Original Article

Graphene on Dentistry: A Bibliometric and Scientometric Analysis

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Abstract

Background: Today, the development of dental materials is a very important issue. Graphene has been used in dentistry to strengthen many materials. **Aim:** The aim of this study was to analyze leading countries and to identify the preferred journals, the most commonly used keywords, and the most productive authors in the field of graphene. **Materials and Methods:** The search keyword was "graphene" on the Web of Science database; the search was restricted to before 2022. The selected search from the Web of Science database included the title of articles, authors, year of publication, country, citation count, and keywords. An analysis was performed regarding citations and documents, authors, journals, and keywords using a bibliometric software program. All articles were evaluated and subjected to scientometric analysis. **Results:** Twenty six articles were included in the study. There has been a remarkable increase in published articles from past to present, and a regular increase is observed in the number of citations. Dental Materials has highest number of publications among the articles included in the present study. Dr. Rosa, who had the highest number of citations, is also the most effective author. Graphene has many studies in dentistry with different materials. As per the data obtained, graphene, graphene oxide, and peri-implantitis are the most used keywords and Singapore and China are at the forefront of the countries where the articles are published. **Conclusion:** This bibliometric analysis reveals the progress and trend of research on graphene in dentistry and extensive collaborations between authors, countries, and institutions. The findings of this study can help inspire researchers to plan new studies and collaborate on graphene.

Keywords: *Bibliometric analysis, graphene, nanoparticles, nanotechnology, scientometric analysis*

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Introduction

Nowadays, graphene is widely researched and attracts attention in medicine, such as drug delivery carriers, imaging agents, and tissue engineering substrates due to its superior mechanical, optical, and physicochemical properties.[1,2] Graphene, a two-dimensional honeycomb structure made of pure carbon, may be the strongest, thinnest, and stiffest material ever composed.[3,4] Graphene derivates quickly realize chemical bonding with other substances because of their big specific surface area, lamellar structure, and abundant oxygen-containing function groups (carboxyl, hydroxyl, etc.).[5] It has lots of superior properties such as excessive chemical stability, good antibacterial activity, anticorrosion, excellent biocompatibility, and positive tribological features.[6,7] The breaking strength of graphene is 42 N/m and it has the highest Young's modulus (0.5–1 TPa) among any known material.[8] It can be used in hard tissue engineering due to its superior mechanical properties.[2] Moreover, graphene can maintain its structural properties even when exposed to water, human cells, and biomolecules.[9]

By adding graphene to materials such as bioactive calcium silicate cement and hydroxyapatite, the hardness and mineralization of these materials can be increased.[10,11] Graphene is appropriate for the

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proliferation and adhesion of osteoblasts and could have osteogenic differentiation in dental pulp stem cells.[4,7] Similarly, it has been reported that graphene may contribute to the specific differentiation of mesenchymal stem cells and provide osteogenic differentiation.[12] In addition, graphene oxide (GO) nanosheets are very efficient in inhibiting the increase of dental pathogens[13] and supporting the proliferation and cellular activity of periodontal ligament stem cells.[14]

The GO is an oxidized form of graphene made by the powerful oxidation of graphite. It presents functional groups of low atomic numbers that can combine GO with several biomolecules.[15] It has been reported that graphene can serve as an antibacterial material as it is highly cytotoxic to bacteria.[16] GO probably causes this reduction in bacterial viability through physical degradation and chemical oxidation.[17,18] Atom-thick graphene can be used on dental implants as a coating and prevent bacterial growth.[19] Graphene sheets and their derivatives have also been found to serve as suitable substrates for the dispersion and stabilization of antibacterial nanoparticles (TiO2, ZnO, Fe3O4, and Ag).[16,20]

Graphene is a relatively new and researched material in dentistry and can be used in many fields. This study aimed to review the research progress of graphene in dentistry by using a bibliometric approach. This powerful tool can include identifying contributing researchers, countries, and journals and analyzing high-impact keywords. Moreover, this study is purposed to review the studies on graphene and reveal its importance.

