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New Ways of Materials Engineering Implementation in the Selection Processes of Biomaterials Intended for the Production of Dental Implants – Narrative Literature Review

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The usage of knowledge obtained by connecting various scientific areas provides new opportunities for developing multidisciplinary branches to improve processes, procedures, technologies, and products. The present paper is devoted to the description of new approaches to material engineering and its possibilities in the process of the selection of materials intended for the production of dental implants. To ensure the conciseness of the article, a selection of state-of-the-art of scientific contributions is created in the introductory part in the form of a summary table, based on which the following parts of the article are elaborated. The first view of new ways of materials engineering is provided through the elaboration of the categorization of the setting of biological materials used in the production of dental implants, while taking into account current trends, technologies and findings. The second view of new ways of materials engineering is an extended complex process of selection and implementation of biomaterials intended for the production of dental implants originally created and adopted by the American Dental Association. Future studies should investigate the comprehensive analysis of technologies for the production of dental implant materials and also analysis of ways of digitization in the production of dental implants.

Keywords: smart biomaterials, dental implants, American Dental Association, engineering.

1. INTRODUCTION

Materials engineering is currently one of the fastest developing and most promising branches of technical sciences, which focuses primarily on the topic of materials in the context of research, development, design of their most suitable properties, identification of modern technological processes for their processing, control of their properties and qualities in concurrence with the possibilities of their most appropriate implementation [1]. The above-mentioned topic of material engineering is dynamically developing not only as a separate branch of technical sciences in the field of engineering, chemistry, medicine and the like, but also as an interdisciplinary technical science combining industrial biotechnology, engineering, medical engineering and others. The interdisciplinary nature of material engineering is supported by current and modern research [2, 3], which requires a broad-spectrum perception of the topic, while involving multidisciplinary knowledge of an interdisciplinary nature in cooperation with high expertise and compatibility of researchers of several scientific disciplines. The field of interdisciplinarity of materials engineering undoubtedly includes dental implantology, which requires the expertise of teams consisting primarily of doctors, material engineers and technologists [4]. The field of dental implantology deals with the introduction of allogeneic biocompatible material to the bone surface or into the bone of the upper and lower jaw, its fixation and preservation in this environment and subsequently with the production of specifically designed fixed and removable dentures. In the field of dental implantology concentrates on three main areas of interest. The first area includes exploring the implant surface topography to establish the degree to which the surface in the structure, coating and especially the adhesion of the applied materials can be influenced. The second area includes the development of new implants and the third area embraces material engineering itself [5, 6]. The topicality of the subject matter with a wide range of solutions is also confirmed by the summary state-of-the-art (Table 1) that was created.

The importance of the presented research review is also based on the analysis of the number of currently published research in related fields (e. g. more than 24,000 publications were published in the Web of Science database), thereby confirming its timeliness and continuous development of multidisciplinary issues. This article also points to gaps in the publication of more extensive publications, scientific monographs, and scientific books that would summarize the previous knowledge based on of which future studies could be carried out.

2. CLASSIFICATION APPROACHES FOR BIOMATERIALS APPLIED IN DENTAL IMPLANTS

In the production of dental implants, the implant material itself plays an important role, which belongs to the so-called biomaterials, i.e. synthetically prepared substances used to replace the soft and hard tissues of the human body.

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Table 1. Interdisciplinary nature of scientific disciplines of materials engineering and dentistry – up to date

Authors	Short description of research
Abraham, A.M., Venkatesan, S. (2022) [7]	Descriptive categorization of bio-implants specifying their properties as far as their mechanical and biological agents are concerned.
Hosseini-Faradonbeh, S.A., Katoozian, H.R. (2022) [8]	Summary of biological and mechanical attributes specified in 9 categories when assessing the long-term stability of implants using the finite element method.
Khened, V., Bhandarkar, S., Dhatrak, P. (2022) [9]	The use of mathematical methods (Taguchi, ANOVA, Pareto) for modeling dental implants with a focus on creating a rationalized thread design solution.
Jambhulkar, N., Jaju, S., Raut, A. (2022) [10]	Identification of dental implant surface treatments and their comparison in order to summarize general information on the possibilities of suitable technology for surface treatment in dental implantology.
Sharma, D., Mathur, V.P., Satapathy, B.K. (2021) [11]	Creating an overview of the currently used production processes focusing on designing appropriate structures and 3D constructions for clinical trials with subsequent implementation in dentistry.
Anjum, S., Rajasekar, A. (2021) [12]	Summary of engineering technologies applied in the surface treatment of dental implants focusing on improving the interaction of implant and tissue, specifically for research of modification of existing techniques as well as the design of biomaterials.
Kittur, N., Oak, R., Dekate, D., Jadhav, S., Dhatrak, P. (2021) [13]	An overview of approaches to measuring the stability of dental implants in order to present various methods that need to be correctly implemented to guarantee its accuracy, thus ensuring a subsequent higher value in the recovery process.
García-González, M., Blasón-González, S., García-García, I., Lamela-Rey, M.J., Fernández-Canteli, A., Álvarez-Arenal, Á. (2020) [14]	Summary of information on fatigue testing options for dental implants with specifications for software support.
Kessler, A., Hickel, R., Reymus, M. (2020) [15]	Definition of the current overview of printing technologies and techniques focusing on the definition of appropriate materials for the field of dental implantology with clinical implementation.

