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Mapping global research in dental pulp regeneration: A 10-year bibliometric analysis

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ABSTRACT

Background: Dental pulp regeneration aims to restore the function and vitality of the dental pulp, which is the soft tissue inside the tooth. Research in this field is effective in trying to improve clinical practices and procedures. This study aimed to analyze the literature related to dental pulp regeneration and to create a documented research perspective for this field.

Materials and Methods: This bibliometric study analyzes the research outputs of the subject area of dental pulp regeneration indexed in the Web of Science database between 2013 and 2023. SciMAT software was used to visualize and predict the trends in research on the topic.

Results: In general, it has been observed that the stem cell cluster consistently had the highest number of articles across all periods. As we progressed through time, the significance of this cluster continued to grow, eventually becoming a crucial component in the motor theme during the last period. In addition, a significant portion of the studies conducted during different periods focused on identifying suitable materials for scaffold formation. Various materials, including polymers and bioactive glasses, were proposed as viable options for scaffold formation in different periods.

Conclusion: Dental pulp stem cells (DPSCs), scaffold networks, growth factors, and regulatory factors are the three main factors that influence dental pulp regeneration. By analyzing maps and thematic clusters in dental pulp regeneration research, as well as considering indicators such as repetition frequency, centrality, and citation of these clusters, researchers can identify the strengths, weaknesses, and gaps in current research.

Key Words: Bibliographic network, dental pulp regeneration, science in literature, scientometric, SciMAT

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INTRODUCTION

The advancement of biological strategies, specifically tissue engineering, has emerged as a prominent approach in dental research in the current era. This approach focuses on the regeneration and biomineralization of dental tissues that have been lost. In the context of dentin pulp regeneration, the intricate process is driven by the interactions between various elements such as stem cells, signaling molecules,

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biomaterials, and the microenvironment in the periapical region.[1] Notably, this innovative treatment method gained recognition from the American Dental Association in 2011. However, despite its acceptance, the establishment of evidence-based guidelines that offer the most suitable outcomes is still a work in progress. These guidelines are gradually being developed through numerous clinical and fundamental research studies.[2]

In the last 15 years, there have been numerous endeavors in the medical and dental fields to regenerate and replace diseased tissue or organs. One significant advantage of reconstruction techniques is the ability to recreate the original texture and architecture of the affected area. In the field of endodontics, similar efforts have been made through root restorative (RE) procedures. These procedures aim to replace damaged tooth structures, including dentin and root structures, as well as cells of the dentin–pulp complex using biologically based methods. Since its reintroduction, RE has garnered immense interest globally, not only among practitioners but also researchers, academics, and financial institutions. Over the past 15 years, it has emerged as one of the rapidly expanding fields in dentistry.[3] The results of Sheikhshoaei *et al*., who dealt with co-citation and word co-occurrence networks of Iranian articles in the field of dentistry, confirm these findings.[4]

On the other hand, the assessment of research activities is widely recognized as a crucial tool in attaining research performance standards within scientific institutions. The advancement of scientific knowledge has greatly contributed to the expansion of research endeavors in various scientific domains. The quantification of scientific output plays a pivotal role in determining productivity levels. Moreover, the evaluation of scientific output extends to the realm of health-related sciences, where studies have been conducted to gauge the scientific contributions made in these fields.[5,6] For example, Shirani *et al*. reviewed high-quality articles on COVID-19 and effectively summarized them for healthcare providers and the general population.[7] Furthermore, in other studies, artificial neural network methods have been used to analyze the content of scientific resources.[8,9]

One of the scientometric methods employed to gain insights into published research across diverse scientific disciplines is the creation of a scientific map. This approach not only provides a comprehensive overview of the research landscape but also highlights the most influential subject areas. The primary objective of scientific maps is to present a holistic view of research progress, interconnections between different fields, and the evolution of these fields over time[10,11] Drawing a scientific map serves as a potent bibliographic method for analyzing research output. It offers a visual representation of the relationships between scientific disciplines, subject areas, experts, and scholarly texts. The process of creating a scientific map involves observing a specific scientific subject area and delineating the boundaries of research to ascertain its structure and interactions. The ultimate aim of drawing a scientific map is to elucidate the structural and dynamic aspects of research.[12,13] In this regard, three key components are taken into consideration when constructing the scientific structure: individual elements, interconnected elements that form a network, and the interpretation of relationships between these elements. Scientists and researchers have employed various tools to illustrate and depict the structure of science in different fields.[14,15]

Even though several studies have explored and evaluated the outcomes of various aspects of dental restoration from different angles,[3,4,16-18] a comprehensive analysis utilizing the concept mapping method, which is considered a crucial scientific approach for gaining insights into research perspectives, has not yet been conducted specifically in the field of dental pulp reconstruction. Consequently, the objective of this research is to examine the scientific progression of dental restoration through the implementation of the scientific mapping approach. In addition, this study aims to investigate and analyze the scientific metrics of global scientific publications related to dental pulp restoration within the Web of Science database. Thus, the aim of conducting a bibliometric analysis of global research related to dental pulp regeneration is to offer a comprehensive view of the advancements in this significant area of dental research. This analysis also aims to identify key themes that can serve as reference points for shaping research policies in the field.

MATERIALS AND METHODS

Study design

In this study, we recruited all the documents indexed in the Web of Science database with the topic of

dental pulp regeneration and related topics. The analysis of scientific productions in the Web of Science database holds significant value due to its status as the foremost and dependable database for indexing such works. By examining the trends within this database, researchers can obtain evidence that is grounded in the most reliable and authoritative research within their respective fields. Consequently, this study relied on the entirety of documents indexed in this database as the primary data source for information analysis and the creation of scientific maps. To achieve maximum comprehensiveness, SCI-EXPANDED and SSCI collections were selected. The search for the documents took place on January 3, 2024. To illustrate the 10-year thematic process, all the documents available on the Web of Science database in the search field, which were published between 2013 and 2023, were examined and 4739 papers were retrieved and analyzed.

