World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

Check for updates

Utilization of laser technology in surface coating of zirconia implants: Scoping review

Tsabitah Azzahra [1], Ailsa Marvalodya [1], Devy Putri [1], Dyva Amalia [1], Nabila Pramadhani [1], Nadya Javany [1], Nakhwah Ulayyah [1], Putri Alfa [1], Rizky Alif [1], Ryan Syahbana [1] and Anita Yuliati [2,*]

[1] *Magister Program, Dental Health Sciences, Faculty of Dental Medicine, Universitas Airlangga, Surabaya, Indonesia.*
[2] *Department of Dental Material, Faculty of Dental Medicine, Universitas Airlangga, Surabaya, Indonesia.*

World Journal of Advanced Research and Reviews, 2025, 26(01), 1040-1066

Publication history: Received on 09 December 2024; revised on 02 February 2025; accepted on 05 February 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.26.1.0196

Abstract

Background: Zirconia is a leading material in dental implantology, known for its high biocompatibility, good esthetics, and corrosion resistance. However, zirconia implants face major challenges in osseointegration due to their relatively smooth surface properties. Laser surface modification is an attempt to improve the performance of zirconia implants. **Objective:** identify the role of laser technology in the fabrication of zirconia implants.

Methods: Search in electronic databases in the form ofWiley Online Library,PubMed, Scopus, and BMC with the keyword "laser technology AND implants AND zirconia"with a period of time when the journal was published in the last 5 years.

Conclusion: Laser technology has been proven to effectively improve the mechanical and biological properties of zirconia dental implants to prevent peri-implantitis and increase stability.

Keywords: Zirconia Implant Surface; Surface Modification; Zirconia Surface Treatment; Laser Treatment Implant; Laser Modified Implant

1. Introduction

In recent years, the understanding of dental biomaterials has increased manifold, as there is potential for bioengineering of tissues and organ systems. The response of cells and tissues to implants is controlled by the surface properties of biomaterials and the combination of biological prosthetics and tissue engineering and osseointegrated implants has become a cornerstone in dentistry. Currently, dental implants combine aesthetics and long-term durability, with efforts to develop more effective implant materials that can prevent peri-implantitis (P1) as the main factor of implant failure. Analysis of natural and artificial structural elements based on the relationship between structure, physicochemical properties, and mechanics is still needed to prevent peri-implantitis [1] [2]

Various biomaterials and nanomaterials are used in dentistry and implantology. Biomaterials such as metal alloys, dental cements, ceramics, and polymers are used to improve dental conditions, for example in dental implants to replace missing teeth. Nanotechnology helps improve the quality of materials. Dental implants are now coated with biocompatible nano-coatings to enhance osseointegration and ensure longer durability. The use of nanoporous alumina anodes, titanium dioxide nanotubes, and porous silicon are also used in implant development. It is important to find restorative biomaterials that mimic dental tissue to reduce inflammation and support periodontal health. The main goal of implant biomaterial development is to achieve better stability, proper mucosal integration, and increase the life of rehabilitation treatment. Implant surface textures are developed to improve mechanical corrosion resistance and enhance osseointegration. Surface modifications include various techniques such as titanium plasma spray (TPS),

* Corresponding author: Anita Yuliati.

hydroxyapatite (HA) coating, electropolishing, mechanical polishing, acid treatment, sandblasting, oxidation, and laser irradiation. These modifications have been shown to be effective in improving osseointegration, including increasing implant removal torque values and bone quality [3] [4].

Zirconia is a leading material in dental implantology, known for its high biocompatibility, good esthetics, and corrosion resistance. Compared with titanium, zirconia shows advantages in the form of minimal release of metal ions that can trigger inflammatory and allergic reactions, as well as a more natural appearance without producing a gray shadow on the surrounding soft tissue. Thus, zirconia is an attractive option for patients with high esthetic needs or sensitivity to titanium [5] [6].

Zirconia implants face major challenges in osseointegration due to their relatively smooth surface properties. The osseointegration process requires surface modification to create optimal micro and nano roughness, thereby improving bone-implant contact (boneto-implant contact/BIC). Various methods have been developed to achieve this goal, including sandblasting, chemical etching, and laser technology. Among these methods, laser has emerged as a very promising approach because it can produce consistent microstructures without damaging the mechanical properties of zirconia [5] [6]

Miaman pioneered the use of lasers in dentistry in the 1960s, and its applications continue to evolve today with various types of lasers based on their active media. Gas lasers such as carbon dioxide (CO2), Solid state lasers such as Nd:YAG and Er:YAG, Liquid lasers such as Rhodamine G6, Semiconductor lasers, such as GaAs or GaAIA. "Free electron" lasers. These use electron accelerators, but are not suitable for dental applications. Diode lasers, or soft lasers, are used for low-level laser therapy or "biostimulation." Lasers are used in dental procedures such as frenectomy, crown shaping, polymerization, bleeding control, caries detection and removal, pain management, gingivectomy, gingivoplasty, and treatment of other soft tissue lesions. Studies have shown that laser surface modification of zirconia not only increases surface roughness but also creates hydrophobic properties that support cell adhesion and bone formation. Laser-modified surfaces have shown increased mechanical strength at the bone-implant interface and accelerated osseointegration through increasedwettabilityand osteoblast adhesion. Lasers also have the advantage of controlling the depth and pattern of surface modification, which is not possible with other methods such as sandblasting [5] [6] [7] [8].

This systematic review aims to identify the role of laser technology in surface coating of zirconia implants to enhance osseointegration. It is hoped that it will provide a comprehensive insight into the effectiveness of this approach as well as identify future research opportunities.