These materials are thus used in close or direct contact with the human body and serve to enlarge or replace defective parts or materials [16].

It is the suggestion, that for the needs of material bioengineering, biomaterials based on the method of cooperation of the material with living tissue are divided into the following 4 basic groups [17]:

- biotolerant biomaterials;
- bioinerts biomaterials;
- bioactive biomaterials;
- smart biomaterials.

The group of biotolerant materials includes alloys of general and noble metals, which have high quality material properties. They are biologically tolerated by tissues, but they are subject to corrosion, whereby the gradual release of metal into the human body results in metallosis with negative consequences. They are more suitable for short-term implantation [18]. This group includes materials such as Bioker (Au, Pt, Zn, Ir, In), Dentor BIO (Au, Pt, Ag, Cu), or Auropal S (Au, Pd, Ag, Cu, Zn) [19].

Bioinert materials are used when it is necessary to prevent an adverse immune reaction of the body or the formation of a blood clot. They are made of, for example, eye lenses, heads and sockets of joint prostheses, vascular prostheses, heart valves or carriers for the transport of medicaments. The most commonly used bioinert materials include mainly aluminum oxide ceramics, technically pure titanium or its alloys such as Ti-6Al-4V. Also is to possible to include in this category for example Leucite ($KAlSi_2O_6$) or Spinel ($MgAl_2O_4$) [20].

Bioactive materials provide a suitable basis for cell deposition and can form strong direct bonds with the living environment. They promote and regulate cell adhesion, migration and proliferation.

These include some types of metals, bioactive ceramics, glass ceramics, and some types of polymers, for example, Biodentine (Fig. 1), ProRoot MTA, and Predicta Bioactive [18].

Smart biomaterials are able to provide a specific change in properties depending on the change in physiological conditions (pH, temperature, light radiation, humidity). Smart biomaterials include specific smart alloys, composites and ceramics [22]. An important representative of this group are compomers (compound of words ionomer and composite), which are specific in that they release partial fluoride in precisely defined and necessary amounts. In addition, commercially developed compomers can bind fluoride in the form of compounds that ensure the release of separate ions under clinical conditions. Representatives of compomer materials for use in dentistry include, for example, Dyract or F2000 compomer [23] with the most frequent use as root-end filling materials, while it is important to investigate their properties such as adhesion [24] or shear bond strength [25]. Another example of representatives of smart biological dental materials, can be mentioned zirconium dioxide – cercon [26].

In addition to compomers, shape memory alloys are also very often used. These materials are generally characterized by the ability to regain their original shape after previous macroscopic deformation. The acquisition of the original shape form after the implementation of the necessary temperature above the threshold critical level with subsequent cooling [27]. One of the representatives of the Smart biomaterials-shape memory alloy for dental implants category is NiTi shape memory alloy, also known as Nitinol. This specific dental material was subjected to a comprehensive investigation and research of mechanical and microstructural properties in the form of $Ni_{50}Ti_{49.5}$ for the use in biomedicine, where the obtained conclusions were described in 2019 and interpreted in the journal Materials Science & Engineering C [28]. Assessment of the basic properties of the material is necessary for subsequent research into the possibility of its production, prediction, modification, machining and application. For example, research by a group of authors from Germany was devoted to the issue of production and subsequent processing, who described the sequence of the production process and the comparison of the effects of individual steps on the resulting properties of the material [29]. Also based on of the above-mentioned research, it is subsequently possible to implement modifications of materials for practical applications. An example is guided nitinol-retained (Smileloc) Single, which as a modification of general nitinol was implemented during tooth dental restoration in practice and documented by publication in the Oral and Maxillofacial Surgery Clinics [30].