Search strategy

Searching for resources on the topic was done with the following strategy: Pulp* regeneration* OR Regenerative Endodontic* OR Dental Pulp* Regeneration* OR Dentin Regeneration* OR Tooth Regeneration* OR Endodontic Regeneration*. Then, to filter the results and retrieve related results, in Citation Topics Meso, the results were limited to Dentistry and Oral Medicine. Citation Topics are algorithmically derived citation clusters (using an algorithm developed by CWTS, Leiden). For Meso-topics, the documents' stability is higher than 90%.[19] After searching with the mentioned formula, finally, 65,265 records related to the field of emergency medicine were retrieved and included in the study.

Data analysis tool

To analyze the results, SciMAT-v1.1.04 was used. SciMAT is an open-source science mapping software tool that implements the aforementioned software requirements. SciMAT is based on the science mapping analysis approach presented by Cobo *et al*. (2011), which allows us to carry out science mapping studies under a longitudinal framework.[20]

Analysis configuration

Key parameters used to map the global research in dental pulp regeneration were analysis of keywords of papers, including author keyword and keyword plus, which are index terms automatically generated from the titles of cited articles. The analysis configuration was as follows: Unit of analysis: Words (authorRole = true, sourceRole = true, addedRole = true); Kind of network: Co-occurrence; Normalization measure: Equivalence index; Cluster algorithm: Centers simples; Max cluster size: 100; Min cluster size: 4; Evolution measure: Equivalence index; Overlapping measure: Equivalence index. To carry out a detailed analysis and contain information that can be used on a usable scale, we analyzed it in five 2-year periods including 2013–2015, 2015–2017, 2017–2019, 2019–2021, and 2021–2023.

RESULTS

Baseline characteristics of studied documents

The search results show that 4739 documents have been published in the Web of Science database from the beginning of 2013 to the end of 2023. Based on this, most of the documents published were related to 2022 with 13.41% of the total publications. In general, the findings have shown an increasing slope in the proportion of scientific productions in pulp regeneration, and every year, the attention of researchers has increased to this issue.

In terms of institutions publishing the most scientific productions, the list of institutions that have published more than 2% of scientific productions is presented in Table 1. Based on this, Sichuan University, the University of Michigan, and the University of Michigan System have been at the top of the institutions issuing these documents.

Furthermore, from the point of view of the journals that publish scientific productions in the field of dental pulp regeneration, the findings show that the *Journal of Endodontics* is at the top of the journals by a margin, and it alone has published nearly 9.5% of all scientific productions and somehow it can be said that the core journal is topical in this field. In Table 1, journals publishing more than 2% of documents are presented. It is worth noting that except *Clinical Oral Investigations Journal*, the rest of the journals were all in the first quarter (Q1) and all these journals had an IF between 3.4 and 7.6, which can indicate the importance of these journals in the dental pulp regeneration subject area.

Longitudinal results

Overlapping map

The evolution of keywords is depicted in Figure 1. Each subperiod is represented by circles, with the number of keywords inside. The arrows connecting

Table 1: Baseline characteristics of studied documents.

A			B		
Publication years	**Record count**	**Percentage of 4739**	**Affiliations**	**Record count**	**Percentage of 4787**
2022	642	13.411	Sichuan University	176	3.677
2021	596	12.450	University of Michigan	127	2.653
2020	556	11.615	University of Michigan system	127	2.653
2019	475	9.923	Egyptian Knowledge Bank	121	2.528
2023	474	9.902	Seoul National University Snu	113	2.361
2017	386	8.064	University of Zurich	111	2.319
2018	378	7.896	University of Texas system	96	2.005
2014	345	7.207			
2016	341	7.123			
2015	339	7.082			
2013	255	5.327			

C				
Publication titles	**Record count**	**Percentage of 4787**	**Impact factor (2022)**	**Quartile**
Journal of Endodontics	449	9.380	4.2	Q1
International Endodontic Journal	138	2.883	5	Q1
Clinical Oral Implants Research	124	2.590	4.3	Q1
Clinical Oral Investigations	106	2.214	3.4	Q2
Journal of Dental Research	103	2.152	7.6	Q1
Journal of Periodontology	100	2.089	4.3	Q1

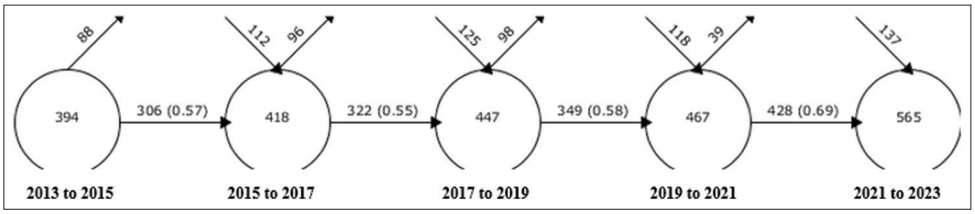

Figure 1: Overlap fractions (incoming and outcoming keywords between successive subperiods).

consecutive subperiods indicate the number of shared keywords, with the similarity index (overlap fraction) shown in parentheses. The upper-incoming arrows indicate the number of new keywords in the subperiod, while the upper-outcoming arrows represent the keywords that are not present in the next subperiod (i.e. discontinued). For instance, in the third studied subperiod (2017–2019), there are 447 keywords, out of which 349 keywords continue to the next studied subperiod (2019–2021). The remaining 98 keywords are not retained in the subsequent subperiod. The similarity index between the third and fourth subperiods is 0.58.

Evolution map

Figures 2 and 3 illustrate the progression of research in the field of dental pulp regeneration based on the number of published documents and mean citation of documents. The solid lines indicate that the connected themes share the same name or that one theme's name is a subset of the other. On the other hand, a dotted line signifies that the themes share common elements that are not reflected in their names. The thickness of the lines represents the inclusion index, while the size of the spheres corresponds to the number of published documents for each theme.

Despite the dense nature of the graph in Figures 2 and 3, it is still possible to identify distinct thematic areas. The different color shadows in the figure group together themes that belong to the same thematic area. Some themes may have multiple shadows, indicating their association with more than one thematic area. Conversely, some themes lack a shadow, suggesting that they do not fall within any specific thematic area.