2. Methods

The article design that will be included in this review issystematic review, namely a synthesis of systematic literature studies by identifying, analyzing, and evaluating through the collection of existing data with guidance.The Preferred Reporting Items for Systematic Reviews and Meta-Analyses(PRISM). Based on the problem formulation, it is necessary to carry out a PICO analysis (population:zirconia implants, intervention: utilization of laser technology on the biological and mechanical properties of implants,comparison: the laser technology method used in each article, andoutcome:the influence of laser technology in improving the biological and mechanical properties of zirconia implants). The articles used were obtained from the search results in electronic databases in the form of PubMed, Scopus,and BMC with the keyword "laser technology AND implants AND zirconia". Articles were then selected based on inclusion criteria, namely: articles published in the last 5 years from 2020 to 2024, in the form of review articles, case reports, Scopus-indexed proceedings, reputable international journals in the form offull textfully accessible, Sinta 1 accredited national journal. Exclusion criteria include: research journals that do not use laser technology in zirconia implant surface coating, comments to the editor, letters, interviews, notes, guidelines, and erreta. After selecting articles based on inclusion and exclusion criteria, the author extracted information in the form of authors, research methods, research results, and conclusions.

3. Result

Searching articles from the three databases (PubMed, BMC, and Scopus) obtained 464 articles with details of 349 articles found in Wiley Online Library, 37 articles found in PubMed, 58 articles in BMC, and 20 articles in Scopus. The articles were then selected by excluding 12 duplicate articles, then the articles were filtered according to the inclusion and exclusion criteria and 389 articles were obtained. Then, the articles were re-checked for eligibility and excluded 15 articles, leaving 48 articles from which information about the authors, research methods, research results, and conclusions was extracted. The article selection process is shown in Figure 1 and the results of data extraction for 48 articles are shown in Table 1.