Extended classification (Fig. 2) is created based on the latest findings from the literature review, and in the opinion of the authors of this article, it is necessary to extend and process the new classification for dental materials, namely the extension by the "smart" category. This category includes materials based on alloys, ceramics, and composites, but also partial parts of materials in the form of fibers, and materials used for the production of coatings for dental implants.

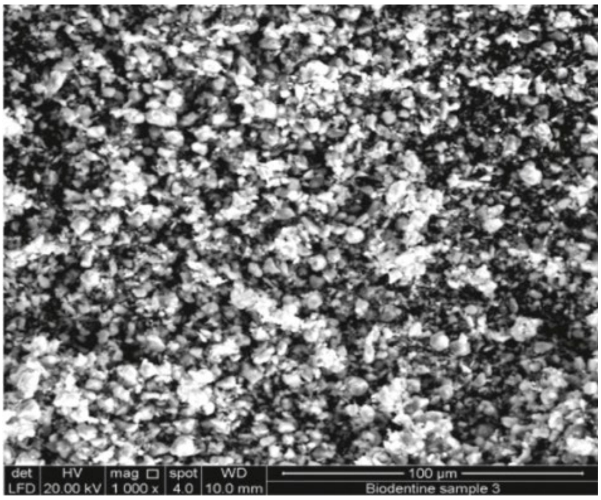

Fig. 1. SEM of Biodentine (×1000) [21]

Biomaterials can also be classified based on the type of material (Fig. 3).

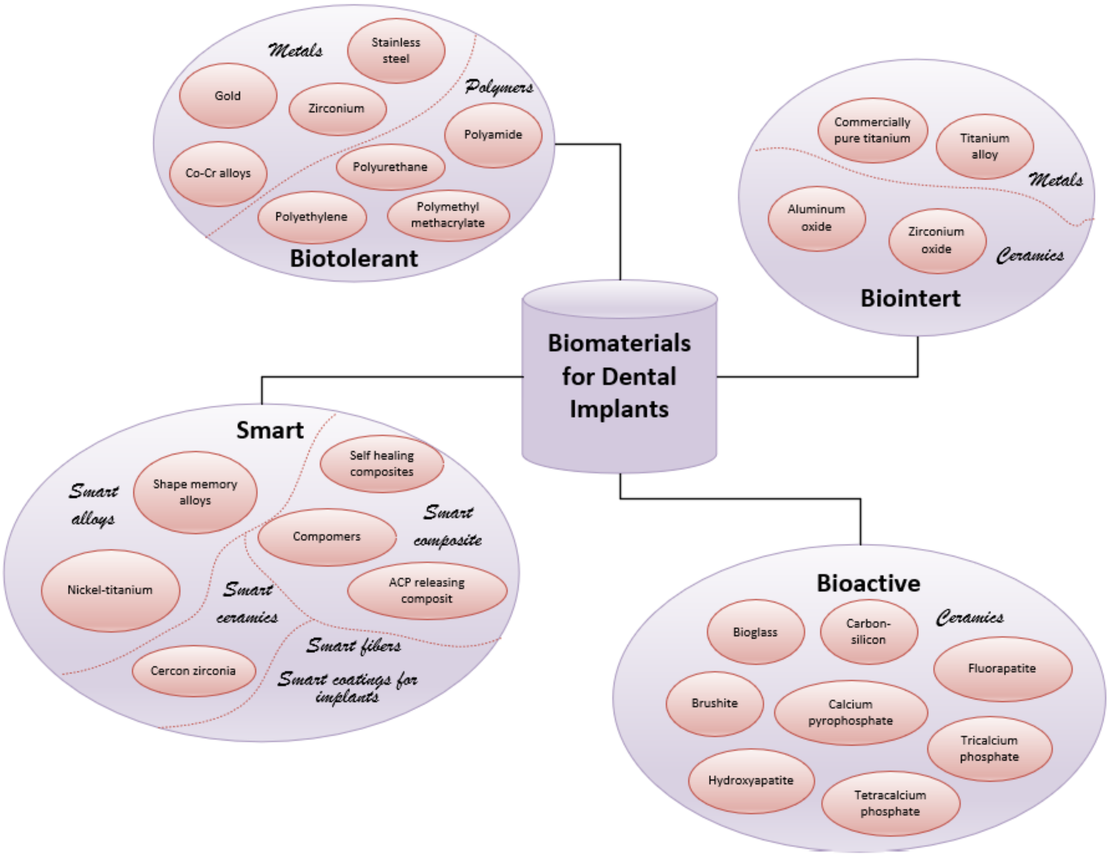

Fig. 2. Extended classification of biomaterials used in dentistry with examples

According to this classification, the following main groups of biomaterials are identified [31]:

