irrigating solutions, thereby reducing the need for endodontic instruments and canal enlargement [32]. The first study on GentleWave was published 10 years ago, in 2014 [16]. The year 2019 saw the highest number of publications on GentleWave, reflecting a growing interest in studying this device. Since then, the number of publications has experienced another peak in 2022, indicating the current relevance of discussing topics related to irrigation in the field of endodontics. These publication peaks correlate with promising results associated with GentleWave, particularly in the effective removal of the smear layer [26], tissue dissolution [16], and improved healing outcomes [32]. Such advancements not only encourage further research but also underscore the significance of GentleWave in modern clinical practice.

The JOE has published the most studies on GentleWave, followed by IEJ. These two journals are considered leaders in research and clinical practice in endodontics, and their high JIFs reflect the quality and relevance of the information they provide to researchers and clinicians in this field. Previous bibliometric reviews have consistently demonstrated more publications for

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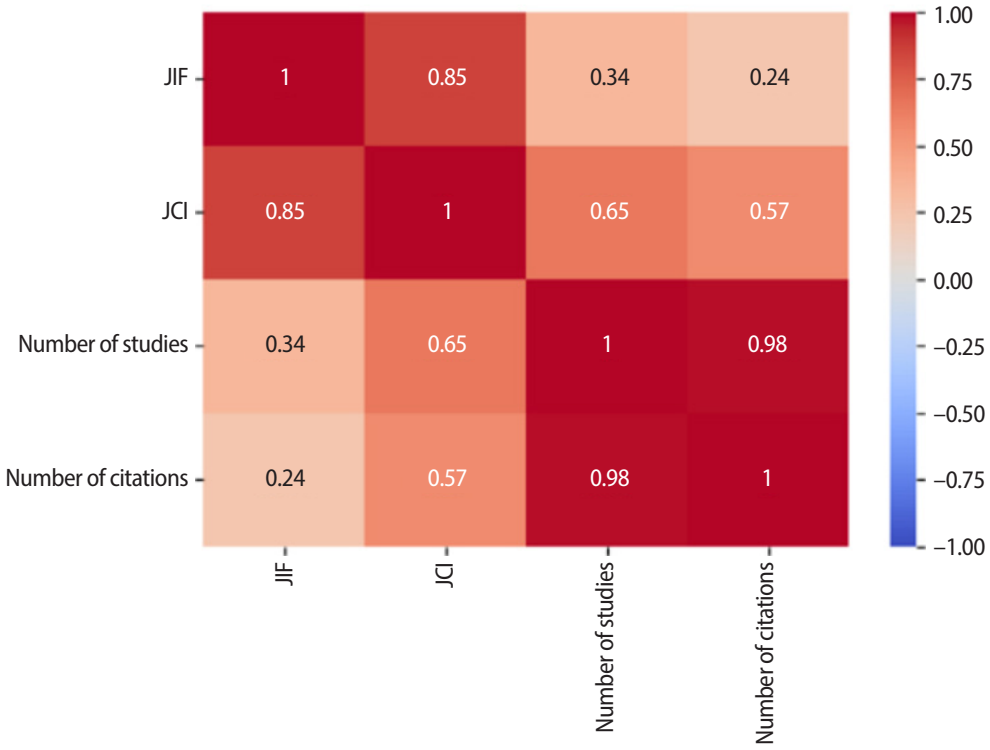

Figure 4. Correlation matrix between the following variables: Journal Impact Factor (JIF), Journal Citation Indicator (JCI), number of studies, and number of citations. Correlation coefficients range from −1 (perfect negative correlation) in blue to 1 (perfect positive correlation) in red, with significance set at $\alpha = 0.05$.

both JOE and IEJ [24,53–58]. The significant influence of these publications on endodontic practice justifies their prominence in this bibliometric review.

Haapasalo and Shen were the most cited authors and had the highest number of published articles, attributed to their pioneering investigations of this new technology. The most cited article, "*Tissue dissolution by a novel multisonic ultracleaning system and sodium hypochlorite*" [16], was also the first published on GentleWave, which explains its high citation count as it has become a foundational reference for other authors. Despite being the most cited work on the subject, it has yet to reach 100 citations to be considered a classic in the field [52,59], illustrating that, even 10 years after the publication of the first article, the topic has not been thoroughly studied and explored.

This bibliometric analysis revealed that the United States and Canada dominate the scientific production on this topic, with the United States leading in total publications and citations. The University of British Columbia stands out as the most productive institution on GentleWave studies, with the highest volume of published articles and citations. The fact that this equipment is manufactured by an American company may contribute to the concentration of research in North America, particularly in the United States and Canada. Additionally, the high cost of the equipment may limit the ability to conduct studies in other regions of the world. It is also worth noting that previous bibliometric analyses in endodontics have similarly found that the United States ranks among the countries with the highest number of publications and citations [24,55,56,60,61].