Strategic diagrams

To interpret the results of the strategic diagram, it is necessary to mention its basic concepts. Two measures can be used to represent the identified networks: centrality and density. Centrality quantifies the level of interaction between a network and other networks. It also measures the significance of external connections

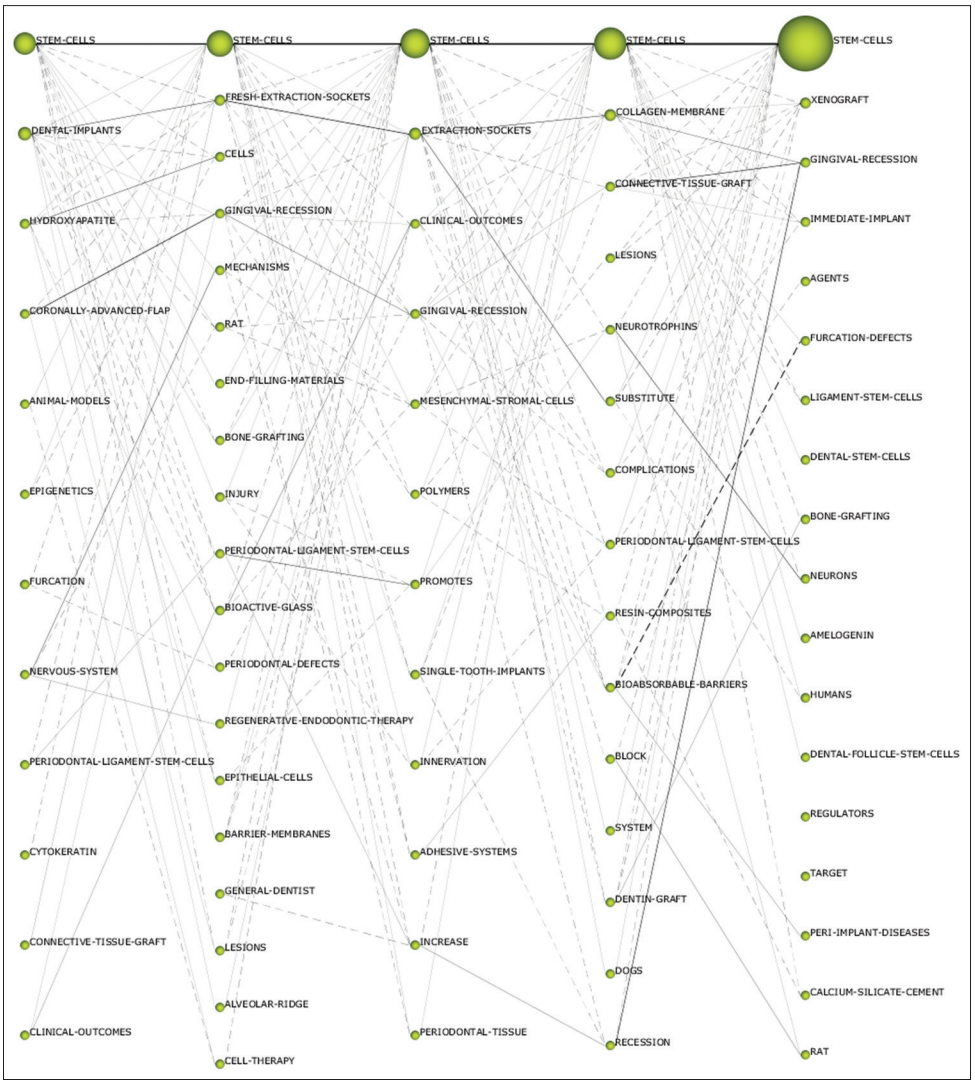

Figure 2: Thematic evolution of the dental pulp regeneration research field (2013–2023) based on document count.

to other themes. This value can be interpreted as an indicator of the theme's importance in the overall advancement of the analyzed research field. On the other hand, density, which will be referred to as density from now on, assesses the internal strength of the network. It gauges the intensity of internal connections among all the keywords that describe the research theme. This value provides a measure of the theme's progression.[21,22] Furthermore, to present a more suitable picture of the thematic clusters of each subperiod, information on centrality, density, document counts, and average citations of each cluster has been provided [Table 2]. According to this, themes located in the upper right quadrant of a research field are not only well-developed but also crucial for its structure. These themes, known as motor themes, exhibit strong centrality and high density. Their placement in this quadrant indicates that they are externally related to concepts that apply to other closely related themes. On the other hand, themes situated in the upper left quadrant possess well-developed internal connections but lack significant external ties, making them of marginal importance to the field. These themes are highly specialized and peripheral in nature. In contrast, themes found in the lower left quadrant are both weakly developed and marginal. They have low density and centrality, often representing emerging or disappearing themes. Finally, the lower right quadrant encompasses themes that are important for the research field but have not been fully developed. This quadrant encompasses transversal and general basic themes.[22]

In the period from 2013 to 2015, the stem cells, dental implants, and hydroxyapatite clusters had the highest centrality with 401.5, 247.19, and 115.23,