- metallic biomaterials;
- bioceramics;
- polymeric biomaterials;
- composite biomaterials.

Metallic biomaterials are used due to their high mechanical resistance to wear and impact, high strength and toughness. Their disadvantage is the low corrosion resistance in contact with the physiological environment. Another disadvantage is the much higher value of Young's modulus of elasticity as compared to the human bone. Examples of metals used in medicine are Ag, Au, Ti and its alloys, stainless steel and Co-Cr alloys.

The main reason for the implementation of bioceramics in dentistry is their high biocompatibility. Based on the available research, for dental implants, the application of aluminium oxide (Al_2O_3) or zirconium oxide (ZrO_2) is the most appropriate. The disadvantages of ceramic materials include high brittleness, low tensile strength and low elasticity.

Polymeric biomaterials are biocompatible materials that are used to produce implants. Among other properties, they are also characterized by high similarity with natural tissues. In some cases, biointegration, i.e. the connection of artificial and natural tissue, occurs. Polymeric materials are used in prosthetics and are produced in various forms: viscous liquids, fibers, films and textiles. In theory, it is possible to prepare a large number of polymers, but in practice, ten to twenty types of compounds are mainly used in medicine.

Composite biomaterials combine the most suitable properties of the metallic, ceramic, polymer and natural materials, achieving the required biocompatibility, high strength and corrosion resistance. This produces, for example, carbon composites and bone cements used in dentistry as dental substitutes.

3. POSSIBILITIES OF SELECTION AND IMPLEMENTATION OF MATERIALS USED IN THE MANUFACTURE OF DENTAL IMPLANTS

In the process of selection and implementation of materials for the production of dental implants, attention is focused primarily on their primary characteristics and properties. The American Dental Association outlines several guidelines for dental implants [32]:

- assessment of physical properties, focusing on assurance of sufficient strength;
- demonstration of production simplicity and sterilization potential without degradation of the material;
- safety and biocompatibility assessment, including cytotoxicity testing and tissue interference characteristics;
- the rectification of deficiencies;
- at least two independent long-term prospective clinical studies demonstrating efficacy.

It is appropriate to extend the above instructions for dental implants from the point of view of material engineering and bioengineering by:

- demonstration of the suitability of the selection of software solutions for creating the digital form of the dental implant concerning economic efficiency and in order to meet all the requirements determined above;
- comprehensive assessment of the risks associated with the implantation process of the selected material itself;
- demonstration of the control process of manufactured dental implants following determined requirements and regulations;
- partial focus on design solutions – the creation of at least two alternative design solutions for implant design (design and marketing perspective on the topic).

The synergy of the above as well as the proposed instructions (guidelines) for the dental implants production process can achieve a complex sequence within the implementation process from the research and development phase to the regeneration phase.

4. MINI REVIEW IN MATERIALS ENGINEERING AND ITS POSSIBILITIES IN THE SELECTION PROCESSES OF MATERIALS INTENDED FOR THE PRODUCTION OF DENTAL IMPLANTS

To ensure a comprehensive summary of the topic, an analysis of scientific studies on the topic under review was also carried out, which were published in renowned scientific databases WoS and Scopus. The survey was prepared on 06 September 2022, from the beginning of the millennium (2000 – 2021), which is associated with the rapid development of science and technology, in conjunction with the increase in the development of new materials, technologies, methods and processes.

The Web of Science database was analyzed in accordance with the conceptual framework of the aspects of materials, dental implants and the selection process. Over the chosen period, more than 24,000 publications were published in the Web of Science database on the respective topic, while continuous monitoring indicates the increasing trend of research (Fig. 4). This increasing trend is conditioned, among other things, by better availability of new materials as well as possibilities of carrying out research in the field of materials engineering.