Microbiology was the most frequently addressed topic in the studies, as the disinfection of the root canal system is the primary goal of GentleWave. Additionally, microorganisms are the main cause of periapical diseases and the most common contributors to endodontic treatment failure [62–64]. This topic was followed by root canal debridement and apical pressure, which are directly related to the equipment's mechanism of action

and the need for canal enlargement for cleaning, as well as the potential extrusion of septic-toxic content beyond the apex due to operational pressure. The most prevalent keywords identified in the analyzed literature were "GentleWave system," "Irrigation," and "Debridement." These terms directly correspond to the primary research focus and the predominant *in vitro* study designs employed to evaluate this new technology.

The correlation matrix conducted in our study revealed a strong positive correlation (0.98) between the number of published studies and the number of citations, suggesting that as the number of studies on a topic increases, the total number of citations tends to rise consistently. This is expected, as a higher volume of studies often leads to greater recognition and serves as a reference for other researchers [65]. A moderate positive correlation (0.57) was observed between the number of citations and the JCI, indicating a significant relationship between the citations an article receives and the JCI of the journal in which it was published. The JCI reflects the influence of a journal by considering the citations received by its published articles. This moderate correlation suggests that journals with a higher indicator tend to have articles with more citations, but this relationship is not as direct or strong as that between the number of studies and citations. The correlation of 0.65 between the number of studies and the JCI is positive and moderate to strong. This implies that journals publishing a greater number of studies tend to have a higher JCI, reflecting that journals with a larger volume of publications often have greater visibility and influence in the scientific community. The strong positive correlation of 0.87 between the JIF and the JCI indicates a very strong and positive relationship. This suggests that journals with a higher JIF also tend to have a similarly high JCI, as demonstrated in a previous study [66]. Both metrics reflect the impact and influence of a journal, and this strong correlation is expected, as they both assess the relevance and recognition of journals within the scientific community, albeit through slightly different approaches. The correlations between the number of citations and the JIF (0.24) and between the number of studies and the JIF (0.34) were considered low. In summary, the analysis of the correlation matrix reveals that while the number of studies and the number of citations are strongly correlated, the relationship between journal impact metrics (JCI and JIF) and citations is more variable.

In vitro/*ex vivo* studies currently dominate the research landscape due to their ability to evaluate new equipment and techniques under controlled conditions, enabling precise control and isolation of experimental variables. These controlled investigations provide fundamental evidence that supports subsequent clinical research development. However, while such findings offer valuable preliminary data, they cannot be fully extrapolated to the clinical setting, which involves multifactorial issues and complex variables that influence outcomes [67]. The current literature reflects this gap, with only three clinical studies published to date [30,32,42]. This underscores the critical need for more rigorous clinical investigations, particularly well-designed randomized controlled trials that would provide higher levels of evidence. Additionally, conducting systematic reviews that consolidate and critically analyze the available information is essential for advancing the understanding and practical application of these findings.

A notable strength of this study is the absence of filters based on publication year, citation count, or language, allowing for a broad and comprehensive analysis of all relevant publications available at the time of research. Although this bibliometric study has limitations that should be considered, such as the use of a single database for article extraction, the Web of Science remains the most established database for bibliometric research. The selection of this database was intentional, as it aligns with standard methodological approaches in endodontic research and ensures compatibility with VOSviewer software [23,24,52,55]. Web of Science provides standardized, high-quality citation data from rigorously indexed journals, offering reliable metrics while maintaining methodological consistency with previous studies in the field. While multi-database analyses can expand search scope, our approach prioritizes data integrity and reproducibility within a well-structured citation index system [68].

CONCLUSIONS

The bibliometric analysis reveals a predominance of

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in vitro/*ex vivo* studies published on the GentleWave system, highlighting the need for more clinical research and systematic reviews. The concentration of scientific production in the United States and Canada limits the geographic diversity of publications. The strong correlation between the number of studies and citations reflects the growing recognition of this technology.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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AUTHOR CONTRIBUTIONS

Conceptualization, Project administration, Supervision: Oliveira Neto RS, Alcalde MP, Duarte MAH. Data curation: Oliveira Neto RS, Amorim JVO, Duarte MAH. Formal analysis: Oliveira Neto RS, Souza TM, Duarte MAH. Funding acquisition, Resources: Oliveira Neto RS, Duarte MAH. Investigation: Oliveira Neto RS, Souza TM, Amorim JVO, Duarte MAH. Methodology: Oliveira Neto RS, Souza TM, Lima TO, Silva GF, Vivan RR, Alcalde MP, Duarte MAH. Software: Neto RS, Souza TM. Validation: Lima TO, Silva GF, Vivan RR, Alcalde MP, Duarte MAH. Visualization: Oliveira Neto RS, Souza TM, Amorim JVO. Writing - original draft preparation: Oliveira Neto RS, Souza TM, Amorim JVO. Writing - review & editing: Oliveira Neto RS, Lima TO, Silva GF, Vivan RR, Alcalde MP, Duarte MAH. All authors read and approved the final manuscript.

DATA SHARING STATEMENT

The datasets are not publicly available but are available from the corresponding author upon reasonable request.

SUPPLEMENTARY MATERIALS

Supplementary Table 1. Articles on GentleWave

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