Material and Methods

On January 27, 2022, an electronic search was made to identify detailed literature sources using the Clarivate-owned Web of Science (WoS) database. The search keyword was "Graphene" on the WoS database; the search was restricted to before 2022; after that, the results were filtered as the document-type articles and category of the documents as dentistry oral surgery medicine. The data extracted from WoS were evaluated for inclusion and exclusion criteria 3 different times by one researcher. Prejudice was eliminated by evaluations made at different times and objective results were obtained. Only original articles in English were included in the study, and review studies were excluded from the scope of the study. The full texts of all studies included in the study were recorded.

The selected search from the WoS database included the title of articles, authors, year of publication, country, citation count, and keywords. The records that obtained WoS were exported in Tab Delimited File format as a complete record and cited references were processed using a bibliometric software program (VOSviewer v1.6.14.; Center for Science and Technology Studies, Leiden University). After that, results were summarized and processed with a spreadsheet. Data obtained by the WoS functions of "citation report" and "analyze results" were collected. In addition, the areas and materials where graphene is used frequently in the articles included in this study were also evaluated and a scientometric analysis was made on the results of these studies.

Keywords were investigated with the help of density visualization. Visual analysis for the number of publications was presented in a bubble and the distance between the bubbles specified its association with other items. The collaboration and citation network were visualized by network or overlay with VOSviewer. The number of publications was indicated with the size of the bubble, the distance between bubbles showed the relatedness of the two items, and the color of each bubble had different meanings in different visualizations.

Results

Thirty five articles were displayed as a result of the search and 9 of these articles were excluded because they were book chapters or the full text could not be accessed. In addition, 3 articles were excluded because they were review articles. Thus, 26 articles were included in the study and the articles were listed with the highest number of citations at the top. Based on the WoS database, Table 1 shows the title, first author, publication year, journals, country, total citations, and average per year information of the graphene-related articles evaluated present study as per the number of citations in descending order. The top-cited article among the articles on graphene was cited 54 times.[21] There were 20 researchers who contributed to the top-cited articles as first authors. Studies were grouped as more or less than 6 authors as per the number of authors and it was seen