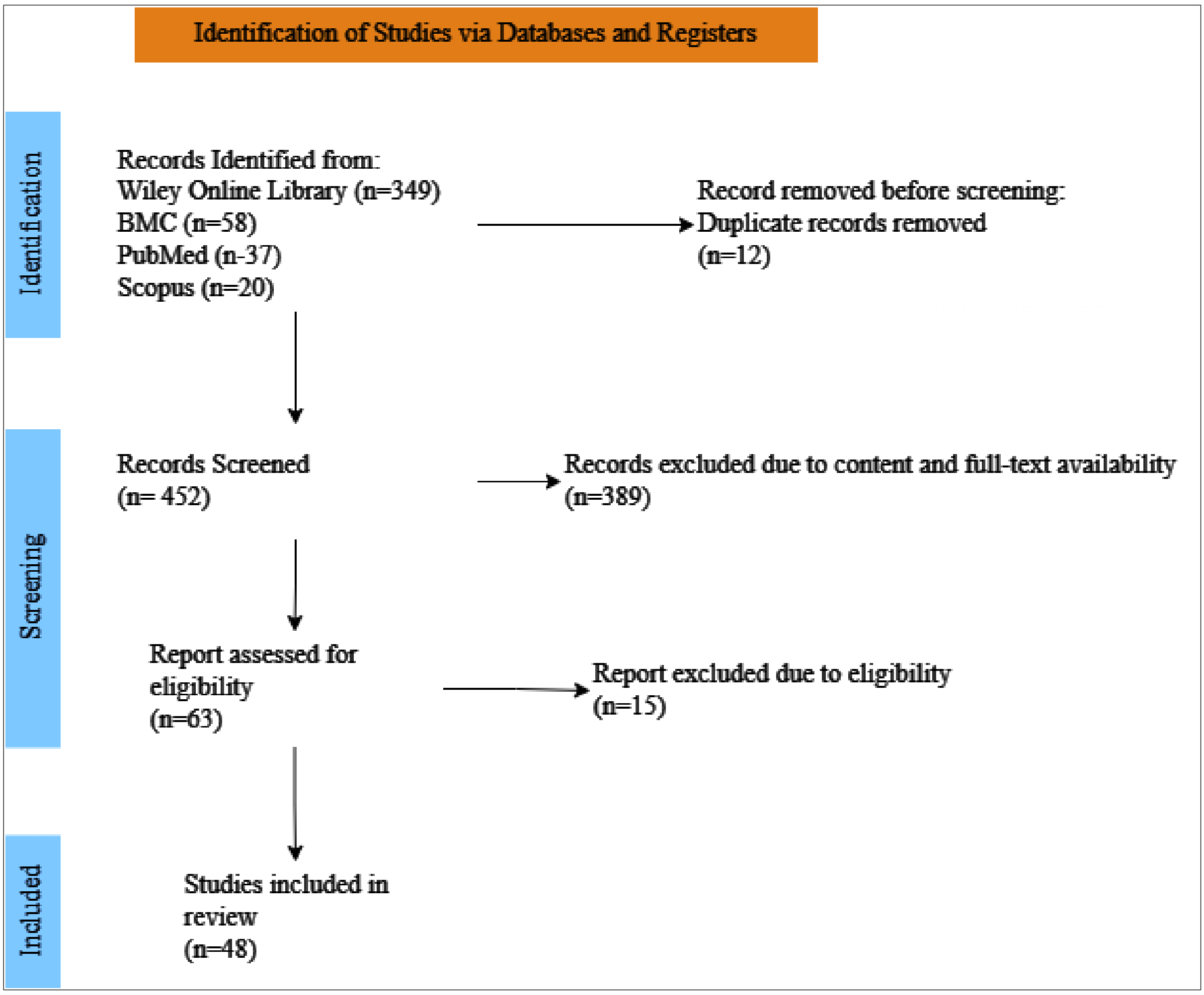

Figure 1 PRISMA Diagram of Literature Selection Results

Table 1 Data Extraction Results

No	Writer	Method	Results	Conclusion
1.	Faria et al., (2020) [27]	The design and parameters of the Nd:YAG laser to produce micropatterns on zirconia dental implants with variations in depth, width, and walls were analyzed by SEM.	In the mechanical test of soft tissue adhesion on the surface of the micro pattern is influenced by depth and width. Laser technology as a potential method to create dental implants with micro patterns that can protect against bacterial invasion.	Laser technology has proven to be effective and flexible in creating micro-textured patterns with varying widths, depths and dimensions of zirconia surface walls without cracks or defects.
2.	Moura et al., (2020) [28]	Silver-based micro-wire laser on zirconia substrate was subjected to three scanning variations: laser power, speed, and number of passes, to determine the effect on the quality and depth of the	Silver-based micro-wire laser on zirconia substrate produces electrical performance suitable for dental implant applications. There is a	Silver-based micro-wire laser on zirconia substrate can enhance the functionality of smart active implants in

		micro-wire laser produced. Electrical conductivity was measured with accurate resistivity.	decrease in the flexural strength of zirconia, from 795 MPa to 422 MPa, the value is still above the ISO standard limit set. The resistivity magnitude is higher than pure silver due to the sintering process.	producing good electrical conductivity.
3.	Tzanakakis et al., (2020) [31]	Cylindrical monolithic ceramic samples with a diameter of 10 mm were sintered. After sintering, the samples were fixed in epoxy resin to stabilize them. Then the surface of the samples was smoothed. The samples were divided into five with different treatments. The control group received no additional treatment, abrasion treatment with glass beads, using alumina beads measuring 50 µm and 90 µm with the sandblasting method, thermal treatment using a Yb:KGW laser producing linearly polarized pulses.	The surface of zirconia ceramic samples differed significantly in roughness and volume fraction parameters. Alumina particles of 90 µm, and femtosecond laser treatment increased the surface roughness and monoclinic phase content potentially improving the adhesion properties of zirconia ceramics in dental applications. Sandblasting treatment had minimal impact on roughness and monoclinic phase.	Alumina blasting and femtosecond laser treatment increased the roughness and volume fraction of monoclinic phase in zirconia ceramics.
4.	Li et al.. (2020) [33]	The SLM method is used to create composites consisting of: titanium (Ti) and zirconia ($ZrO2$) powders in various proportions to create composites. The metal powders are spread in a thin layer on the printing platform, a high-powered laser is used to melt and selectively fuse the powder particles according to a predetermined 3D design. This process takes place in a controlled atmosphere, using nitrogen or argon inert gas, to prevent oxidation. Composite characterization is analyzed to assess the microstructure, mechanical testing, biocompatibility of the material in biomedical applications.	The addition of zirconia ($ZrO2$) in a certain proportion increases the tensile strength, hardness of the composite and better structural stability. The biocompatibility test of the composite supports cell growth that has better interaction with osteoblast cells, thus improving the integration of the implant with bone tissue.	$ZrO2$/Ti composites show potential for use in clinical applications, especially in orthopedics and dentistry.
5.	Pu et al., (2020) [38]	The zirconia surface was laser processed to produce micro patterns on the surface of the material. The energy parameters and pulse duration were set to produce optimal textures to improve interaction with water. Then silanization, the textured zirconia surface was coated with silane to improve hydrophobic	The surface of zirconia is superhydrophobic with high water contact angle. Surface roughness, increased interaction between the surface and water molecules. After silanization, carbon content CC (H), plays a role in changing the	The laser texturing process produces micro patterns that increase surface roughness, increasing the water contact angle. The zirconia surface is superhydrophobic with a very high contact angle. The carbon content CC

		properties. Tested with water contact angle to evaluate wettability in both treatments. Surface characterization analysis using electron microscopy and profilometry to assess surface morphology and roughness.	hydrophobic properties. The results of electron microscopy analysis: many micro-pits and cracks in the laser area. The laser ablation process affects the surface morphology positively.	(H), plays a role in changing wettability.
6.	Okutan et al., (2020) [39]	Eighty zirconia samples were divided into eight with different treatment protocols, including a control group. Air abrasion and femtosecond laser treatment before and after sintering process. The abrasion process uses alumina particles to increase surface roughness. Laser treatment uses ultrashort pulses to create micro-patterns on the zirconia surface. Surface roughness was measured by a profilometer. Shear test with a universal machine. Each group was compared to determine the effectiveness in increasing surface roughness and resin bond strength.	The control group had the lowest Ra value and bond strength, the femtosecond laser group showed the highest Ra value and bond strength. Laser treatment before sintering (FBS) and the combination of FBS with air abrasion after sintering (FBS + AAS) significantly increased both parameters. Air abrasion after laser treatment did not show any significant changes compared to laser treatment alone.	Femtosecond laser treatment, prior to sintering, resulted in the highest increase in Ra (surface roughness) values contributing to the enhancement of the interaction between resin and zirconia. The combination of laser treatment and air abrasion after sintering also showed positive results, although not as effective as single laser treatment.
7.	Elkharashi et al., (2020) [49]	The lasering debonding process is carried out selectively to break the luting cement bond without damaging the structure of the zirconia crown or implant abutment. Post-laser testing: ensures that there is no significant damage to the crown and abutment. Electron microscopy (SEM) analysis to evaluate the post-debonding surface condition.	SEM and energy-dispersive X-ray spectroscopy (EDS) analysis showed no visual damage or changes in material composition on the crown or abutment surfaces after laser application. Both types of lasers are safe to use without damaging the zirconia structure. The effectiveness of the erbium laser type has been shown to be an alternative for removing zirconia crowns from zirconia implant abutments.	Erbium laser can be recommended as a safe and effective method for removing zirconia crowns from implant abutments, especially in clinical contexts where restoration is required.
8.	Garofalo et al., (2021) [24]	One hundred and sixty 3Y-TZP implants were divided into five groups: negative control (NC), sandblasting (SB), and three laser groups, namely crossed-line laser (LC), random-hatching laser (LR), and parallel waves laser (LW). Flexural strength test, crystal change analysis by XRD, surface roughness measurement by 3D laser profilometry and SEM were	The LR group (852.0 MPa) did not show any significant difference in flexural strength compared to NC (819.8 MPa) ($p > 0.05$). All laser groups showed higher Weibull modulus compared to NC and SB indicating better reliability and homogeneity of strength, while the	Laser surface treatment creates a homogeneous, highly reproducible and accurate surface microstructure on zirconia implants.