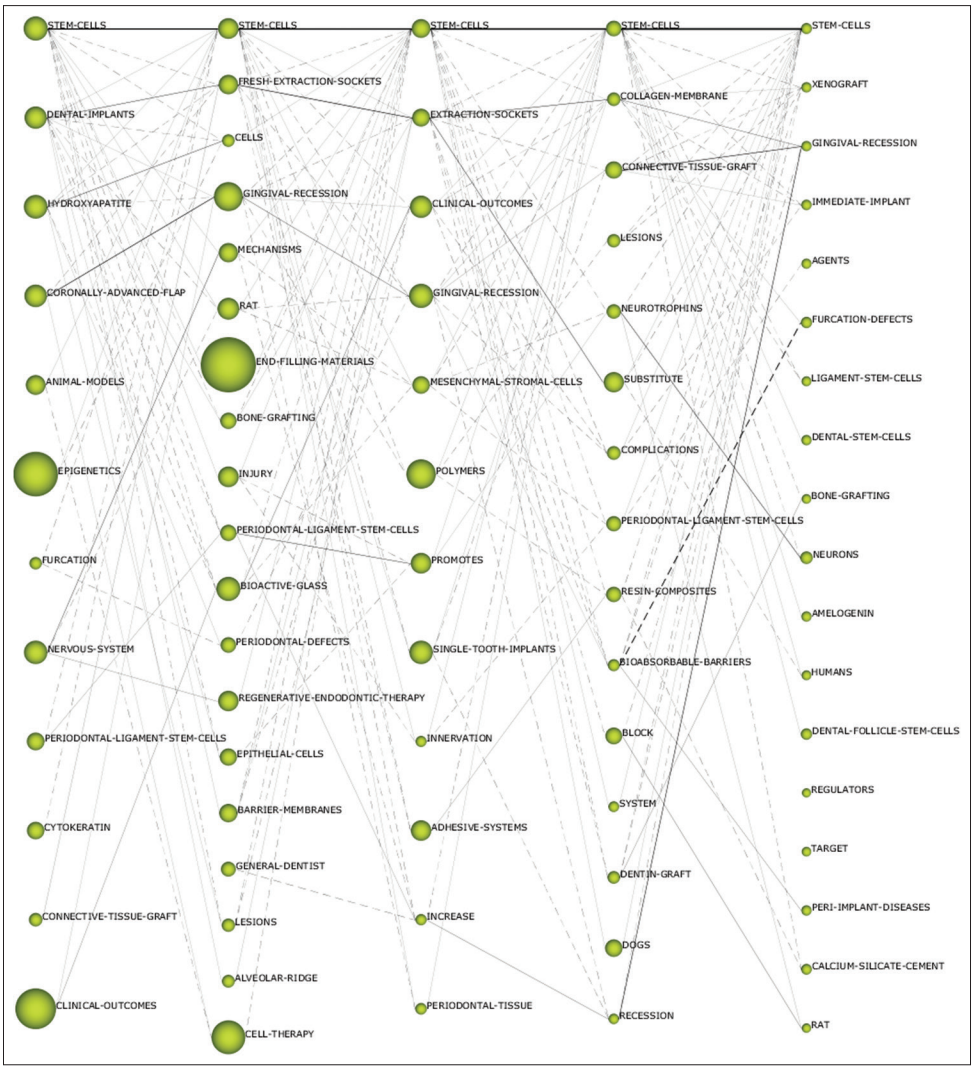

Figure 3: Thematic evolution of the dental pulp regeneration research field (2013–2023) based on average citation.

respectively. The cytokeratin, coronally advanced flap, and epigenetic clusters had the highest density with 112.5, 72.18, and 50, respectively. In other words, the stem cells, dental implants, and hydroxyapatite clusters were the most important in the overall advancement of the dental pulp regeneration field during this period, while the cytokeratin, coronally advanced flap, and epigenetic clusters had the highest level of development in the dental pulp regeneration knowledge network from 2013 to 2015. In terms of quantity, the highest research focus was on the stem cells, dental implants, and hydroxyapatite clusters, which aligns with the centrality index. However, in terms of citations, the epigenetic cluster has been one of the most important topics in this field with an average of 94.67 citations, followed by the stem cell cluster with 40.25 and the hydroxyapatite and nervous system clusters with an average of approximately 38.5 citations. Based on the thematic strategic diagram between 2013 and 2015, the clusters of coronally advanced flap, nervous system, and animal models were located in the motor quadrant and not only developed well but also are vital for the structure of research in dental pulp regeneration. Cytokeratin, epigenetic, and clinical outcome clusters are located in the highly developed and isolated quadrant. In other words, they have a very specialized and peripheral nature. Clusters of stem cells, hydroxyapatite, and dental implants, despite the importance of the topic in the research field of dental pulp regeneration, are not fully developed and are placed in the basic and transversal quarters. The connective tissue graft cluster is placed in the emerging or declining quarter. Despite the placement of each cluster in different quarters, there is a difference in terms of the number of productions and the amount of reference

Table 2: Subperiod information based on centrality, density, document counts, and average citations of each cluster

Subperiod	Cluster name	Centrality	Density	Documents count	Average citations
2013–2015	Stem cells	401.5	20.98	342	40.25
	Dental implants	247.19	21.42	109	35
	Hydroxyapatite	115.23	23.7	18	38.67
	Coronally advanced flap	49.19	72.18	4	35.5
	Animal models	34.31	30.48	3	28
	Epigenetics	5.93	50	3	94.67
	Furcation	21.79	21.53	4	8.5
	Nervous system	29.7	34.17	3	38.33
	Periodontal ligament stem cells	15.75	26.36	3	23
	Cytokeratin	17.74	112.5	1	22
	Connective tissue graft	14.62	20.31	2	11.5
	Clinical outcomes	15.72	31.77	2	84
2015–2017	Stem cells	423.07	20.69	451	30.81
	Fresh extraction sockets	116.53	23.52	38	27.82
	Cells	84.06	18.9	15	9
	Gingival recession	52.09	30.38	9	53
	Mechanisms	37.54	23.39	7	26.86
	Rat	49.86	16.87	6	33.67
	End filling materials	32.24	95.54	3	123
	Bone grafting	15.4	23.15	3	19
	Injury	17.22	14.68	4	30.75
	Periodontal ligament stem cells	27.66	61.67	3	19.33
	Bioactive glass	38.93	5.95	5	40.2
	Periodontal defects	16.97	65	2	17
	Regenerative endodontic therapy	12.14	34.17	3	30
	Epithelial cells	25.37	26.67	2	21.5
	Barrier membranes	15.71	6.25	4	24.5
	General dentist	10.16	37.5	2	15.5
	Lesions	9.88	15.28	3	11
	Alveolar ridge	14.03	7.92	3	10
	Cell therapy	14.63	10.83	3	66
2017–2019	Stem cells	435.14	19.74	528	25.99
	Extraction sockets	169.32	21.6	75	23.43
	Clinical outcomes	59.62	11.86	9	34.78
	Gingival recession	49.58	13.66	14	39.71
	Mesenchymal stromal cells	33.92	21.43	5	22.2
	Polymers	37.5	93.06	3	54.33
	Promotes	18.99	25.38	5	30.6
	Single tooth implants	26.37	22.5	6	38.33
	Innervation	21.48	43.52	2	5
	Adhesive systems	0	200	1	30
	Increase	22.79	12	4	5.5
	Periodontal tissue	19	54.17	2	6.5
2019–2021	Stem cells	405.71	17.28	604	17.2
	Collagen membrane	134.96	15.77	66	11.39
	Connective tissue graft	46.46	13.39	14	21.79
	Lesions	16.08	66.75	5	11
	Neurotrophins	24.12	35.44	4	14
	Substitute	30.45	8.15	6	29.67
	Complications	25.93	24.91	4	12.5
	Periodontal ligament stem cells	28.23	8.14	4	15.75
	Resin composites	10.68	58.33	2	16.5
	Bioabsorbable barriers	29.58	9.44	4	7.25

