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Original article

Bibliometric analysis of zirconia publications between 1980 and 2021: Global productivity and publication trends

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Abstract

Purpose: With an increase in patients' aesthetic demands and advancements in dental technologies, tooth-colored materials have grown in popularity. This study aimed to statistically analyze the scientific output of zirconia.

Methods: Articles published between 1980 and 2021 were downloaded from the Web of Science database and analyzed using various statistical/bibliometric methods. Correlations were evaluated using the Spearman's coefficient. Time-series forecasting was used to predict the number of articles in the coming years.

Results: Of the 18773 recordings, 16703 (88.9%) were articles. China contributed the most to the literature (n=3345, 20%). The Chinese Academy of Sciences was the most active institution (n=666). Furthermore, *Ceramics International* was the journal that published the most articles (N=611). *The Journal of Catalysis* was the journal with the highest average number of citations per article (average number of citations, 81.4). A high level of significant correlation was found between the number of articles produced by different countries on zirconia and gross domestic product (r=0.742, $P<0.001$).

Conclusions: It is expected that zirconia research will continue to increase parallel with the increase in aesthetic expectations. Recent trends include dental implants, resin cement, surface roughness, shear bond strength, monolithic zirconia, osseointegration, flexural strength, aging, geochemistry, zircon U-Pb dating, detrital zircon, adhesion, computer-aided design-computer-aided manufacturing, bond strength, adsorption, titanium, spark plasma sintering, corrosion, SEM, zirconium dioxide, surface modification, XRD, finite-element analysis, and yttria-stabilized zirconia. Clinicians and scientists interested in zirconia can refer to this comprehensive article as a useful resource for the relevant global and multidisciplinary outcomes.

Keywords: Zirconia, Dental materials, Bibliometric analysis, Research trends

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1. Introduction

Patients' increasing aesthetic expectations have motivated the development of new materials and techniques, resulting in the application of all-ceramic systems as an alternative to widely used metal-supported ceramic restorations [1-3]. The zirconium coating is crystalline zirconium dioxide (ZrO_2). Its mechanical properties are very similar to those of metals, but they give a natural tooth appearance in a white-ivory color [4]. Zirconia is frequently a preferred biomaterial in dentistry for full-contour monolithic restorations because of its superior mechanical and chemical properties compared to other ceramic systems, aesthetic performance comparable to metal-ceramic restorations, high biocompatibility, low corrosion potential, volumetric stability, and an elastic modulus comparable to that of steel [5]. The strongest and hardest of all dental ceramics, zirconia has a flexural strength of 900-1200 MPa and fracture toughness of 9-10 MPa/mm^2 according to *in-vitro* studies [6-9].

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The use of zirconium oxide was first suggested in 1969 in relation to its orthopedic application [4,10]. Since the late 1990s, partially stabilized zirconia has been suitable for dental use because of its form, excellent strength, and superior fracture resistance. The introduction of zirconia-based ceramics as restorative dental materials has aroused great interest [8,11]. Recently, zirconia-based ceramics have become increasingly attractive owing to capability developments in computer-aided design-computer-aided manufacturing (CAD-CAM) technology in prosthetic dentistry, where strength and aesthetics are extremely important [11,12].

Three forms of zirconia—yttrium cation-doped tetragonal zirconia polycrystals (3Y-TZP), magnesium cation-doped partially stabilized zirconia (Mg-PSZ), and zirconia-hardened alumina (ZTA) have been used in dentistry to date [12]. Biological, mechanical, and clinical studies have indicated that ZrO_2 restorations are both well-tolerated and sufficiently resistant [4]. Monolithic zirconia ceramic restorations have been widely used, especially in posterior-group teeth where chewing forces are high, and new interest has arisen in preventing clinical failures in zirconia-based restorations. In addition to the elimination of fractures, the reduced occlusal space requirement appears to be a clear advantage of monolithic zirconia restorations [8].

Although the number of global studies on zirconia, which plays an important role in the field of dentistry, has increased recently, there are still no comprehensive studies in the literature. This study analyzed scientific articles on zirconia published between 1980 and 2021 using statistical and bibliometric methods.

Bibliometrics, as is well known, is the statistical analysis of publications, especially scientific articles, books, and congress abstracts [13]. Statistical and bibliometric literature analyses have been conducted on many important medical subjects, especially recently [13-16]. Bibliometric studies provide researchers with important information and new ideas on a topic by showing past and current trends [15]. Bibliometric research reveals information such as the most active countries, institutions, journals, authors, the most cited influential studies, and international collaborations in a field or research topic [16].

2. Materials and methods

The Web of Science Core Collection (WoS by Clarivate Analytics) database was used for literature review. The search period was determined to be 1980-2021 (access date: 02/01/2022), which marks the beginning of WoS registration. Two searches were performed.

Using the first search method, all publications tagged in the dentistry and medicine research fields in WoS with the phrase “zirconia” in the title were found. Reproducibility codes for researchers to access similar documents (search findings may vary depending on different access dates): (TI=(zircon*) Refined by Research Areas: Dentistry Oral Surgery Medicine OR Radiology Nuclear Medicine Medical Imaging OR Biochemistry Molecular Biology OR Biotechnology Applied Microbiology OR Pharmacology Pharmacy OR Surgery OR Orthopedics OR General Internal Medicine OR Biophysics OR Research Experimental Medicine OR Urology Nephrology OR Oncology OR Transplantation OR Public Environmental Occupational Health OR Cell Biology OR Dermatology OR Life Sciences Biomedicine Other Topics OR Paediatrics OR Cardiovascular System Cardiology OR Health Care Sciences Services OR Medical Informatics OR Pathology OR Microbiology OR Endocrinology Metabolism OR Immunology OR Neurosciences Neurology OR Nutrition Dietetics OR Anatomy Morphology OR Genetics Heredity OR Respiratory System OR Medical Laboratory Technology OR Ophthalmology OR Rheumatology OR Developmental Biology OR Evolutionary Biology OR Gastroenterology Hepatology OR Physiology OR Tropical Medicine OR Emergency Medicine OR Geriatrics Gerontology OR Integrative Complementary Medicine OR Obstetrics Gynecology OR Rehabilitation. Timespan: All years. Indexes: SCI-Expanded, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI.