During the analysis of publications in the Web of Science database, the attention was also focused on the analysis of documents by type. In the analyzed period, documents of the article's type have the highest representation with over 88 % share.

Reviews on the subject matter represent approximately 7.5 % of the total publications and the third most frequently represented type of documents publishing research results and scientific ideas of the subject matter are Proceeding Papers with more than 6.5 % share. However, the analysis of publications by document type (Fig. 5) indicates a significant gap in the publication of more extensive scientific works, such as books, as only two voluminous scientific books were published in the analyzed period.

From the point of view of the conducted analysis, a very significant attribute – the field (category) of research – was included as the third aspect. This analysis (Fig. 6) monitored the basic areas in which publications were categorized.

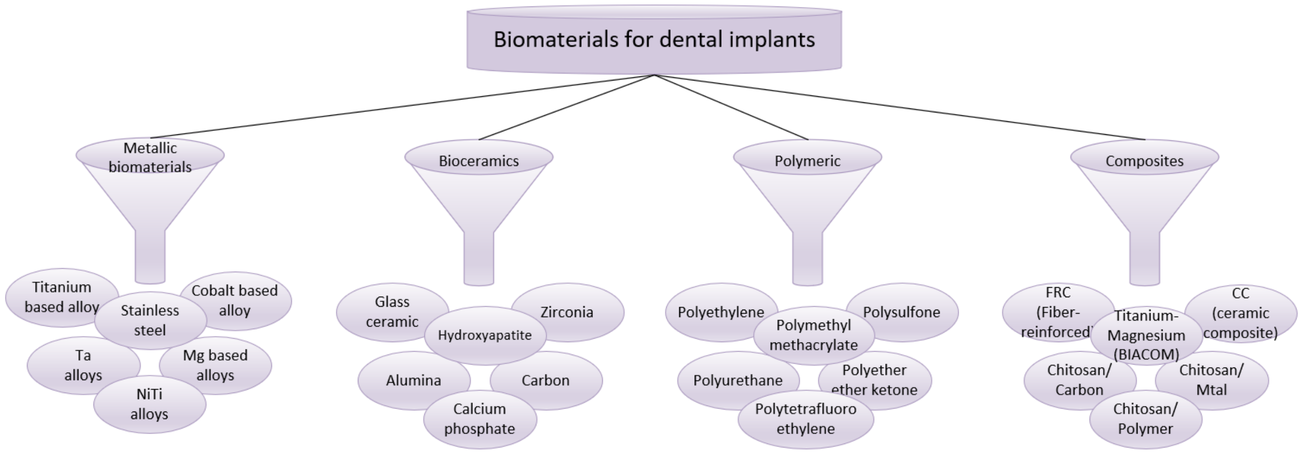

Fig. 3. Examples of biomaterials for dental implants

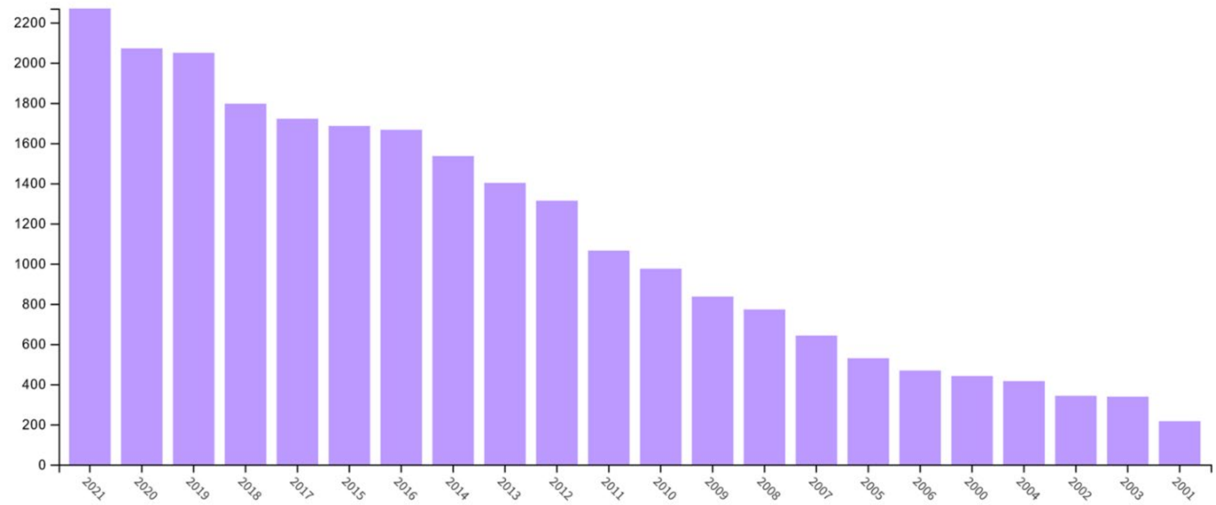

Fig. 4. Development of the number of publications on the subject in the Web of Science database