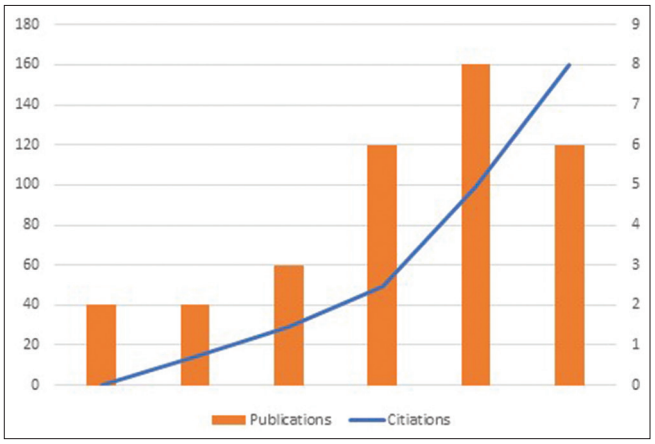

Figure 1: Annual number of publications and citiations on graphene

Table 1: The articles on graphene

Title	First Author	Journals	Publication Year	Country	Total Citations	Average per Year
Graphene oxide-based substrate: physical and surface characterization, cytocompatibility, and differentiation potential of dental pulp stem cells	Rosa, Vinicius	Dental Materials	2016	Singapore	54	7.71
Nano-graphene oxide incorporated into PMMA resin to prevent microbial adhesion	Lee, Jung-Hwan	Dental Materials	2018	South Korea	45	9
CVD-grown monolayer graphene inducesos osteogenic but not odontoblastic differentiation of dental pulp stem cells	Xie, Hano	Dental Materials	2017	Singapore	43	7.17
Improvement of the mechanical, tribological and antibacterial properties of glass ionomer cements by fluorinated graphene	Sun, Li	Dental Materials	2018	China	30	6
Growth and accelerated differentiation of mesenchymal stem cells on graphene-oxide-coated titanate with dexamethasone on surface of titanium implants	Ren, Na	Dental Materials	2017	China	28	4.67
Hydrophobicity of graphene as a driving force for inhibiting biofilm formation of pathogenic bacteria and fungi	Agarwalla, Shruti Vidhawan	Dental Materials	2019	Singapore	21	5.25
Inhibiting Corrosion of Biomedical-Grade Ti-6Al-4V Alloys with Graphene Nanocoating	Malhotra, R	Journal of Dental Research	2020	Singapore	20	6.67
The synthesis of nano silver-graphene oxide system and its efficacy against endodontic biofilms using a novel tooth model	Ioannidis, Konstantinos	Dental Materials	2019	England	19	4.75
Flexural strength, biocompatibility, and antimicrobial activity of a polymethyl methacrylate denture resin enhanced with graphene and silver nanoparticles	Bacali, Cecilia	Clinical Oral Investigations	2020	Romania	16	5.33
Graphene oxide-based experimental silane primers enhance shear bond strength between resin composite and zirconia	Khan, Aftab A	European Journal of Oral Sciences	2019	Saudi Arabia	14	3.5
Minocycline hydrochloride-loaded graphene oxide films on implant abutments for peri-implantitis treatment in beagle dogs	Qian, Wenhao	Journal of Periodontology	2020	China	9	2.25
Inhibitory effect of reduced graphene oxide-silver nanocomposite on progression of artificial enamel caries	Wu, Ruixue	Journal of Applied Oral Science	2019	China	9	2.25
Functionalized Graphene Oxide Shields Tooth Dentin from Decalcification	Nizami, M. Z., I	Journal of Dental Research	2020	Japan	8	2
Osseointegration and biosafety of graphene oxide wrapped porous CF/PEEK composites as implantable materials: The role of surface structure and chemistry	Qin, Wen	Dental Materials	2020	China	7	2.33
Transcriptomics and Functional Analysis of Graphene-Guided Osteogenic Differentiation of Mesenchymal Stern Cells	Lv, Long Wei	Chinese Journal of Dental Research	2018	China	7	1.4
Evaluating a Cobalt-Tetraphenylporphyrin Complex, Functionalized with a Reduced Graphene Oxide Nanocomposite, for Improved Tooth Whitening	Su, I-Hsuan	Journal Of Esthetic and Restorative Dentistry	2016	Taiwan	7	1
Nano-graphene oxide with antisense vicR RNA reduced exopolysaccharide synthesis and biofilm aggregation for Streptococcus mutans	Wu, Shizhou	Dental Materials Journal	2020	China	5	1.67
Antibacterial and mechanical properties of reduced graphene-silver nanoparticle nanocomposite modified glass ionomer cements	Chen, Jingwen	Journal of Dentistry	2020	China	4	1.33

Contd...

Table 1: Contd...