In the second method, in all research fields except for dentistry and medicine, keywords related to dentistry (dentistry; dental material; orthopedic; clinical; *in vivo*; *in vitro* study; university clinic; private clinic; research group; biocompatibility; compatibility; osseointegration; endosseous implants; implant abutments; implant placement; peri-implant hard tissue response; peri-implant soft tissue response; esthetic; aesthetic; zirconia-based ceramic crowns; all-ceramic crowns; ceramic crowns; monolithic crowns: low-temperature aging degradation; alumina; Y-TZP zirconia; metal oxide; zirconium oxide; zirconium coating; zirconium oxide ceramic post; post and core; posts; strength; strength degradation; fracture toughness; hardness; stiffness; elastic limit; veneering ceramic fracture resistance; complication; indication; wear of opposing teeth; denture; fixed partial denture; cementation; cement; composite; filler) with the word “zirconia” in the title and in the abstract and keywords sections (Topic in WoS) have been reached. Repeatability codes: (TI=(zircon*) AND TS=(dental) OR TI=(zircon*) AND TS=(dentistry) OR TI=(zircon*) AND TS=(“dental material*”) OR TI=(zircon*) AND TS=(orthopedic) OR TI=(zircon*) AND TS=(clinic*) OR TI=(zircon*) AND TS=(“in vivo”) OR TI=(zircon*) AND TS=(“in vitro study”) OR TI=(zircon*) AND TS=(biocompatibility) OR TI=(zircon*) AND TS=(compatibility) OR TI=(zircon*) AND TS=(osseointegration) OR TI=(zircon*) AND TS=(“endosseous implant*”) OR TI=(zircon*) AND TS=(“implant abutment*”) OR TI=(zircon*) AND TS=(“implant placement”) OR TI=(zircon*) AND TS=(“peri-implant”) OR TI=(zircon*) AND TS=(esthetic*) OR TI=(zircon*) AND TS=(aesthetic*) OR TI=(zircon*) AND TS=(“ceramic crown*”) OR TI=(zircon*) AND TS=(“monolithic crown*”) OR TI=(zircon*) AND TS=(“low-temperature aging degradation”) OR TI=(zircon*) AND TS=(alumina) OR TI=(zircon*) AND TS=(“Y-TZP zirconia”) OR TI=(zircon*) AND TS=(“metal oxide”) OR TI=(zircon*) AND TS=(“zirconium oxide”) OR TI=(zircon*) AND TS=(“zirconium coating”) OR TI=(zircon*) AND TS=(“post and core”) OR TI=(zircon*) AND TS=(posts) OR TI=(zircon*) AND TS=(strength) OR TI=(zircon*) AND TS=(“fracture toughness”) OR TI=(zircon*) AND TS=(hardness) OR TI=(zircon*) AND TS=(stiffness) OR TI=(zircon*) AND TS=(“elastic limit”) OR TI=(zircon*) AND TS=(“veneering ceramic fracture resistance”) OR TI=(zircon*) AND TS=(complication) OR TI=(zircon*) AND TS=(“wear of opposing teeth*”) OR TI=(zircon*) AND TS=(denture) OR TI=(zircon*) AND TS=(“fixed partial denture”) OR TI=(zircon*) AND TS=(cementation) OR TI=(zircon*) AND TS=(cement) OR TI=(zircon*) AND TS=(composite) OR TI=(zircon*) AND TS=(filler) Timespan: All years. Indexes: SCI-Expanded, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI).

All articles found were downloaded from the WoS database, and studies not directly related to dentistry or medicine were excluded. Statistical analyses were performed using SPSS (version 22.0; SPSS Inc., Chicago, IL, USA). Distribution normalities were evaluated using the Kolmogorov-Smirnov test. Spearman correlation analysis was used to determine whether there is a relationship between world publication productivity on zirconia and various economic indicators—gross domestic product (GDP) and GDP per capita—obtained from the World Bank [17]. Statistical significance was set at $P<0.05$.

The exponential smoothing estimator (Seasonality Analysis (Time Series Forecasting) Using the Holt-Winters Method) in Microsoft Office Excel was employed to predict the number of articles for the next 5 years based on past publication trends. The website (https://app.datawrapper.de) was used for geographic mapping. The VOSviewer (Version 1.6.16, Leiden University’s Center for Science and Technology Studies) package program was used for bibliometric network visualization and citation analysis [18].

3. Results

A total of 18773 relevant recordings on zirconia, published between 1980 and 2021 were found in the WoS database. Of these recordings, 88.9% (n=16703) were articles, 12% (n=2254) were proceedings, 1.8% (n=332) were review articles, 1.7% (n=322) were meeting abstracts, and the remainder were of other publication types (Early Access, Notes, Book Chapters, Editorial Materials, Letters, Corrections, News Items, Retracted Publications, Retractions, Corrections, Additions, Data Papers, Reprints, Book Reviews, Discussions, and Withdrawn Publication). Bibliometric analyses were performed for 16703 articles. Of these, 96.5% (n=16118) were in English, 1.9% (312)