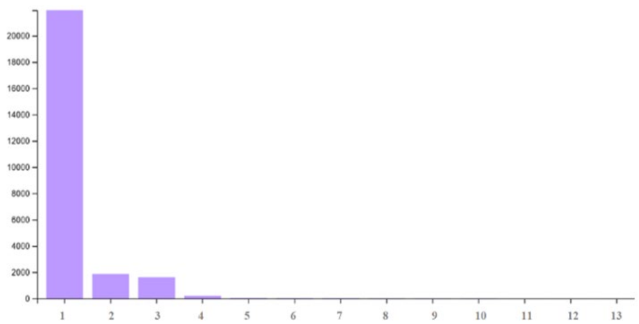

Fig. 5. Development of the number of publications on the subject in the Web: 1 – article; 2 – review article; 3 – proceeding paper; 4 – book chapters; 5 – editorial material; 6 – meeting abstract; 7 – early access; 8 – retracted publication; 9 – correction; 10 – letter; 11 – book; 12 – news item; 13 – reprint

As expected, the largest share included the category of "Dentistry Oral Surgery Medicine" representing up to 60 % of published sources. The interdisciplinarity of the analyzed topic can also be confirmed based on of this analysis, as the second most published category is "Engineering Biomedical" with more than 20 % followed by the area of the combination of material engineering and biological sciences "Materials Science Biomaterials" representing 15 %.

The review of the Scopus database was carried out with the same input conditions as the previous database due to the subsequent possibility of a deeper comparative analysis of both databases. More than 60,000 publications on the respective subject are registered in the Scopus database in the analyzed period, with an average annual increment of more than 2,500 publications. Looking at the graphical interpretation of the development of the number of publications (Fig. 7), a significant upward trend in the publication of new information and achieved results can be observed, which, as mentioned above, is conditioned, among others, by better availability of new materials or possibilities of conducting research in the field of materials engineering.

The conceptual analysis of the second aspect of the second database was also devoted to the analysis of the publications from the perspective of the document type for subsequent comparison (Fig. 8).

Scientific research papers represent the largest representation, with more than 47,000 publications.

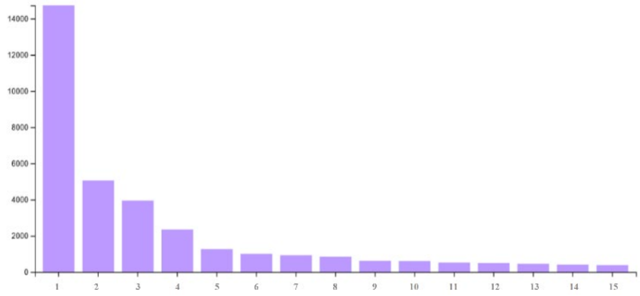

Fig. 6. Graphical interpretation of publications published on the subject in terms of research in the Web of Science database: 1 – dentistry oral surgery medicine; 2 – engineering biomedical; 3 – materials science biomedical; 4 – materials science multidisciplinary; 5 – physics applied; 6 – metallurgy metallurgical engineering; 7 – chemistry physical; 8 – physics condensed matter; 9 – materials science ceramics; 10 – medicine general internal; 11 – surgery; 12 – nanoscience nanotechnology; 13 – materials science composites; 14 – chemistry multidisciplinary; 15 – medicine research experimental

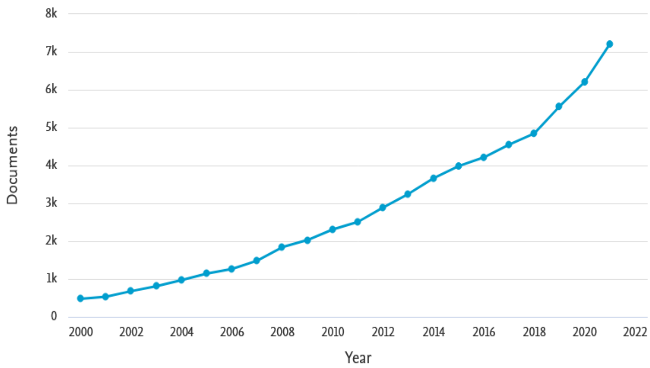

Fig. 7. Development of the number of publications on the subject in the Scopus database

Reviews of professional works, summaries of findings and mini reviews represent almost 8,000 articles in the analyzed period, and the third most extensive representation are the chapters in professional books amounting to more than 3,000.