Title	First Author	Journals	Publication Year	Country	Total Citations	Average per Year
Persistent inhibition of Candida albicans biofilm and hyphae growth on titanium by graphene nanocoating	Agarwalla, Shruti Vidhawan	Dental Materials	2021	Singapore	3	1.5
Graphene Nanocoating: High Quality and Stability upon Several Stressors	Rosa, V	Journal of Dental Research	2021	Singapore	2	1
Artifact expression of polylactic acid/ hydroxyapatite/graphene oxide nanocomposite in CBCT: a promising dental material	Nejaim, Yuri	Clinical Oral Investigations	2020	Brazil	2	0.67
Nano-graphene oxide with antisense walR RNA inhibits the pathogenicity of Enterococcus faecalis in periapical periodontitis	Wu, Shizhou	Journal of Dental Sciences	2020	China	2	0.67
Synthesis and characterization of graphene oxide-zirconi (GO-ZrO_2) and hydroxyapatite-zirconia (HA-ZrO_2) nano-fillers for resin-based composites for load-bearing applications	Ilie, Nicoleta	Journal of Dentistry	2021	Germany	1	0.5
Graphene Oxide Enables the Reosteogenesis of Previously Contaminated Titanium In Vitro	Qin, W.	Journal of Dental Research	2020	China	1	0.33
Synergistic effects of graphene quantum dots and carbodiimide in promoting resin-dentin bond durability	Chen, Wendy	Dental Materials	2021	China	0	0
Graphene nanocoating provides superb long-lasting corrosion protection to titanium alloy	Malhotra, Ritika	Dental Materials	2021	Singapore	0	0

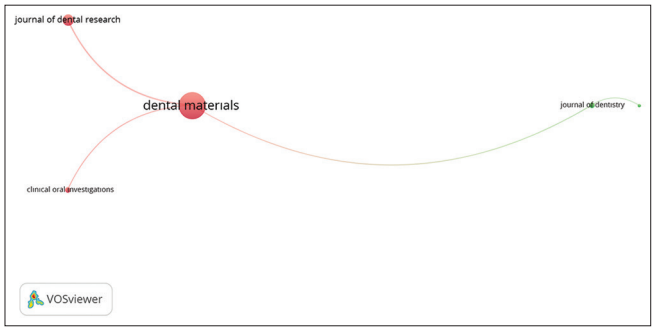

Figure 2: Journals publishing on graphene

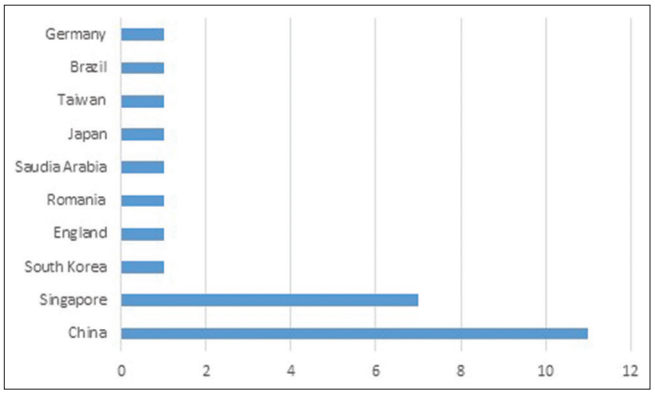

Figure 3: Number of publications by country

that the number of articles in both groups was equal. The author with the most-cited articles was Vinicus Rosa with 7 articles. Considering the annual average number of citations, Dr. Lee is the most cited author.[22]

Figure 1 demonstrates the trend of scientific articles published related to graphene by year of publication. The first article was published in 2016, as per the search made in the database after the necessary filters were selected. There has been a remarkable increase in published articles from past to present except for 2021. In addition, a regular increase is observed in the number of citations.

The most influential articles in graghene were published in 11 journals. As per the criteria of this study, the journal with the most articles was Dental Materials (42.3%), followed by the Journal of Dental Research (15.3%), Clinical Oral Investigations (7.6%), and Journal of Dentistry (7.6%), respectively. Figure 2 shows the number of articles on graphene, the journals in which it is published, and the citation relationships. The size of the bubble, the distance between bubbles showed the relatedness of the two items, and the color of each bubble had different meanings in different visualizations. When the number of publications is evaluated as per the journals, Dental Materials has the highest number of publications among the articles included in the present study.