		performed to evaluate the effects of surface treatment.	increase in monoclinic phase peak was only seen in the SB group.	
9.	Li et al., (2021) [25]	Fifty-seven zirconia implants were divided into three groups: sintered; sandblasted with 110 µm aluminum oxide after sintering; and a group of micropatterns formed by femtosecond laser measuring 50 µm wide, 30 µm deep, and 100 µm apart. The surface morphology was observed by SEM and 3D laser microscopy. The surface roughness was measured for each group and the size of the micropatterns was analyzed. The crystal phase was analyzed by XRD. The specimens were tested for flexural strength at three points, and the Weibull distribution was used to analyze their strength characteristics.	SEM results showed that the surface of the micropattern was regular without defects, with higher Ra (9.42 µm) compared to sandblasted (1.04 µm) and sintered (0.60 µm). The micropattern group had significantly lower flexural strength (547.92 MPa) than sandblasted (986.22 MPa) and sintered (946.46 MPa), the Weibull modulus of the micropattern was higher (23.46) than the other groups.	Femtosecond laser successfully forms micro-nanostructures on the surface of zirconia, but this has a negative effect on the flexural strength of zirconia.
10.	Wawrzyk et al., (2021) [26]	Irradiation of the implant was performed using a diode laser with a wavelength of λ = 810 nm in three repetition variations (1 × 15 s, 2 × 15 s, 3 × 15 s). Microbial contamination tests on the implant surface were performed using the culture method, with identification of microorganisms using the next-generation sequencing (NGS) technique.	Laser treatment of implant surfaces, regardless of the duration of exposure, effectively removes microorganisms from the surfaces used for dental implant repair and has no detrimental effect on the tested materials.	Laser power and exposure duration, effectively reduce microorganisms without damaging the structural and morphological properties of the zirconia implant surface.
11.	Cano-Velazquez et al., (2022) [30]	The thermal effects of laser irradiation on nanocrystalline yttria-stabilized zirconia (nc-YSZ) ceramics as biomedical cranial implants have been investigated using a combination of experimental and computational methods. The study shows that during laser exposure, the temperature generated in nc-YSZ remains below the threshold that can cause thermal damage to biological tissues, making it suitable for biomedical applications. Through thermal imaging experiments, researchers were able to measure the induced temperature changes and calibrate a computational model to describe the thermal effects that occur.	The results show that laser irradiation of nanocrystalline yttria-stabilized zirconia (nc-YSZ) ceramics results in a steady temperature increase below 10 °C, indicating that this material is safe for biomedical applications, especially as a cranial implant. The study also found that the developed computational model can predict the temperature profile with high accuracy, with a maximum deviation of 5% compared with the experimental data. Important thermal-optical parameters, such as thermal conductivity and absorption coefficient,	Laser irradiation of nanocrystalline yttria-stabilized zirconia (nc-YSZ) ceramics resulted in a temperature increase that remained below 10 °C, indicating that this material is safe for use as a biomedical implant, especially a cranial implant. The developed computational model successfully predicted the temperature profile with high accuracy, with a maximum deviation of 5% compared to the experimental data.

			affect the thermal behavior of nc-YSZ under laser irradiation.	
12.	Sun et al., (2021) [32]	Microgroove patterning (MG) was performed on the surface of zirconia structures to evaluate its effect on osteogenesis. The treatments performed included: 1) Mirror-polished with colloidal silica (PL), 2) Blasted with 100 μm aluminum oxide particles at an air pressure of 0.4 MPa (SLA), 3) Blasted with 100 μm aluminum oxide particles at an air pressure of 0.4 MPa and etched with HF (40%) for 1 hour (SLA-AC), and 4) Etched with femtosecond laser (MG).	The micro-grooved (MG) surface structure on zirconia implants has a significant positive impact on osteoblast behavior and mechanical stress distribution in the surrounding bone. In vitro, the MG surface enhances osteoblast adhesion, proliferation, and differentiation, increasing the activity of osteogenesis-related genes such as Runx2, ALP, and OPN. The MG surface significantly increases roughness and hydrophilicity, contributing to better cell morphology and higher osteogenic differentiation.	MG surface treatment increases roughness and hydrophilicity, which contributes to increased osteoblast adhesion, proliferation, and differentiation.
13.	da Cruz et al., (2021) [34]	YSZ discs were fabricated and processed by two texturing techniques, namely conventional milling and Nd:YAG laser treatment. All samples, including controls, were processed by sandblasting and acid etching. Human osteoblasts and fibroblasts were cultured for 14 days to observe cell behavior. Cell morphology and adhesion were observed to assess the interaction between cells and the implant surface. Cell viability, interleukin-1β, osteopontin, type I collagen, alkaline phosphatase activity, and interleukin-8 were measured to evaluate the biological response to surface treatment. Data were statistically analyzed to determine the significance of differences between treatment groups.	Surface texturization by conventional milling resulted in significant increases in osteoblast viability and biochemical activity, such as osteopontin and type I collagen production. Fibroblasts were not affected by the texturization method. Furthermore, no advantages were found in macrotexturization compared to sandblasting and acid etching methods which are currently considered the gold standard for zirconia implants.	Surface treatment of Yttria-stabilized zirconia (YSZ) using conventional milling techniques was more effective in increasing osteoblast cell viability and differentiation compared to treatment using Nd:YAG laser.
14.	da Silva et al., (2021) [36]	Sintered zirconia samples were prepared and divided into several groups based on the treatments received: control (untreated), silica coating, and laser treatment. The silica coating process was carried out using a deposition technique to ensure an even distribution on	The silica-coated surface and laser treatment significantly increased the flexural strength and bond strength of dental zirconia. The test results showed that the silica-coated samples had higher bond strength to resin cement	Silica coating after sintering process resulted in the highest flexural strength, reaching 1149.5 MPa. Laser treatment, although it can improve the surface characteristics, actually reduces the overall