However, higher diversity can be observed in the analysis of publications published on the subject in terms of research (categorization) (Fig. 9), with the largest number of publications included in the field of Materials Science (more than 30,000 publications). The second most frequent categorization of publications is the area of "Engineering" with more than 20,000 documents and the third most frequent area was the area of "Dentistry". Based on this analysis, it is possible to confirm the multidisciplinary nature of the topic, as the first two categories with the highest number of articles fall into the field of science and technology, and only the third category is from the field of medicine.

Based on the collected data, it is possible to carry out a comprehensive summary and comparison of the collected data for both databases. The evaluation of the development of the number of publications is carried out in tabular form (Table 2) through percentage shares for individual databases and subsequently through the overall indicator of the percentage share difference. The graphical interpretation (Fig. 10) shows the proportion of published documents in individual databases over the analyzed period.

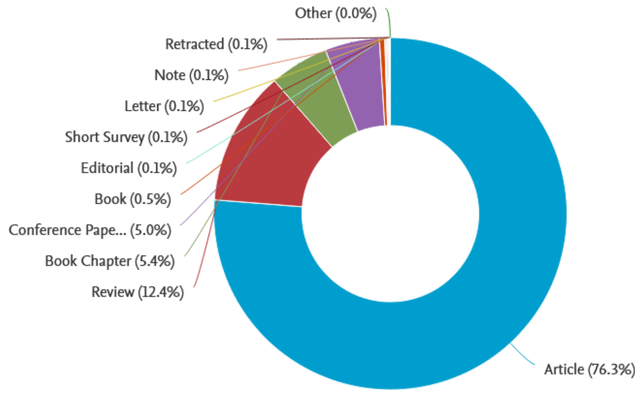

Fig. 8. Graphical interpretation of the publications on the topic in question in terms of the type of document in the Web of Science database

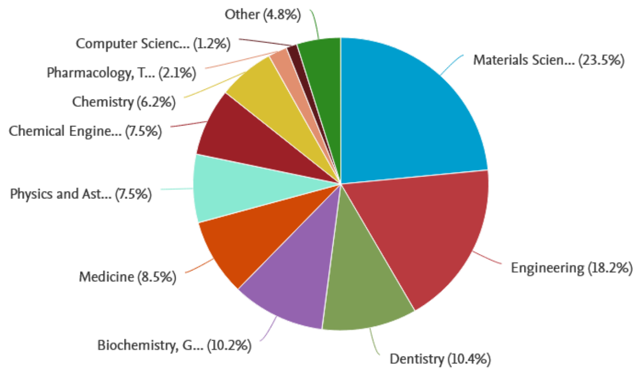

Fig. 9. Graphical interpretation of publications on the subject in terms of research in the Scopus database

From the process of comparison of the first analysis, it is clear that the total number of publications registered in the Scopus database, is several times higher, which may be influenced by several attributes (journal indexation, availability, however, in the implementation of cumulative calculations, the maximum difference in the number of publications is set at 2.30 % and the minimum at 0.03 %.

Comparison of the second analyzed parameter – the type of document (Table 3) proved unambiguous in the publication of scientific-research articles and reviews in both databases, but from the point of view of the analyzes, a significant lack of professional monographs and extensive publications in the form of books or book chapters is noticeable.

The third parameter analyzed in both cases confirms the multidisciplinary nature of the examined topic, as the publications are assigned to categories both in the field of science and technology and in the field of medical sciences. An interesting finding, however, is the fact that in the Scopus database there are more scientific publications classified with a focus on the field of science and technology Materials Science and Engineering (41.7 %) and, by contrast, in the WoS database there is a primary categorization for the areas of Dentistry and Biomedical Engineering (82.1 %).