The top-cited articles originated from 10 countries. Figure 3 shows the countries and numbers of the articles that have been published related to graphene. As per the

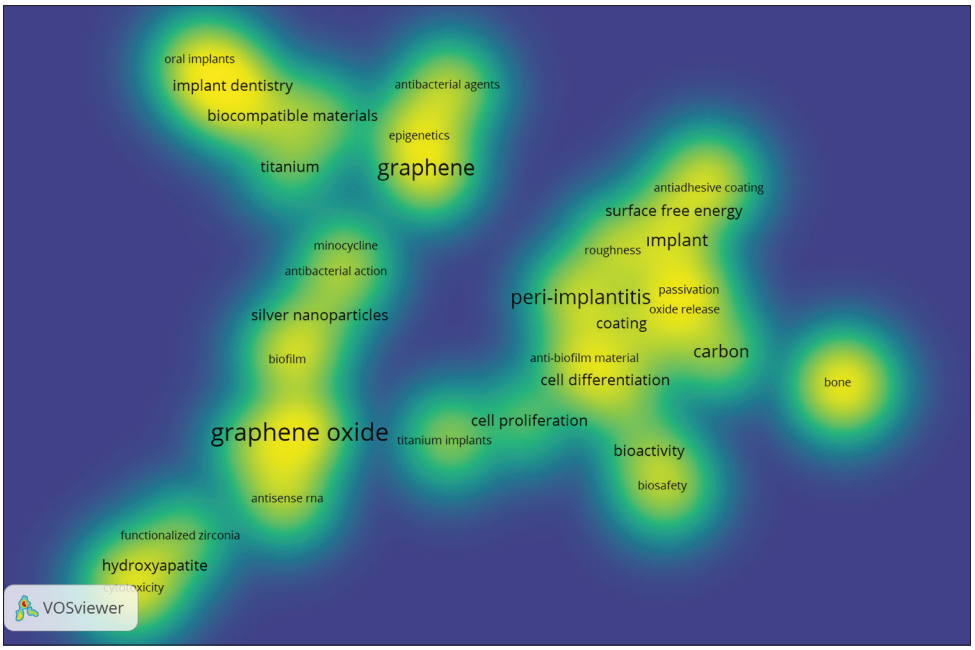

Figure 4: Density visualization of different keywords used in graphene

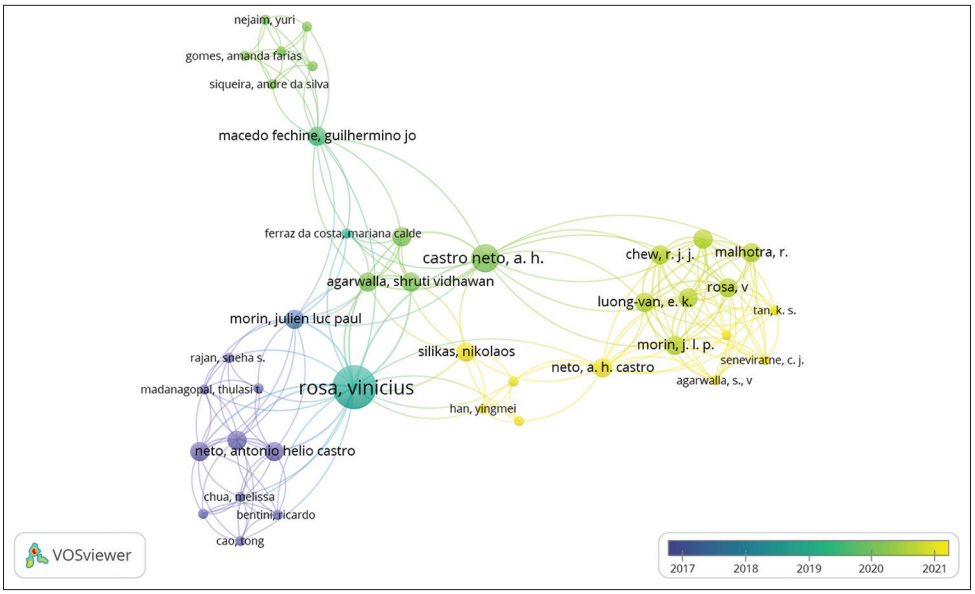

Figure 5: Collaboration networks among authors

data obtained, Singapore and China are at the forefront of the countries where the articles published about graphene were published. When the institutes of the first authors were evaluated, the 3 institutions that produce the most articles were as follows: National University of Singapore (26.9%), Sun Yat Sen University (7.6%), and Sichuan University (7.6%).