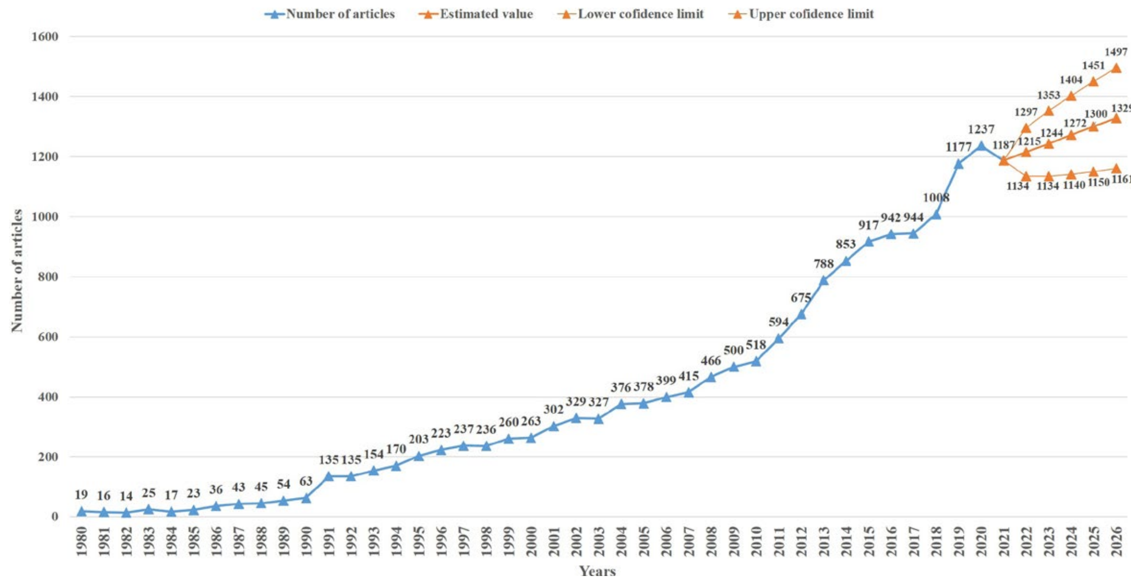

Fig. 1. Distribution of articles published on zirconia by year and estimated number of articles for future years

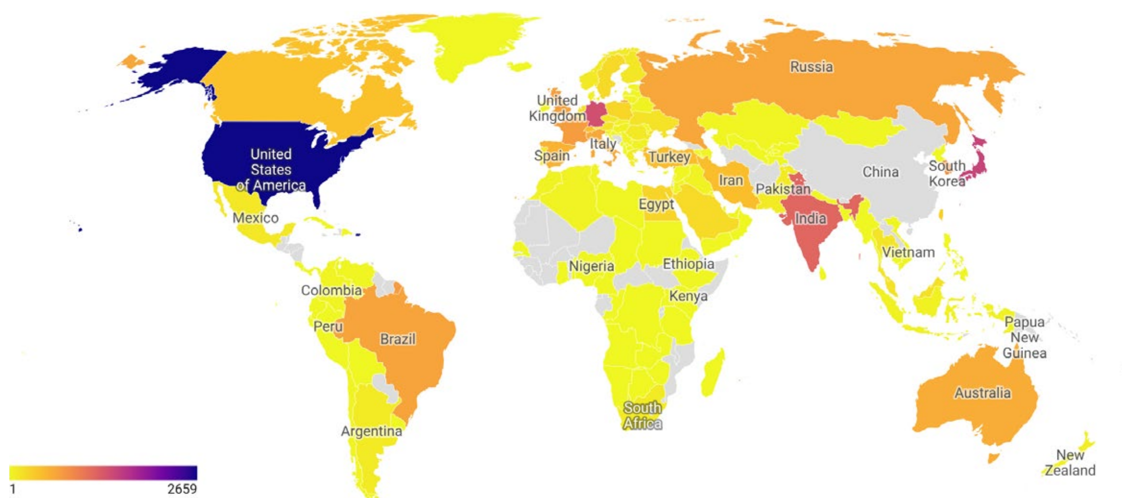

Fig. 2. Distribution of articles published on zirconia by country

in Chinese, and the remainder were in other languages (Japanese (n=86) and Russian (44), French (35), Korean (31), German (26), Spanish (18), Portuguese (12), Malay (6), Turkish (5), Polish (4), Czech (2), Romanian (2), Croatian (1), Serbian (1)).

3.1. Development and future trend of publications

The distribution of the number of published articles by year is shown in **Figure 1** together with a line graph. According to the exponential smoothing estimation model, 1215 (Confidence Interval:1134-1297) articles will be published in 2022, and a total of 1329 (CI%:1161-1497) articles will be published in 2026 (**Fig. 1**).

3.2. Active countries

The distribution of the number of articles according to the countries of the world is shown in **Figure 2**. The top 20 countries with the highest number of articles published by number of articles are China (n=3345, 20%), USA (2659, 15.9%), Japan (1514, 9%), Germany (1409, 8.4%), India (1201, 7.1%), South Korea (819, 4.9%), France (731, 4.3%), UK (701, 4.2%), Brazil (673, 4%), Russia (646, 3.8%), Italy (634, 3.7%), Australia (602, 3.6%), Spain (545, 3.2%), Switzerland (454, 2.7%), Iran (452, 2.7%), Turkey (451, 2.7%), Canada (432, 2.5%), Taiwan (314, 1.8%), Egypt (274, 1.6%), and Poland (264, 1.5%).