Table 2. Evaluation of the development of the number of publications on the subject while comparing the monitored databases

Year	Number of publications		Comprehensive percentage representation		Total WoS/Scopus
	WoS database	Scopus database	WoS database	Scopus database	
2021	2269	7211	9.24 %	11.54 %	2.30 %
2020	2071	6209	8.44 %	9.94 %	1.50 %
2019	2049	5562	8.35 %	8.90 %	0.56 %
2018	1796	4849	7.32 %	7.76 %	0.45 %
2017	1721	4554	7.01 %	7.29 %	0.28 %
2016	1666	4216	6.79 %	6.75 %	0.04 %
2015	1685	3987	6.86 %	6.38 %	0.48 %
2014	1535	3663	6.25 %	5.86 %	0.39 %
2013	1402	3249	5.71 %	5.20 %	0.51 %
2012	1313	2892	5.35 %	4.63 %	0.72 %
2011	1065	2512	4.34 %	4.02 %	0.32 %
2010	975	2311	3.97 %	3.70 %	0.27 %
2009	836	2032	3.41 %	3.25 %	0.15 %
2008	772	1843	3.15 %	2.95 %	0.19 %
2007	642	1487	2.62 %	2.38 %	0.24 %
2006	468	1266	1.91 %	2.03 %	0.12 %
2005	529	1146	2.16 %	1.83 %	0.32 %
2004	415	973	1.69 %	1.56 %	0.13 %
2003	338	812	1.38 %	1.30 %	0.08 %
2002	342	681	1.39 %	1.09 %	0.30 %
2001	216	534	0.88 %	0.85 %	0.03 %
2000	441	478	1.80 %	0.77 %	1.03 %

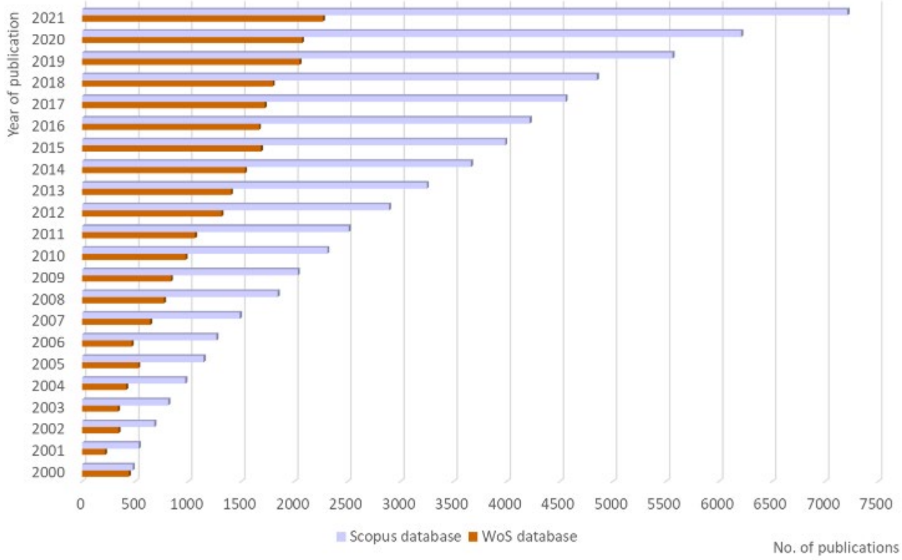

Fig. 10. Proportion of published documents in individual databases over the analyzed period

Table 3. Comparison of publications by document type

Document type	Number of publications		Percentage representation	
	WoS database	Scopus database	WoS database	Scopus database
Article	21936	47638	89.37 %	76.26 %
Review article	1874	7720	7.63 %	12.36 %
Proceeding/Conference paper	1618	3115	6.59 %	4.99 %
Book chapters	220	3371	0.90 %	5.40 %
Book	2	308	0.01 %	0.49 %

5. CONCLUSIONS

The article provides the latest summary of findings in the field of material bioengineering for medical applications with a focus on dental implants. Based on these findings and the implemented state-of-the-art, in the first part, a modification of the categorization of biomaterials was created with their extension to smart biological materials for dental applications. Subsequently, in the second part, an expanding framework of the guideline of the American Dental Association (the largest and oldest association of dentists committed to the public's oral health, ethics, science, and professional progress) was created, focusing on the issue of material bioengineering and technology. The presented article points to the continuous development of interdisciplinary sciences, which are progressing in synergy with science and research, and therefore there is a need to innovate and disseminate them, also by supplementing the conducted research or theoretical-analytical studies.

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