		the zirconia surface. Next, laser treatment was applied with parameters set to optimize changes in surface characteristics. After treatment, all samples were tested for flexural strength using a flexural test, and surface characteristics were analyzed using electron microscopy and profilometry to assess roughness and morphology. The bond strength between zirconia and resin cement was also tested to determine the effectiveness of the applied treatment.	compared to the control group. In addition, laser treatment also increased the flexural strength and improved the surface characteristics of zirconia, resulting in a smoother and hydrophilic surface. Microscopic analysis revealed that the surface patterns resulting from these treatments contributed to a better interaction between zirconia and the adhesive material.	flexural strength, especially at longer pulse width settings. The treatment group showed low bond strength values after aging process, indicating that the bond stability between zirconia and resin cement is not optimal.
15.	Silva et al., (2021) [46]	Zirconia discs are divided into several groups based on the texturing method used. Conventional milling: groove pattern is created Conventional Milling: pore pattern is created The laser groove pattern is created with a Nd:YAG laser. Laser pore patterns are created with an Nd:YAG laser. Single colony inoculation of Streptococcus oralis was inoculated into Brain Heart Infusion (BHI) medium and incubated anaerobically at 37 °C until the exponential growth phase with an optical density (OD) of 0.05. Each group of discs was inserted into 24 wells, and a suspension of Streptococcus oralis was added, incubated under anaerobic conditions at 37 °C. The number of colony forming units (CFU) was counted to assess biofilm formation on each disc surface. Analysis using Kruskal-Wallis followed by post hoc pairwise comparisons to determine statistical significance, with a significance level of $p < 0.05$.	Biofilm formation on zirconia surfaces textured with an Nd:YAG laser showed significant differences in the ability of Streptococcus oralis to form biofilms. GL (Laser Flow Pattern): lower increase in bacterial colony count (CFU), indicating that this surface is more effective in inhibiting biofilm formation. PL (Laser Pore Pattern): showed a reduction in CFU count, but was not as effective as the groove pattern. GM and PM (Conventional Milling): showed higher CFU counts, indicating that these methods are less effective in preventing biofilm formation compared to laser treatment. Implant Design shows that surface texturing using Nd:YAG laser can be an effective strategy to reduce biofilm formation on zirconia implants, in increasing the success of dental implants and reducing the risk of infection. Statistical analysis showed significant differences between treatment groups.	Laser microscopy technology can improve the performance of dental implants by controlling biofilm formation, for long-term implant success and safety.

16.	Li et al., (2022) [20]	Three types of surface treatments of zirconia implants were compared: mirror group, laser-generated micropattern group*femtosecond*, and air-blasted and acid-etched groups. Biocompatibility and osteogenic differentiation were tested on MC-3T3-E1 cells.	The femtosecond laser technique produced regular micropatterns with a width of about 5 μm and a rougher zirconia surface (Ra = 271.7 ± 67.2 nm), a stable tetragonal crystal system. PCR test results showed that the expression of osteogenesis-related genes, osteopontin (OPN) and alkaline phosphatase (ALP), was higher in this group compared to the other groups.	The femtosecond laser technique produces fine micro patterns on the surface of Y-TZP, increasing its roughness and wettability, increasing adhesion and supporting the differentiation of pre-osteoblasts into osteoblasts, making it a potential choice in the manufacture of Y-TZP implants.
17.	Li et al., (2022) [21]	Fluorinated hydroxyapatite (FHA) coated zirconia implants were fabricated using pulsed laser deposition (PLD) to create a biologically active surface that is: uniform, dense, crack-free, has good mechanical strength, and has favorable biological properties. The samples were implanted in Sprague-Dawley rats.	Cell growth, ALP, mineralization, new bone volume in FHA coated samples increased. Good crystalline structure, fluorine incorporation in hydroxyapatite lattice without detecting secondary phase. Increased mechanical stability and high bioactivity of the film.	The use of PLD to deposit FHA layers on the surface of zirconia implants resulted in more promising characteristics for implant fabrication compared to the unmodified ones.
18.	Moura et al., (2022) [22]	Using laser technology to prepare the surface of zirconia implants subtractively (creating micro-cavities).	Laser technology successfully creates micro cavities on the surface of zirconia implants so that the implants become more retentive.	Laser technology methods can improve the quality and retention of zirconia implants.
19.	Staehlke et al., (2022) [23]	Polished zirconia implants were microstructured using a laser. The samples were also activated with argon plasma using kINPen®09. Surface topography was analyzed by SEM and surface resistance was tested. In vitro studies with human gingival fibroblasts (HGF-1) focused on cell spreading, morphology and actin cytoskeleton organization within the first 24 hours.	Laser-induced microstructure after argon plasma activation, the surface becomes hydrophilic with 60 μm pores and 13.7° contact angle. HGF-1 cells adhered evenly to the polished zirconia, cell spreading was inhibited in the pores. Cells on the laser-induced surface could be spread well. Argon plasma activation for 1 minute increased the adhesion and spreading of HGF-1 cells even after 2 hours of incubation, cells grew in the pores.	The combination of laser microstructure and argon plasma activation on zirconia is optimal for enhancing gingival cell attachment.
20.	Birand et al., (2022) [42]	Zirconia crown samples were bonded to titanium base using	Debonding time varies depending on the crown	Er,Cr:YSGG laser irradiation is a safe and