Cluster analysis was conducted for 86 countries that resulted in at least five articles from 163 countries producing publications on zirconia and authors who have international cooperation, and according to the results of the analysis, nine different clusters related to international cooperation were formed. These comprise Cluster 1, red, 20 countries; Cluster 2, green, 16 countries; Cluster 3, blue, 15 countries; Cluster 4, yellow, 11 countries; Cluster 5, purple, seven countries; Cluster 6, turquoise, six countries; Cluster 7, orange, four countries; Cluster 8, brown, four countries; Cluster 9, pink colors, three coun-

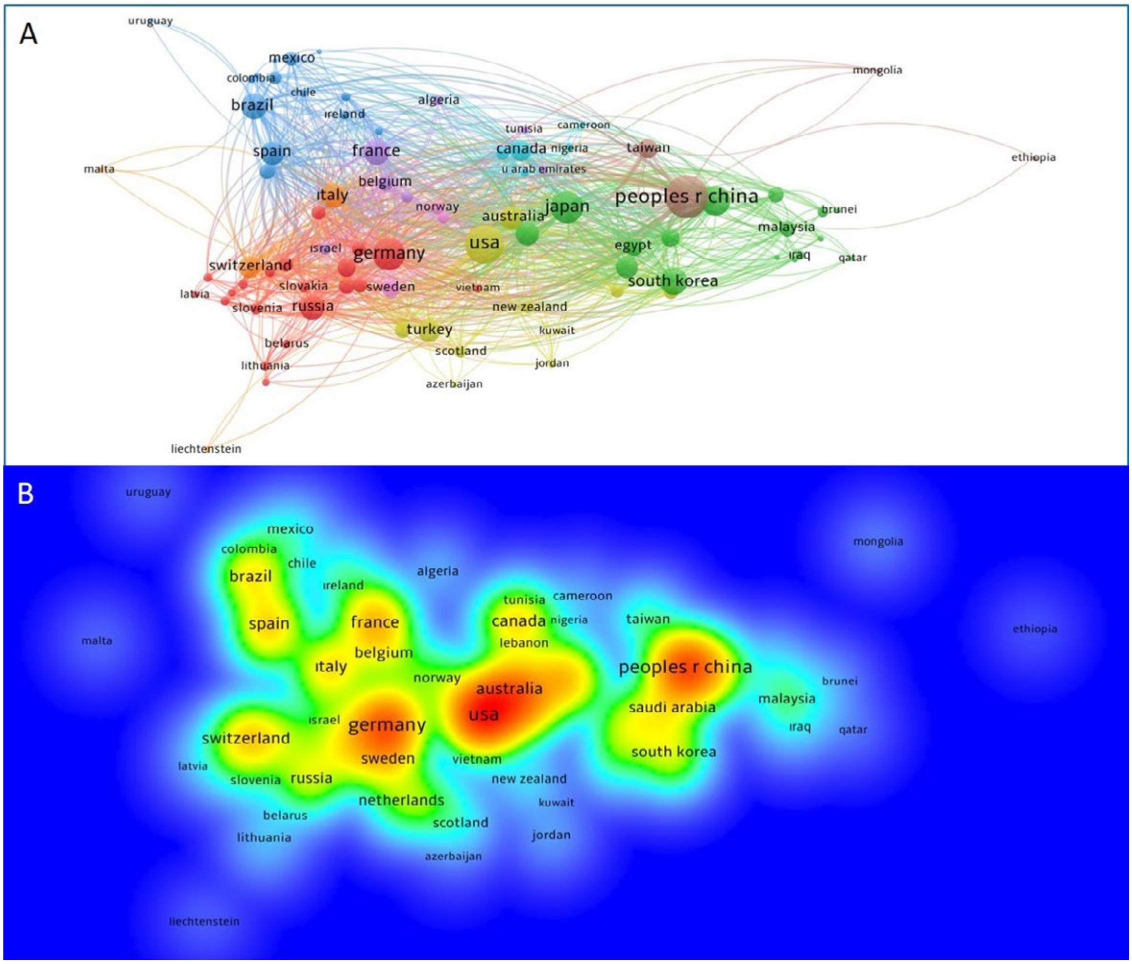

Fig. 3A. Network visualization map of cluster analysis on international collaboration between countries on zirconia
Footnote: Colors indicate clustering. The size of the circles indicates the number of articles
Fig. 3B. Density map for international collaboration of countries on zirconia
Footnote: The strength of the international collaboration score increases from blue to red (blue-green-yellow-red)

tries (**Fig. 3A**). The cooperation density map, created according to the countries' total cooperation scores, is presented in **Figure 3B**.

3.3. Correlation analysis

There were statistically positive and highly significant correlations between the number of articles and GDP and the number of articles and GDP per capita (r=0.742, P<0.001; r=0.701, P<0.001).

3.4. Active authors

The 15 most active authors, each of whom produced over 50 articles on zirconia, were Zhang Y (n=94), Ozcan M (88), Chevalier J (66), Valandro LF (63), Hammerle CHF (61), Wang Y (61), Bottino MA (56), Chen Y (54), Liu Y (54), Sailer I (53), Wang H (53), Wang J (53), Kern M (52), Lee JH (52), and Santosh M (52).

3.5. Active institutions

The top 20 out of the 8561 institutions that produced the most articles on zirconia are the Chinese Academy of Sciences (n=666), Centre Nationale de la Recherche Scientifique (443), Russian Academy of Sciences (358), China University of Geosciences (298), United States Department of Energy (DOE) (251), Indian Institute of Technology system (IIT) (246), University of California system (246), Egyptian Knowledge Bank (EKB) (237), Council of Scientific and Industrial Research (CSIR) India (189), Consejo Superior de Investigaciones Científicas (CSIC) (183), University of Zurich (180), Chinese Academy of Geological Sciences (161), Tsinghua University (157), Helmholtz Association (155), Chinese Academy of Sciences (CAS) (154), Universidade Estadual Paulista (153), Universidade De São Paulo (150), Seoul National University SNU (147), il Consiglio Nazionale delle Ricerche (CNR) (136), and Peking University (133). There were also 58 institutions that produced and collaborated with 50 or more articles. The network visualization map, which shows international cooperation, article productivity, and the institutions with the most cited articles, is shown in **Figure S1**. The institutions with the most international cooperation were the Chinese Academy of Sciences (298), China University of Geosciences (166), Chinese Academy of Geological Sciences (146), Peking University (68), University of Zurich (65), and University of Hong Kong (55). The most cited institutions were Australian National University (average number of citations,61.5), University of Hong Kong (46.3), Chinese Academy of Geological Sciences (42.6), University of Freiburg (42.4), University of Western Australia (42.1), Peking University (40.9), University of California, Los Angeles (39.6), China University of Geosciences (38.4), and Nanjing University (36.2).