Figure 4 shows a mapping of the keywords used in the research included in this study. Yellow highlighted words symbolize keywords with higher frequency. As per the data obtained, the 10 most commonly used words were graphene, GO, peri-implantitis, carbon, implant, cell differentiation, bioactivity, hydroxyapetite, implant dentistry, and silver nanoparticles.

A collaboration network was developed for the coauthors who had contributed to articles on the top-cited article list. The collaborative network was mainly centered on highly productive authors [Figure 5]. Dr. Rosa who had the highest number of citations is also the most effective author. Bubble size shows the number of documents, and connection length shows the closeness of collaboration.

When the evaluated researches were examined, graphene or GO has been used on lots of areas such as

periodontics,[23] dental materials,[5,20,24] implantology,[18,25] endodontics,[26] and restorative dentistry.[27,28] In addition, graphene and its derivatives are combined with PMMA resin,[22,29] titanium dental implants,[2] membranes for osteogenic regeneration,[30] cement,[7] adhesives,[31–33] and tooth-whitening procedures.[34] When the study designs of the articles included in this bibliometric analysis were evaluated, it is seen that the majority of the studies were *in vitro* studies (92.4%) and the remaining articles are animal studies.

Discussion

This study aimed to determine and analyze the main features of the top most-cited articles published about graphene. Publication year acts as an important factor with the citation count of an article. Citiation count is usually reaching a peak in 3-10 years and then drops. The older articles have at a higher chance of getting cited when compared with the recently published ones. Although graphene is a newly introduced material in the field of dentistry, it has high citation rates.[35] The results from the literature search showed that the number of articles on graphene has been increasing from past to present. This indicates that research on this subject will be popular in the coming years.

The current analysis shows that Dental Materials and Journals of Dental Research are the two journals with the highest contribution. This situation indicates that these journals are distinguished journals with high citation rates to publish their graphene research. The authors attach great importance to journal impact factor and the suitability of these journals to the subject while choosing the appropriate journal for academic research. Journals with higher impact factor values are given the status of being more important or carry more prestige in their respective fields. In this study, when we look at the 2 journals with the most publications on graphene, both have high impact factors (Dental Materials = 5.687, Journals of Dental Research = 8.924). When similar bibliometric analysis studies in the field of dentistry are examined, especially in material research, journals such as Dental Materials, Journal of Dental Research, Journal of Dentistry, and the Journal of Prosthetic Dentistry, Clinical Oral Investigations, and Materials come to the fore.[36–39]

The number of citations for many articles was found to be higher in Google Scholar than in WoS, which indicates that there may be changes in the number of citations due to differences in databases due to changes in the journals scanned. Ahmad *et al*. also reported that citation numbers fluctuate when different databases are queried, and a more specific evaluation may not be possible because Google Scholar also includes conference papers, technical reports, and theses, and there is no option to sort search results as per the number of citations.[36]

When we evaluate at the countries where the first authors originated in this study, China and Singapore are at the forefront. Looking at similar bibliometric analysis studies, the USA, Germany, and the UK, along with China, are among the countries that the first authors belong to.[35,36,38,40,41] Countries with high citation rates are generally more economically stable. Countries with shortfalls in research facilities and socioeconomically less developed countries have contributed relatively little to this research area.[38]

On the other hand, Karobari *et al*. and Adnan *et al*. reported that the rate of *in vitro* studies in the results of their bibliometric analysis study was higher than that of other study designs. The results of this study are also compatible with these studies and it has been determined that there are proportionally more articles with *in vitro* study design.[35,40] The reason for this can be explained by the ethical problems, complications, and the risk of harming the patient, especially in the use of new materials in clinical studies. On the other hand, more clinical studies are needed for better analysis of dental materials.