Contd...

Table 2: Contd...

Subperiod	Cluster name	Centrality	Density	Documents count	Average citations
	Block	10.5	63.33	2	20.5
	System	11.23	27.5	3	4.33
	Dentin graft	10.82	19.44	2	9
	Dogs	13.73	16.25	2	22
	Recession	13.29	17.36	2	3.5
2021–2023	Stem cells	381.45	13.67	1,215	4.75
	Xenograft	90.39	6.41	42	2.81
	Gingival recession	40.28	23.41	21	3.19
	Immediate implant	40.49	18.27	12	3.58
	Agents	19.12	21.67	4	2.75
	Furcation defects	18.32	8.15	6	5.33
	Ligament stem cells	12.14	17.1	4	2
	Dental stem cells	21.1	9.31	6	2.83
	Bone grafting	13.67	4.17	5	1.4
	Neurons	13.5	16.5	4	9.25
	Amelogenin	13.6	2.99	4	3.25
	Humans	9.4	4.58	5	1.6
	Dental follicle stem cells	4.32	33.33	2	6
	Regulators	2.12	15.28	3	0
	Target	14.79	19.79	2	1.5
	Peri-implant diseases	18.43	4.17	3	3
	Calcium silicate cement	15.84	5.95	3	4
	Rat	5.79	5.58	3	0.33

to the scientific productions of each cluster. These differences is drawn based on the two indicators of the frequency of the number of documents and the number of citations in Figures 4 and 5.

During the period between 2015 and 2017, the clusters of stem cells, fresh extraction sockets, and cells exhibited the highest centrality values of 423.07, 116.53, and 84.06, respectively. Similarly, the clusters of end filling materials, periodontal ligament stem cells, and regenerative endodontic therapy demonstrated the highest density values of 95.54, 61.67, and 34.17, respectively. This implies that the thematic clusters of stem cells, fresh extraction sockets, and cells played a crucial role in the overall advancement of dental pulp regeneration during this specific period. On the other hand, the clusters of end filling materials, periodontal ligament stem cells, and regenerative endodontic therapy, which exhibited the highest density, experienced the most significant level of development within the knowledge network. From a quantitative perspective, the majority of research efforts were focused on the clusters of stem cells, fresh extraction sockets, and cells, aligning with the centrality index. However, in terms of citations, the bioactive glass cluster emerged as one of the most important topics in this field, with an average of 40.2 citations. It was followed by the rat clusters with 33.67 citations and fresh extraction sockets with an average of 30.81 citations. According to the thematic strategic diagram, the clusters of end filling materials, periodontal ligament stem cells, epithelial cells, mechanisms, gingival recession, and fresh extraction sockets are situated in the motor quadrant. These clusters are not only well-established but also crucial for the research framework in dental pulp regeneration. On the other hand, the regenerative endodontic therapy and bone-grafting clusters are located in the highly developed and isolated quadrant, indicating their specialized and peripheral nature. Despite their thematic significance in dental pulp regeneration research, the clusters of bioactive glass stem cells are not fully developed and are positioned in the basic and transversal quarters. Finally, the cluster comprising lesions, cell therapy, alveolar ridge, injury, and barrier membranes is placed in the emerging or declining quarter.

From 2017 to 2019, the clusters of stem cells, extraction sockets, and clinical outcomes exhibited the highest centrality scores, with values of 435.14, 169.32, and 59.62, respectively. On the other hand, the polymers, innervation, and periodontal tissue clusters demonstrated the highest density scores, with values of 93.06, 54.17, and 43.52, respectively. In terms of citations, the polymer cluster stood out as one of the most significant topics in the field, with an