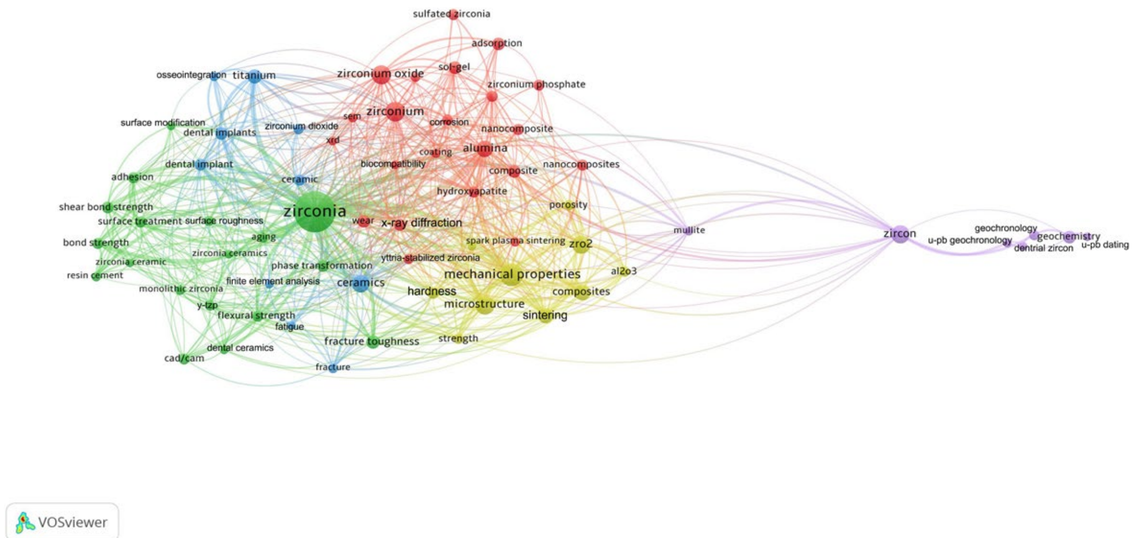

Fig. 4. Network visualization map for cluster analysis based on keyword analysis on zirconia. Colors indicate clustering
Footnote: Keywords in the same cluster have the same color. The size of the circles indicates the number of uses for a keyword

3.6. *Active journals*

A total of 16703 articles on zirconia were found in 1968 different journals. The 59 most active journals that produced 50 or more articles, the total number of citations received by the journals, and the average number of citations per article are presented in **Table 1**.

3.7. *Citation analysis*

Among the 16703 articles published between 1982 and 2021, the first 20 articles with the highest number of citations, according to the total number of citations, are presented in **Table 2**, and the average number of citations to the beginning of the year is given.

3.8. *Co-citation analysis*

A total of 309242 studies were cited in the reference sections of all 16703 articles analyzed. Among these studies, the first nine studies that received the most co-citations (350 or more citations) were Piconi et al. (1999) [19] (number of co-citations, NC:895), Denry et al. (2008) [12] (NC:644), Garvie et al. (1975) [20] (NC:504), Sun et al. (1989) [21] (NC:503), Hannink et al. (2000) [22] (NC:399), Garvie et al. (1972) [23] (NC:397), Manicone et al. (2007) [4] (NC:391), Chevalier (2006) [24] (NC:369), and Kern et al. (1998) [25] (NC:350).

3.9. *Trend topics*

In all 16703 articles published on zirconia, 24072 different keywords were used. Among these keywords, 67 different keywords that were used in at least 65 articles are listed in **Table 3**. A clustering analysis of these keywords is shown in **Figure 4**. The trend network visualization performed to reveal trending topics is shown in **Figure S2**, and the citation network visualization performed to reveal the most cited topics is shown in **Figure S3**.

4. Discussion

In the decade from 1980 to 1990, between 14 and 63 zirconia articles (average number of articles, 32) were published each year. Since 1990, there has been a remarkable increase in the number of articles. By 1991, the number of articles exceeded 100. During the period 1991-2006, between 135 and 399 articles (average number of articles, 258) were produced annually. During the period 2007-2017, between 415 and 944 articles (average number of articles, 692) were produced annually, respectively. The number of articles published in 2018 exceeded 1000, and 1237 articles were published in 2020. There has been a significant increase in the number of articles published, especially recently. According to the Seasonality Analysis (Time Series Forecasting) results obtained in Excel using the Holt-Winters method (Seasonality Analysis (Time Series Forecasting) in Excel Using Holt-Winters Method) when the forecast results for the next 5 years were evaluated, it was determined that the number of articles showed an increasing trend. Zirconia-based ceramics as restorative dental materials began to become widespread in dentistry in 1990 [8-11], which is reflected in the increase in publications since then. Recently, zirconia-based ceramics have become popular with the latest developments in CAD-CAM technology in prosthetic dentistry [11,12], which has been suggested to be the reason for the number of publications recently.