The most cited article in graphene was an *in vitro* analysis by Rosa *et al*.[21] that focused on physical and surface characterization, cytocompatibility, and differentiation potential of GO-based substrate on dental pulp stem cells. This study has shown that the GO-based substrate allowed stem cell attachment proliferation and raised the expression of several upregulated genes in mineral-producing cells.[21] The next highly cited article was by Lee *et al*., in which the authors searched the effect of nano-GO on Polymethylmethacrylate (PMMA) resin. The study results showed that nano-GO inhibits microbial adhesion and shows promise in improving the antimicrobial properties of materials.[22] The third cited article was conducted by Xie *et al.* that researched the effect of chemical vapor deposition (CVD)-grown monolayer graphene on odontoblastic and osteogenic differentiation of dental pulp stem cells. This study showed that graphene induces osteogenic differentiation and, thanks to this feature, has the potential to be used as a substrate for bone tissue engineering research.[4]

Publications mainly focused on flexural strength, microstructure, surface characterization, cytotoxicity, antibacterial activity, differentiation potential, and clinical recommendations, with researchers exploring the features and potencies of graphene and derivates.[15,42–45]

Graphene is a promising material with its biocompatible and superior properties. Lee *et al*. showed that the specimen extracts containing GO nanoparticles did not significantly reduce the viability of oral keratinocytes compared with the control group.[22] In addition, Qin *et al*. reported significantly that GO-modified composites exhibit enhanced osseointegration and bioactivity in vivo.[5] Similarly, many studies announced that graphene promotes osteogenic differentiation on stem cells.[2,4,21,30]

In this analysis, many studies evaluate the antibacterial effects of graphene and its derivatives.[7,20,23,31,43] Sun *et al*. and Chen *et al*. evaluated the effects of graphene on the glass ionomer cement. They showed that the addition of graphene decreased biofilm activity and increased the antibacterial effect.[7,20] Wu *et al*. declared that GO and silver combination could be a promising antibacterial agent for caries prevention.[31] Similarly, Wu *et al*. showed that GO increased bactericidal activity.[43]

Both Sun *et al*. and Chen *et al*. evaluated the effect of graphene on the flexural strength of glass ionomer cement. Sun *et al*. found that the addition of graphene increased the fracture strength of the glass ionomer cement, while Chen *et al*. found that it did not make a statistically significant difference.[7,20] Bacali *et al*. showed that when graphene nanoparticles were used together with PMMA, the flexural properties of PMMA improved.[29]

When we look at the other studies included in this study, it is striking that the use of graphene and titanium together is quite common.[18,25,30,44,45] Malhotra *et al*. has been reported that nanographene coating on titanium contributes to making titanium corrosion resistant, protecting titanium from dissolution and maintaining the structural integrity of titanium in the long term.[24,25] In addition, when we look at the not very common study areas of graphene and its derivatives, GO was included in the canal irrigation solution in endodontics. It was seen that GO provided a statistically significant decrease in biovolume.[26] Similarly, a study where graphene is not very common has shown that GO added complex allows improved tooth bleaching and shorter times.[34]

The use of only the WoS database as a search engine in this bibliometric analysis is one of the limitations of this study. For this reason, some articles on the subject published in journals that are not included in the WoS database may have been omitted. Since graphene is a promising material in many areas of dentistry, more *in vivo* and *in vitro* studies are needed to evaluate the long-term clinical performances of graphene better.

Conclusion

Based on the findings of this bibliometric analysis, the following conclusions were drawn:

1. Publications on graphene significantly increased because of scientific collaboration among different countries and authors.
2. Popular studies on graphene were mostly on stem cells, titanium, and composite.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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