		two types of cement: resin modified glass ionomer cement and resin cement. The samples were irradiated with laser parameters: irradiation time and laser power, time for debonding process, measuring the residual bond strength after laser treatment. The morphology of the zirconia and titanium surface structures was analyzed by scanning electron microscopy (SEM). The data were statistically analyzed to determine the effectiveness of the laser in facilitating debonding without damaging the underlying structure of the implant.	thickness and the type of cement used, the Er, Cr: YSGG laser is able to reduce debonding time significantly compared to conventional methods. Surface morphology analysis showed that the laser did not cause significant damage to the surface structure of titanium or zirconia.	effective method for removing zirconia crowns from titanium bases, providing a better alternative to traditional techniques that can damage implants.
21.	Dikicier et al., (2022) [43]	Sixty samples, consisting of 30 zirconia (Ceramill Zi) and 30 lithium disilicate glass (IPS e.max CAD), were fabricated in standard sizes (5 mm x 5 mm x 1.5 mm) and sintered according to the manufacturer's instructions. Each sample was subjected to surface treatments: etching with 4% hydrofluoric acid (HF), airborne particle abrasion with 110 µm alumina (AP), and Er:YAG laser irradiation. The samples were divided into three treatment groups: Group A (HF + AP), Group B (Er:YAG + AP), and Group C (Er:YAG + HF). Surface roughness was measured by a perthometer to determine the Ra values before and after treatment. The results were statistically analyzed.	The combination of acid treatment and airborne particle abrasion resulted in smoother surface roughness on lithium disilicate glass ceramics compared to zirconia. Samples etched with hydrofluoric acid (HF) with abrasion showed lower average roughness (Ra) values, smoother surfaces and were ready for restorative applications in dentistry. Zirconia samples irradiated with Er:YAG laser showed increased surface roughness, not as effective as other treatment combinations. Surface morphology undergoes changes in roughness.	Selecting the right combination of surface treatments is critical to improving the surface quality of CAD/CAM ceramics, which can affect the long-term success of dental restorations.
22.	Okutan et al., (2022) [44]	Monolithic zirconia block samples were divided into several groups based on surface treatment. Each group was treated in a different way to evaluate the effect of surface pattern variation. Irradiation using femtosecond laser with parameters: wavelength, electrical frequency, and electrical energy. Obtaining different surface patterns, such as horizontal lines, cross	Surface modification using femtosecond laser microscopy technology significantly increases the flexural strength of monolithic zirconia, providing a basis for better clinical applications in dental restorations.	The use of femtosecond laser microscopy technology can improve the mechanical properties of dental materials, especially in restorative applications using monolithic zirconia.

		patterns, to determine the effect on flexural strength. Surface roughness characterization was analyzed using profilometry, visualization of surface patterns with a scanning electron microscope (SEM). Flexural strength was tested with universal. Failure analysis on samples was tested with fractography. Statistical analysis to determine the significance of differences between treatment groups.		
23.	Hassouna et al., (2022) [48]	A prospective study involving patients who received one-piece titanium implants and one-piece zirconia implants modified with sputtering technology.	After 5 years, the success rate for zirconia implants was 97.2%, while titanium implants also showed comparable results. Bone Loss Marginal: The average marginal bone loss after 5 years was 1.1 mm, indicating long-term stability of both implant types. The mean probing depth did not show any significant difference between the two implant types, with a mean value of approximately 3 mm. Reported technical and biological complications were relatively low in both groups, with no significant difference in the frequency of events between titanium and zirconia implants.	Both titanium and zirconia implants can provide long-term stability in terms of marginal bone loss and probing depth. Zirconia implants can be considered as a valid alternative to titanium implants, especially for patients with titanium intolerance or in certain aesthetic situations.
24.	Cai et al., 2022 [40]	Eighty titanium blocks were prepared with standard sizes and zirconia sheets with varying thicknesses (1 mm, 2 mm, 3 mm, and 4 mm), each consisting of 20 samples. Zirconia crowns were bonded to the titanium blocks using two types of cements, namely resin modified glass ionomer cement (RelyX Luting 2) and resin cement (Clearfil SA Luting), all specimens were stored at 100% humidity for 48 hours. Er:YAG laser was used to remove the zirconia crowns, and the time required for removal	The results showed that the time required to remove zirconia crowns varied depending on the thickness and type of cement used. Specifically, crowns with a thickness of less than 2 mm were removed faster when using resin modified glass ionomer cement compared to resin cement. Bond strength analysis showed no significant difference between the 1 mm and 2 mm thickness groups on	This study concluded that the Er:YAG laser is an effective non-invasive tool for removing zirconia crowns from titanium abutments, offering a safer alternative to traditional methods using rotary instruments. The study found that the removal time for zirconia crowns varied depending on the crown thickness and the type of cement used, with the best results achieved in crowns less