Among the 20 most active countries in dental zirconia publication, 13 are developed countries (USA, Japan, Germany, South Korea, France, UK, Italy, Australia, Spain, Switzerland, Canada, Taiwan, and Poland), while the other seven (China, India, Brazil, Russia, Iran, Turkey, Egypt) were countries that, while developing, already had large economies. Considering the highly significant correlation between article productivity and economic development indicators in our study, the economic development level of countries is the primary contributor to the productivity of publications on zirconia. The fact that China ranks first in the list, and countries such as Brazil, India, and Russia are also among the top 20 can be explained by access to raw materials [26], as zirconium mines are numerous in these countries.

From the density map for the total cooperation score, the countries with the most intensive cooperation were determined to be USA, China, Germany, Japan, France, Australia, England, Switzerland, Italy, Brazil, Spain, Canada, and Sweden. When the co-authorship is

Table 1. Top 59 most active journals that have published more than 50 articles on zirconia

Journals	RC	C	AC	Journals	RC	C	AC
Ceramics International	611	9485	15.5	*Journal of Materials Research*	87	2029	23.3
Journal of the American Ceramic Society	461	18324	39.7	*Journal of Applied Physics*	85	3078	36.2
Journal of the European Ceramic Society	429	11112	25.9	*Journal of Materials Science Letters*	85	829	9.8
Journal of Prosthetic Dentistry	321	8493	26.5	*İnternational Journal of Applied Ceramic Technology*	83	647	7.8
Dental Materials	258	14739	57.1	*Journal of Power Sources*	81	2415	29.8
Journal of Materials Science	254	4672	18.4	*Materials Chemistry and Physics*	81	1587	19.6
Surface & Coatings Technology	189	4812	25.5	*Journal of Catalysis*	79	6431	81.4
Journal of Alloys and Compounds	170	3307	19.5	*Journal of Dentistry*	78	3072	39.4
Materials Science and Engineering A-Structural Materials Properties Microstructure and Processing	167	4526	27.1	*Rare Metal Materials and Engineering*	78	125	1.6
Precambrian Research	159	9991	62.8	*Scripta Materialia*	76	2185	28.8
Acta Petrologica Sinica	158	3194	20.2	*Journal of the Ceramic Society of Japan*	74	330	4.5
Materials	151	868	5.7	*Applied Physics Letters*	72	3273	45.5
Dental Materials Journal	148	2814	19.0	*Clinical Oral Investigations*	72	1511	21.0
Lithos	141	5751	40.8	*Journal of the Electrochemical Society*	71	1798	25.3
Journal of the Mechanical Behavior of Biomedical Materials	140	2117	15.1	*International Journal of Hydrogen Energy*	68	1524	22.4
Journal of Prosthodontics-Implant Esthetic and Reconstructive Dentistry	131	1720	13.1	*Journal of Adhesive Dentistry*	67	1230	18.4
Applied Catalysis A-General	128	5058	39.5	*Gondwana Research*	66	3263	49.4
Journal of Nuclear Materials	125	2993	23.9	*Advances in Applied Ceramics*	65	327	5.0
Clinical Oral Implants Research	118	3958	33.5	*Catalysis Letters*	58	1627	28.1
Journal of Advanced Prosthodontics	117	1505	12.9	*Wear*	58	1748	30.1
International Journal of Prosthodontics	116	4262	36.7	*Ore Geology Reviews*	57	1181	20.7
Applied Surface Science	114	2727	23.9	*Clinical Implant Dentistry and Related Research*	56	1635	29.2
İnternational Journal of Oral & Maxillofacial Implants	107	2327	21.7	*Materials Science & Engineering C-Materials for Biological Applications*	56	895	16.0
Solid State Ionics	105	4016	38.2	*Journal of Biomedical Materials Research Part B-Applied Biomaterials*	55	1516	27.6
Materials Letters	102	1605	15.7	*Geological Journal*	54	360	6.7
RSC Advances	97	1732	17.9	*International Geology Review*	52	1027	19.8
Thin Solid Films	97	1981	20.4	*International Journal of Refractory Metals & Hard Materials*	51	801	15.7
Acta Materialia	90	3941	43.8	*Journal of Prosthodontic Research*	50	420	8.4
Journal of Chromatography A	90	2602	28.9	*Journal of Sol-Gel Science and Technology*	50	712	14.2
Journal of Asian Earth Sciences	88	3053	34.7				

Abbreviations: RC, record count; C, number of citation; AC, average citation per document.

examined, it is seen that cooperations are clustered by geographical proximity (for example: Group 1: (Austria, Belarus, Bulgaria, Croatia, Czech Republic, Estonia, Finland, Germany, Hungary, Kazakhstan, Latvia, Lithuania, Poland, Romania, Russia, Serbia, Slovakia, Slovenia, Ukraine); Group 2: (Egypt, Iran, Iraq, Qatar, Saudi Arabia, Sudan, India, Bangladesh); Group 3: (Chile, Brazil, Argentina, Uruguay, Venezuela, Colombia, Cuba, Mexico); Group 4: (Sweden, Norway, and Denmark), but there are also some long-distance exceptions, (for example: Group 1: (Germany, Vietnam); Group 2: (England in UK, South Korea); Group 3: (New Zealand, Turkey, USA, Singapore); Group 4: (Canada, Kenya, etc.).

The journals that published most articles on zirconia were *Ceramics International*, *Journal of the American Ceramic Society*, *Journal of the European Ceramic Society*, *Journal of Prosthetic Dentistry*, *Dental Materials*, *Journal of Materials Science*, *Surface & Coatings Technology*, *Journal of Alloys and Compounds*, and *Materials*. Science and Engineering a-Structural Materials Properties Microstructure and Processing were determined to be *Precambrian Research*, *Acta Petrologica Sinica*, *Materials*, *Dental Materials Journal*, *Lithos*, and *Journal of the Mechanical Behavior of Biomedical Materials*. It can be suggested that authors who wish to publish articles on zirconia should first consider these journals. When the citation analyses of journals were evaluated, the most influential journals, according to the average number of citations per article, were *Precambrian Research*, *Dental Materials*, *Acta Materialia*, *Lithos*, *Journal of the American Ceramic Society*, *Applied Catalysis a-General*, *Solid State Ionics*, and the *International Journal of Prosthodontics*.