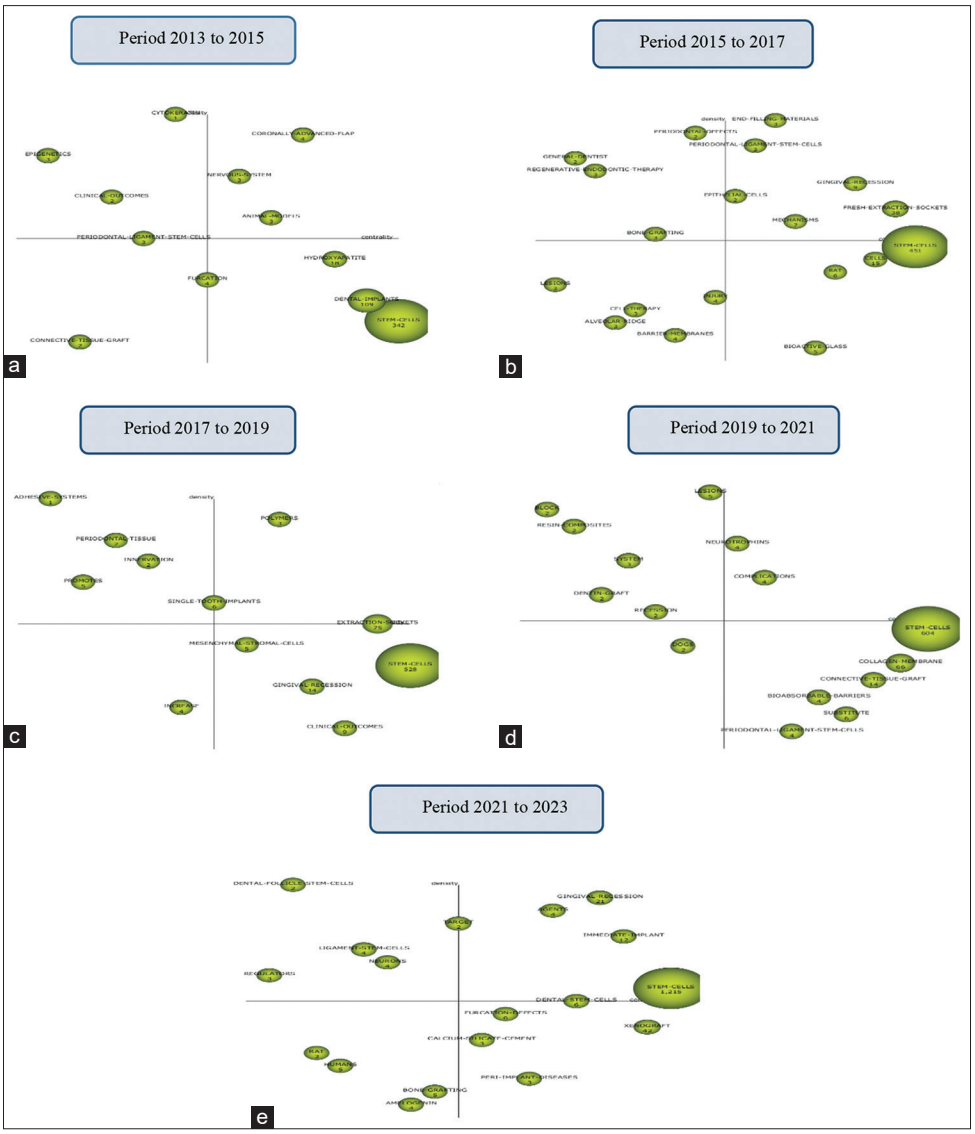

Figure 4: Strategic diagram based on number of published documents; (a) period 2013–2015, (b) period 2015–2017, (c) period 2017–2019, (d) 2019–2021, (e) 2021–2023.

average of 54.33 citations. Following closely were the gingival recession clusters with 39.71 citations and the single tooth implant cluster with an average of 38.33 citations. Analyzing the thematic strategic diagram, we observe that the polymer cluster is situated in the engine quadrant. The "Adhesive System, Periodontal Tissue, Promotes, and Innervation" clusters are located in the highly developed and isolated quadrant. Conversely, the mesenchymal stromal cell, stem cell, gingival recession, and clinical outcome clusters, despite their importance in dental pulp regeneration research, are not fully developed and are positioned in the basic and transversal quarters.

From 2019 to 2021, the stem cell, collagen membrane, and connective tissue graft clusters have demonstrated the highest centrality values, with 405.71, 134.96, and 46.46, respectively. Similarly, the lesion, block, and resin composite clusters have exhibited the highest density, with values of 66.75, 63.33, and 58.33, respectively. These findings emphasize the significance of these clusters in the field. In terms of citations, the substitute cluster has emerged as one of the most important topics, with an average of 29.67 citations. It is closely followed by the connective tissue graft clusters with 21.79 citations and the block cluster with an average of 20.5 citations. The thematic strategic diagram provides insights into the positioning of different clusters. The neurotrophin and complication clusters are situated in the motor quadrant, indicating their relevance to the field. Conversely, the lesion, block, system, dentin graft, and