		was recorded. If the crown could not be removed after five minutes of laser irradiation, the residual bond strength was measured using a universal testing machine. The bonding surface and the irradiated surface of the zirconia sheets were analyzed using a scanning electron microscope (SEM). Data were statistically analyzed using the Kruskal-Wallis test to determine significant differences between different groups.	RelyX cement, as well as between the 1 mm thickness group on Clearfil cement. SEM results showed changes in the bonding surface and irradiation surface of the zirconia sheet, but no significant damage due to laser treatment.	than 2 mm thick bonded with resin modified glass ionomer cement (RelyX Luting 2)
25.	Ghalandarzadeh et al., (2023) [19]	Surface modification was performed using a continuous wave carbon dioxide laser with a wavelength of 10.6 µm under air atmospheric conditions. Using samples immersed in SBF solution, distinguishing between treated and untreated samples.	The laser-generated nanoscale grooves significantly enhanced the antibacterial properties by creating a hydrophobic surface. The cellular response to this modification was evaluated over 7 days on the zirconia surface microtexture and compared to the untreated sample. MC3T3-E1 pre-osteoblast cells showed that the modified surface topography enhanced the cellular response, showing increased metabolic activity compared to the untreated sample, as well as changes in cell morphology throughout the test period.	Laser modification can be used as an effective method to design nanometer-scale microtextures, to improve the biological response and antibacterial properties especially in zirconia ceramics in restorative dentistry applications. Especially on Streptococcus mutans and Escherichia coli bacteria.
26.	Li W et al., (2023) [17]	Tetragonal zirconia implants stabilized with 3 mol% yttrium were irradiated with femtosecond laser (FsL) to form micro and submicron patterns, then coated with calcium phosphate (CaP) using pulsed laser deposition (PLD) technique and low temperature solution processing. The implants were implanted in rabbits and evaluated for bone bonding ability.	Implantation in rabbits for four weeks showed that FsL-irradiated and CaP-coated zirconia had significantly better bone bonding ability with increased osteoblast differentiation compared to CaP-coated zirconia without FsL irradiation and untreated zirconia. FsL-irradiated and CaP-coated zirconia showed significantly higher adhesion, even causing host bone fracture in push-out tests.	FsL irradiation of zirconia followed by CaP coating enhances osteointegration and bone adhesion, with adhesion so strong that it causes fracture of the host bone in push-out test. This technique has potential for cementless zirconia joints and dental implants.
27.	Kitajima et al., (2023) [29]	The analysis of the effect of zirconia surface roughness on bacterial biofilm susceptibility	The zirconia hybrid surface has higher surface area roughness compared	The varying nano-trabecula sized zirconia hybrid surfaces can

		was studied. Surface characterization: roughness and protein adsorption on the biological behavior of osteoblasts and interactions with bacteria. Surface roughness was tested by SEM using peak-to-valley roughness (Sz), texture aspect ratio (Str), and core height (Sk) parameters. The chemical composition of the surface was analyzed by X-ray photoelectron spectroscopy (XPS), and the hydrophobic/hydrophilic properties were evaluated by measuring the contact angle. Protein adsorption analysis was measured by a bicinchoninic acid (BCA)-based colorimetric method. Rat bone marrow osteoblast cell cultures were analyzed by gene expression using real-time quantitative polymerase chain reaction (qPCR) after RNA extraction and transcription into cDNA.	to the polished surface, protein adsorption and osteoblast differentiation are increased. Osteoblast proliferation between the surfaces is not significant, the rough hybrid surface with nano-trabecula shows osteoblast differentiation. The surface characteristics improve bone integration of dental and orthopedic implants. Further research is needed on the mechanical properties and susceptibility of bacterial biofilms on the surface.	enhance the biological behavior of osteoblasts, including differentiation and protein adsorption.
28.	Henriques et al., (2023) [35]	Infrared picosecond laser to produce micrometric patterns on the zirconia surface. After the interference pattern process, characterization is performed using electron microscopy and interferometric profilometry techniques to analyze the pattern depth, surface roughness, possible damage to the material.	Electron microscopy analysis shows that the resulting patterns have a well-controlled microstructure, which has the potential to enhance the biological interaction of the material. The test results show that with proper parameter settings, the surface quality can be improved, thereby enhancing the mechanical performance and biocompatibility of the zirconia components.	Laser interference pattern technique can be effectively used to modify zirconia surfaces by producing controlled micrometric patterns. Variations in processing parameters, such as fluence energy, number of pulses, and scanning speed, have a significant impact on pattern depth, surface roughness, and material damage.
29.	Majidian et al., (2023) [18]	Various ratios of barium titanate (BT) were added to 3 mol% yttria stabilized zirconia (3YSZ) implants via conventional sintering. Laser texturing technique was also applied to improve the biological properties of 3YSZ. Surface topography was analyzed using XRD and SEM, and surface roughness and wettability were measured. Pre-osteoblast MC3T3-E1 cells were used for in vitro experiments, cell viability was evaluated using resazurin method and cell morphology and	Laser texturing technique and barium titanate content affected the surface characteristics of 3YSZ implants. Laser textured implants showed lower water contact angles than other samples, indicating better surface hydrophilicity. Cell viability and adhesion on 3YSZ/BT implants increased with increasing barium titanate content and laser power.	Overall, laser-treated 3YSZ/5 and 7 mol% BT implants may be promising candidates for hard tissue repair due to the good cellular response.