Table 2. Top 20 most cited articles according to total citations on zirconia

No	Article	Author	Journal	PY	TC	AC
1	Continental and oceanic crust recycling-induced melt-peridotite interactions in the trans-north China orogen: U-PB dating, HF isotopes and trace elements in zircons from mantle xenoliths	Liu et al.	*Journal of Petrology*	2010	2443	187.92
2	State of the art of zirconia for dental applications	Denry et al.	*Dental Materials*	2008	1152	76.8
3	Archean crustal evolution in the northern yilgam craton: U-PB and HF-isotope evidence from detrital zircons	Griffin et al.	*Precambrian Research*	2004	891	46.89
4	Zirconates as new materials for thermal barrier coatings	Vassen et al.	*Journal of the American Ceramic Society*	2000	886	38.52
5	Age constraint on burmese amber based on U-PB dating of zircons	Shi et al.	*Cretaceous Research*	2012	881	80.09
6	The tetragonal-monoclinic transformation in zirconia: lessons learned and future trends	Chevalier et al.	*Journal of the American Ceramic Society*	2009	840	60
7	Unusual and highly tunable missing-linker defects in zirconium metal-organic framework UIO-66 and their important effects on gas adsorption	Wu et al.	*Journal of the American Chemical Society*	2013	789	78.9
8	What future for zirconia as a biomaterial?	Chevalier	*Biomaterials*	2006	755	44.41
9	Zircon HF-isotope analysis with an excimer laser, depth profiling, ablation of complex geometries, and concomitant age estimation	Woodhead et al.	*Chemical Geology*	2004	739	38.89
10	High-strength zirconium diboride-based ceramics	Chamberlain et al.	*Journal of the American Ceramic Society*	2004	646	34
11	Stabilized zirconia as a structural ceramic: an overview	Kelly et al.	*Dental Materials*	2008	625	41.67
12	Structure and stability of ultrathin zirconium oxide layers on si(001)	Copel et al.	*Applied Physics Letters*	2000	618	26.87
13	Mechanical, thermal, and oxidation properties of refractory hafnium and zirconium compounds	Opeka et al.	*Journal of the European Ceramic Society*	1999	612	25.5
14	Five-year clinical results of zirconia frameworks for posterior fixed partial dentures	Sailer et al.	*International Journal of Prosthodontics*	2007	564	35.25
15	The effect of surface grinding and sandblasting on flexural strength and reliability of Y-TZP zirconia ceramic	Kosmac et al.	*Dental Materials*	1999	550	22.92
16	Strength, fracture toughness and microstructure of a selection of all-ceramic materials. Part II. Zirconia-based dental ceramics	Guazzato et al.	*Dental Materials*	2004	547	28.79
17	Zircon formation versus zircon alteration - new insights from combined U-PB and LU-HF IN-SITU LA-ICP-MS analyses, and consequences for the interpretation of archean zircon from the central zone of the limpopo belt	Gerdes et al.	*Chemical Geology*	2009	542	38.71
18	Bonding to zirconia ceramic: adhesion methods and their durability	Kern et al.	*Dental Materials*	1998	542	21.68
19	Flash sintering of nanograin zirconia in < 5 s at 850 degrees C	Cologna et al.	*Journal of the American Ceramic Society*	2010	530	40.77
20	Conformable amplified lead zirconate titanate sensors with enhanced piezoelectric response for cutaneous pressure monitoring	Dagdeviren et al.	*Nature Communications*	2014	512	56.89

Abbreviations: PY, publication year; TC, total citation; AC, average citations per year.

The most cited study was published in the *Journal of Petrology* by Liu et al. (2010) [27], titled "Continental and Oceanic Crust Recycling-induced Melt-Peridotite Interactions in the Trans-North China Orogen: U-Pb Dating, Hf Isotopes, and Trace Elements in Zircons from Mantle Xenoliths." The second most influential study was published in *Dental Materials* by Denry et al. (2008) [12], titled "State of the Art of Zirconia for Dental Applications." The third most influential study was published in *Precambrian Research* by Griffin et al. (2004) [28], titled "Archean Crustal Evolution in the Northern Yilgam Craton: U-Pb and Hf Isotopic Evidence from Detrital Zircons." The fourth most influential study was published in the Journal of the *American Ceramic Society* by Vassen et al. (2000) [29], titled "Zirconates as New Materials for Thermal Barrier Coatings." The fifth most influential study was published in *Cretaceous Research* by Shi et al. (2012) [30], titled "Age Constraint on Burmese Amber Based on U-Pb Dating of Zircons". The sixth and seventh most influential studies were published in the *Journal of the American Ceramic Society* by Chevalier et al. (2009) [31] titled "The Tetragonal-Monoclinic Transformation in Zirconia: Lessons Learned and Future Trends," and by Wu et al. (2013) [32], titled "Unusual and Highly Tuneable Missing-Linker Defects in Zirconium Metal-Organic Framework UiO-66 and Their Important Effects on Gas Adsorption." When evaluated according to the average number of citations per year, the top five most influential articles were, respectively, Liu et al. (2010) [27], Shi et al. (2012) [30], Wu et al. (2013) [32], Denry et al. (2008) [12], and Chevalier et al. (2009) [31]. According to the co-citation numbers of the analyzed 16703 articles, the most influential studies are Piconi et al. (1999) [19], Denry et al. (2008) [12], Garvie et al. (1975) [20], Sun et al. (1989) [21], Hannink et al. (2000) [22], Garvie et al. (1972) [23], Manicone et al. (2007) [4], Chevalier (2006) [24], and Kern et al. (1998) [25]. It is recommended that dentists and scientists interested in zirconia review these publications first.