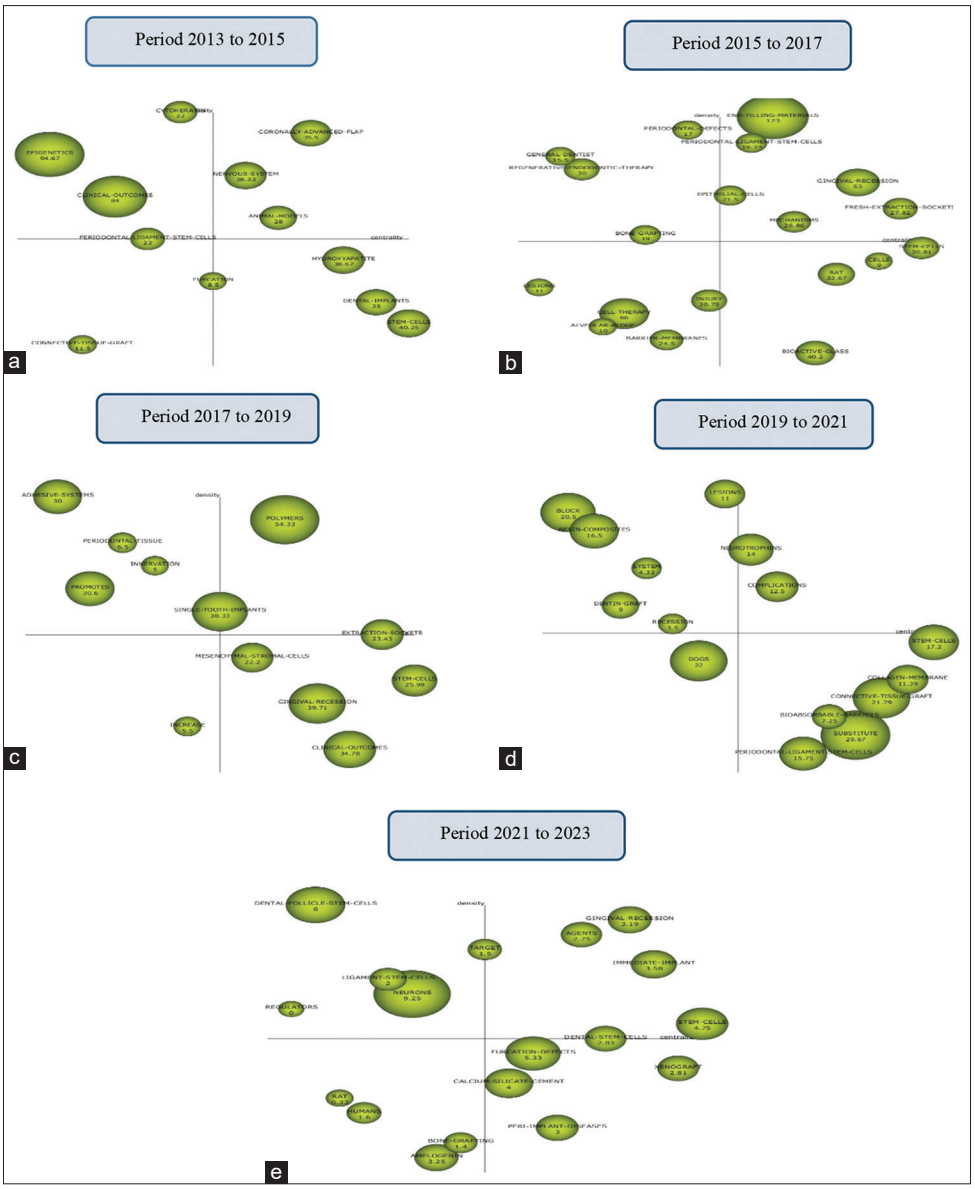

Figure 5: Strategic diagram based on number of citations; (a) period 2013–2015, (b) period 2015–2017, (c) period 2017–2019, (d) 2019–2021, (e) 2021–2023.

recession clusters are located in the highly developed and isolated quadrant, suggesting their advanced status. However, the collagen membrane, connective tissue graft, substitute, periodontal ligament stem cell, and bioabsorbable barrier clusters are positioned in the basic and transversal quarters, indicating that they are not fully developed despite their importance in dental pulp regeneration research. These clusters necessitate further exploration and development to unlock their full potential.

In the period from 2021 to 2023, stem cell, xenograft, gingival recession, and immediate implant clusters have the highest centrality with 381.45, 90.39, 40.28, and 40.49, respectively, and dental follicle stem cell, gingival recession, and agent clusters. They have the highest density with 33.33, 23.41, and 21.67, respectively. In terms of citations, the findings show that the neuron cluster with an average of 9.25 citations was one of the most important topics in this field, followed by furcation defect clusters with 5.33 citations. Based on the thematic strategic diagram, stem cell, gingival recession, immediate implant, and agent clusters are located in the engine quadrant. Ligament stem cell, neuron, dental follicle stem cell, and regulator clusters are located in the highly developed and isolated quadrant. Xenograft, furcation defect, peri-implant disease, and calcium silicate cement clusters are not fully developed

despite their importance in the research field of dental pulp regeneration and are placed in the basic and transversal quarters. Bone grafting and amelogenin clusters are placed in the emerging or declining quarter.

DISCUSSION

The purpose of this study was to create a comprehensive scientific overview of knowledge production in the area of dental pulp regeneration. The findings regarding the overlapping map and the conceptual completion of the subject area of dental pulp regeneration show that over time, the number of keywords has increased. Likewise, there has been an increase in the number of shared keywords between consecutive subperiods. For instance, there were 306 shared keywords between the first and second subperiods, and this number grew to 428 between the fourth and fifth subperiods. Moreover, the similarity index also increased across the subperiods, from 0.57 between the first and second subperiods to 0.69 between the fourth and fifth subperiods. These findings indicate that researchers in the field of dental pulp regeneration are establishing a more consolidated terminology. However, it is worth noting that there is a significant presence of new and transient keywords. This means that there are a considerable number of keywords that are only used in one subperiod and not in subsequent periods. For example, in the fourth subperiod (2019–2021), out of a total of 118 new keywords, 39 were identified as transient keywords.

Findings regarding thematic evolution, based on the number of articles, show that stem cells are not only very important in dental pulp regeneration, but their importance is increasing day by day. Stem cells are undifferentiated cells and can differentiate into various types of vascular cells, nerves, fibroblasts, etc., As a result, the subject of stem cells is related to almost all other subjects related to the restoration of the dental pulp and even the restoration of the periodontium and is the focus of research.

Compared to the number of published documents, the findings show that from the citation point of view, the topic of stem cells has a lesser role and even decreases from period to period. The reason can be the obvious role of stem cells in pulp and periodontium regeneration and its generality in most research. But here other issues become more prominent. Epigenetics is directly related to stem cells and includes gene changes that cause the proliferation and differentiation of stem cells into different types of cells. Clinical outcome is related to furcation and bioactive glass, and bioactive glass itself is related to clinical outcome. The importance of bioactive glass is in vital pulp therapy. End filling material is very important, but it is not related to another issue. Its importance is also in pulp regeneration in teeth with immature apex.

By analyzing data from five different periods over the past decade (2013–2023), it was observed that the topic cluster of the animal model was well-established during the years 2015–2013. This is because preclinical tests are necessary for dental pulp regeneration, and rat and dog teeth were commonly used in these studies.[23] Another crucial area of research focused on the nervous system, as regenerating nervous tissue is a complex and challenging biological process. Since the regeneration of dental pulp also requires the regeneration of nerve terminal clusters, research in this field is of utmost importance. It was found that Dental pulp stem cells (DPSCs) have the potential to transform into neural cells through proliferation and differentiation.[24] The clusters related to epigenetics and clinical trials were situated within the motor theme. Epigenetics, in particular, played a significant role in the development of knowledge regarding pulp regeneration. This cluster also had the highest emission rate, indicating its importance. Epigenetic modulations lead to changes in the gene content of DPSCs, which in turn promote their proliferation and differentiation into various types of cells such as vascular and nerve cells.[25,26] Epigenetics has proven to be effective in the regeneration of dental pulp in cases of reversible pulpitis.[27] While clinical outcomes are of utmost importance, it is crucial to examine theoretical findings at the patient's bedside and test the success rate of the pulp regeneration process. Stem cell and hydroxyapatite clusters are key components in this field. Stem cells, in particular, play a fundamental role in pulp regeneration and have shown the highest centrality and overall significance in the progress of this field. In addition, a significant number of research studies have focused on stem cells. Dental pulp stem cells (DPSCs) are essential in the regeneration of lost dental pulp as they possess the ability to grow and differentiate into various cell types within the dental pulp tissue.[28-30] Hydroxyapatite, on the other hand, is an important but relatively underdeveloped topic that ranks second in terms of

centrality. Regenerating dental pulp requires three essential factors: stem cells, growth factors, and a network or scaffold.[31] Hydroxyapatite, in its various forms, can aid in the absorption of materials and cells by forming a network within the pulp space.[32] Furthermore, it can also be utilized for direct pulp cap procedures.[33]

Between 2015 and 2017, the motor theme section focused on the topic of end filling material, which was considered to be of utmost importance and highly developed. This issue held significant relevance in the treatment of immature teeth requiring root canal treatment. When the pulp tissue is removed from the canals for root canal treatment in these teeth, it is common practice to fill them with either calcium hydroxide or MTA. However, this approach halts the growth and development of the root, leaving the tooth apex exposed. Alternatively, pulp regeneration can be pursued. This involves inducing apical bleeding and forming a blood clot to create a seal in the apical canals, allowing the roots to continue developing. Within the realm of end filling material, the focus lies on determining the best material for achieving an apical seal.[34] In the highly developed and isolated theme quadrant, the regenerative endodontic therapy cluster was situated, representing an independent and specialized area of study. Stem cell and bioactive glass clusters were located in the basic and transversal quadrants, with stem cells being the most prominent in terms of centrality and number of articles during this period. Detailed explanations were provided regarding stem cells, while bioactive glass, which had the highest citation rate, was suggested as a potential scaffold material, although further research and investigation were required.[35] It is worth noting that bioactive glass also had other applications, such as direct pulp caps. Following the bioactive glass cluster, the rat cluster received significant citations, primarily focusing on animal trial subjects.

During the period from 2017 to 2019, the field of polymers was situated within the motor theme quadrant and emerged as a significantly crucial and advanced subject. Among all the clusters, the polymer cluster exhibited the highest density and citation count, indicating its utmost significance. This particular cluster holds great importance because polymers are recommended materials for scaffold construction. The utilization of polymeric scaffolds, in conjunction with stem cells known as DPSCs, facilitates cell attachment, cell proliferation, and angiogenesis.[36,37] In the quadrant characterized by highly developed and isolated themes, clusters related to adhesive systems and promotion were identified. The adhesive system cluster's significance can be attributed to its association with direct pulp cap treatment, which likely contributed to its emergence within this cluster.

From 2019 to 2021, the motor theme focused on neurotrophins and their associated complications. Neurotrophins, which are proteins present in both the brain and peripheral tissues, play a crucial role in stimulating the growth of nerve cells and damaged cells.[38] Consequently, they are essential for the reconstruction of tooth pulp. The complications arising from this process include the response of the pulp tissue, the materials utilized, the clinical response, and the patient's overall response. It is of utmost importance to identify and address these complications effectively. In the highly developed and isolated theme quadrant, clusters of lesions, blocks, and systems are situated. Within this range, lesions exhibit the highest density. Apical lesions can significantly impact the treatment of pulp regeneration and influence the prognosis of the tooth. However, Schmalz *et al*. were able to successfully perform pulp regeneration in a tooth with a preexisting lesion.[39]

Between the years 2021 and 2023, the motor theme section housed stem cells and agents. Notably, during this period, stem cells made their way into the motor quarter, signifying significant advancements in research within this cluster. The cluster transitioned from an undeveloped state to a developed one. Within the highly developed and isolated theme quadrant, clusters such as ligament stem cells, neurons, dental follicle stem cells, and regulators were present. The presence of dental follicle stem cells and ligament stem cells as separate clusters within this section indicates that these subsets of stem cells have been extensively studied and given importance in different periods. The significance of the neuron cluster was previously mentioned. The regulator's cluster holds great specialization and importance in the field of dental pulp regeneration. Various processes involved in this treatment, such as stem cell differentiation, rely on regulatory factors.[40] In the basic and transversal theme quadrants, the calcium silicate cement cluster can be found. This cluster was proposed as a novel material for vital pulp therapy and had connections to various other topics. The importance of this cement lies in its potential use for direct pulp cap

treatment, pulp regeneration, and filling dental pulp in pulpotomy treatment, thereby preserving the vitality of the remaining dental pulp.[41,42]

In general, it has been observed that the stem cell cluster consistently had the highest number of articles across all periods. As we progressed through time, the significance of this cluster continued to grow, eventually becoming a crucial component in the motor theme during the last period. In addition, a significant portion of the studies conducted during different periods focused on identifying suitable materials for scaffold formation. Various materials, including polymers and bioactive glasses, were proposed as viable options for scaffold formation in different periods. Another area of emphasis in the research was the study of different types of cells and their formation processes. Understanding how these cells are formed and their characteristics was a key aspect of the research conducted during various periods. Finally, growth factors and regulators, such as the cluster of regulators that play a vital role in dental pulp regeneration, were also given considerable attention in different periods. It is anticipated that these factors will continue to gain importance in future studies related to pulp regeneration.

CONCLUSION

Further investigations are required to advance dental pulp regeneration despite the extensive research conducted on this topic. Dental pulp stem cells (DPSCs), scaffold networks, growth factors, and regulatory factors are the three main factors that influence dental pulp regeneration. These factors play a crucial role in absorbing different materials and cells, providing a scaffold for regeneration, and promoting the growth and regulation of dental pulp. By analyzing maps and thematic clusters in dental pulp regeneration research, as well as considering indicators such as repetition frequency, centrality, and citation of these clusters, researchers can identify the strengths, weaknesses, and gaps in current research. This analysis can inform future research policies and enhance the effectiveness of dental pulp regeneration studies.

Data availability statement

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Ethics approval statement

This study was approved by ethics in research of Golestan University of Medical Sciences (IR.GOUMS.REC.1402.498).

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Conflicts of interest

The authors of this manuscript declare that they have no conflicts of interest, real or perceived, financial or non-financial in this article.

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