The keyword analysis findings showed that zirconia subjects formed clusters (Cluster 1: (22 keywords) adsorption, alumina, biocompatibility, coating, composite, corrosion, hydroxyapatite, nanocomposite(s), nanoparticles, oxidation, SEM, sol-gel, spark plasma sintering, sulfated zirconia, wear, X-ray diffraction, XRD, yttria-stabilized zirconia, zirconium, zirconium oxide, and zirconium phosphate. Cluster 2 (18 keywords): adhesion, aging, bond strength, CAD-CAM, dental ceramics, flexural strength, fracture toughness,

Table 3. Top 67 most frequently used keywords in articles published on zirconia

Keywords	Number of Uses	Keywords	Number of Uses	Keywords	Number of Uses
adhesion	117	geochemistry	154	sulfated zirconia	115
adsorption	151	geochronology	103	surface modification	73
aging	84	hardness	145	surface roughness	102
Al2O3	105	hydroxyapatite	125	surface treatment	109
alumina	287	mechanical properties	590	titanium	195
biocompatibility	72	mechanical property	69	U-Pb geochronology	69
bond strength	121	microstructure	407	wear	159
cad-cam	115	monolithic zirconia	79	x-ray diffraction	138
ceramic	125	mullite	73	XRD	71
ceramics	313	nanocomposite	109	Y-TZP	99
coating	78	nanocomposites	112	yttria-stabilized zirconia	99
composite	159	nanoparticles	112	zircon	344
composites	271	osseointegration	82	zircon U-Pb dating	72
corrosion	99	oxidation	90	zirconia	2339
dental ceramics	70	phase transformation	139	zirconia ceramic	67
dental implant	127	porosity	93	zirconia ceramics	72
dental implants	162	resin cement	84	zirconium	418
detrital zircon	66	sem	81	zirconium dioxide	103
fatigue	68	shear bond strength	136	zirconium oxide	398
finite element analysis	67	sintering	243	zirconium phosphate	115
flexural strength	108	sol-gel	151	ZrO2	363
fracture	81	spark plasma sintering	76		
fracture toughness	172	strength	107		

monolithic zirconia, phase transformation, resin cement, shear bond strength, surface modification, surface roughness, surface treatment, Y-TZP, zirconia, and zirconia ceramic(s). Cluster 3 (10 keywords): ceramic(s), dental implant(s), fatigue, finite element analysis, fracture, osseointegration, titanium, and zirconium dioxide. Cluster 4 (10 keywords) Al_2O_3, composites, hardness, mechanical properties (s), microstructure, porosity, sintering, strength, ZrO_2. Cluster 5 (7 keywords): detrital zircon, geochemistry, geochronology, mullite, U-Pb geochronology, zircon, zircon U-Pb dating). The most cited keywords were adsorption, geochronology, U-Pb geochronology, geochemistry, zirconia ceramic, dental ceramics, sulfated zirconia, bond strength, dental implants, and zircon U-Pb dating. Recent trends include dental implants, resin cement, surface roughness, shear bond strength, monolithic zirconia, osseointegration, flexural strength, aging, geochemistry, zircon U-Pb dating, detrital zircon, adhesion, CAD-CAM, bond strength, adsorption, titanium, spark plasma sintering, corrosion, SEM, zirconium dioxide, surface modification, XRD, finite element analysis, and yttria-stabilized zirconia.

Only two prior bibliometric studies of zirconia have been reported in the literature. These two studies were conducted by Lorusso et al. (2020) [33], which considered only 29 clinical studies published on zirconia between 2008 and 2020, and Yu et al.'s (2017) [34] basic statistical analysis of 2149 articles between 2009 and 2014. In the current study, 16703 articles published on zirconia between 1980 and 2021 were comprehensively analyzed. This study is more comprehensive than the two former studies in terms of both the number of articles, including citation analysis, keyword analysis, trend topic analysis, correlation and estimation (regression) analysis, and international cooperation analyses, which are superior to other studies.

Since citation and co-citation analyses could not be performed in the PubMed database in the current study, and because there were studies with low impact levels in the Scopus database, only the WoS database was used while scanning the literature. Another reason for using the WoS database is that it indexes articles published in more effective journals with a higher impact factor than other databases such as PubMed and Scopus [13,15]. In addition, the WoS database is more commonly preferred in bibliometric analyses conducted recently [13-16].

5. Conclusions

The following conclusions can be drawn from this comprehensive bibliometric study on zirconia:

1. As a result of the remarkable increase in the number of articles published recently, the number of articles published between 1980 and 2021 reached 16703. The latest trends in zirconia research include dental implants, resin cement, surface roughness, shear bond strength, monolithic zirconia, osseointegration, flexural strength, aging, geochemistry, zircon U-Pb dating, detrital zircon, adhesion, CAD-CAM, bond strength, adsorption, titanium, spark plasma sintering, corrosion, SEM, zirconium dioxide, surface modification, XRD, finite element analysis, and yttria-stabilized zirconia.
2. This article can be a useful resource for scientists and clinicians on the global and multidisciplinary outputs in research on zirconia, as the WoS database indexes the articles published in more effective journals with a higher impact factor than other databases and is more commonly preferred in bibliomet-

ric analyses conducted recently. It has been determined that Western countries with large economies (especially the USA and European countries) and some Far East countries (China, Japan, India, and South Korea) maintained research leadership on zirconia. Although there have been significant international collaborations globally, we believe that comprehensive research on zirconia should also be encouraged in underdeveloped countries.

Conflicts of interest

The authors declare no competing interests with respect to authorship and/or publication of this article.

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