		adhesion were observed using SEM.		
30.	Bihn et al., (2023) [15]	Ti implants manufactured by sandblasting and acid etching (T) were compared with Zr implants divided into 3 groups, namely machined surface group (M), hydrophobic surface group manufactured by femtosecond laser (HF), and nanosecond laser (HN). Biofilm and adhesion of three bacterial species: Aggregatibacter actinomycetemcomitans (Aa), Porphyromonas gingivalis (Pg), and Prevotella intermedia (Pi) were tested on each type of implant evaluated after 48 and 72 hours of incubation using anaerobic chamber model.	Compared with group T, group M showed more than double the number of live bacteria in the three species biofilm samples ($p < 0.05$). Group HF had significantly higher numbers of live bacteria than group T in some biofilm samples at 48 h (Aa and Pi) and 72 h (Pi) ($p < 0.05$), while group HN showed higher numbers of live bacteria in Pi at 48 h (5400 CFU/mL, $p < 0.05$) but lower in Pg at 48 h (3010 CFU/mL) and 72 h (3190 CFU/mL) ($p < 0.05$).	The surface treatment method on zirconia implants greatly influences biofilm formation. Hydrophobic surfaces created using nanosecond lasers have been shown to be highly effective in inhibiting the growth of Pg.
31.	Li et al., (2023) [17]	One hundred and sixty Zr implants were divided into four groups with different surfaces: sintered; sandblasted with 110 µm Al_2O_3; micropatterned with femtosecond laser (50 µm width, 30 µm depth, and 100 µm spacing and 30 µm width, 20 µm depth, and 60 µm spacing).	XRD analysis showed that the micropatterned surfaces fabricated by femtosecond laser did not exhibit significant tetragonal to monoclinic phase transformation. The fatigue strength of sandblasted specimens (728 MPa) was significantly higher than that of sintered specimens (570 MPa), but the fatigue strength of specimens with micropatterned surfaces decreased by about 360–380 MPa.	Femtosecond laser is an effective technique to control the surface microtopography of zirconia implants, further research is needed to improve the fatigue strength properties of the material.
32.	Garcia-de-albeniz et al., (2023) [16]	Nanosecond laser was used to fabricate micropatterns of different sizes (30, 50, and 100 µm) on 3Y-TZP implants. Topography and surface damage were analyzed using confocal laser scanning microscopy (CLSM) and scanning electron microscopy (SEM). X-ray diffraction (XRD) and spectroscopy were used to test the resistance to hydrothermal degradation. Biological studies evaluated the adhesion of mesenchymal stem cells (MSCs) and Staphylococcus aureus adhesion to the micropatterns.	Surface analysis showed damage in the form of material buildup, microcracks, and voids on the micropatterns, with a slight decrease in hydrothermal degradation resistance after laser programming. MSC cells showed significant elongation and alignment on the 50 µm micropatterns, and Staphylococcus aureus adhesion was reduced on the micropatterns.	Micropatterns with a size of 50 µm created by nanosecond laser can help in increasing the adhesion and alignment of MSCs, while reducing the attachment of Staphylococcus aureus bacterial cells.

33.	Henriques et al., (2024) [37]	A short pulse laser source with a wavelength of 532 nm and a pulse duration of 10 ps was used. Laser processing parameters, including fluence energy and pulse overlap, were set to evaluate their effects on the morphology and microstructure of the zirconia surface.	This study successfully generated a processability map for laser processing of zirconia based on the experimental data obtained, highlighting the potential of this technique in biomedical and industrial applications.	This study demonstrates that the direct laser interference pattern (DLIP) technique is effective in producing zirconia surfaces with periodic and multiscale structures that can improve the functional properties of the material. In addition, the analysis shows that the resulting structures not only improve the surface characteristics but also have the potential to improve the biological interactions of zirconia in biomedical applications.
34.	Ji et al., (2024) [41]	This method uses a review method by collecting some information from journals regarding osseointegration of titanium and zirconia-based implants.	Zirconia implants excel in terms of aesthetics, reducing plaque and biofilm formation, which contributes to the health of the peri-implant tissues. This journal also discusses factors that affect osseointegration, including implant surface properties, surface modification techniques, and biological interactions between implants and bone tissue. Hydroxyapatite coating and additional elements such as strontium, increase bone-to-implant contact (BIC) and accelerate the osseointegration process.	Zirconia implants have better aesthetics with a natural appearance and reduce plaque and biofilm formation, which contributes to the health of the peri-implant tissues.
35.	Sulaiman et al., (2024) [45]	A sample of 40 premolar teeth were extracted and scanned to fabricate 40 CAD/CAM crowns. They were randomly divided into four groups (n = 10): G1a: 3 mol% yttria-partially stabilized (3Y-PSZ) zirconia crown bonded with Panavia™ V5 (2-bottle adhesive resin cement). G1b: 3Y-PSZ zirconia crown bonded with RelyX™ Ultimate (1-bottle adhesive resin cement). G2a: lithium disilicate crown bonding with Panavia™ V5.	The Er:YAG laser can be used effectively to debond ceramic restorations regardless of the type of adhesive resin system used, These results provide valuable insights into the potential use of lasers in dentistry, particularly in the context of zirconia crown removal.	Laser techniques are a safer and more efficient alternative to ceramic crowns without compromising the risk of damage to tooth tissue.

		G2b: lithium disilicate crown bonding with RelyX™ Ultimate. Each sample was irradiated with Er:YAG laser with the following parameters: pulse energy: 335 mJ, frequency: 15 Hz, power: 5.0 W, pulse duration: 50 ms (super short pulse mode). Measured each debonding sample, irradiation time. Using scanning electron microscopy (SEM) to evaluate microstructural changes after laser irradiation. Statistical analysis: ANOVA and Tukey HSD post-hoc test with a significance level of $p < 0.05$.		
36.	Alkhudairy, (2024) [47]	A sample of 80 premolar teeth was disinfected with 0.5% chloramine-T solution. Root canal preparation using ProTaper files, followed by obturation. Samples were divided into four groups based on the disinfection method used (n = 20): Group 1: 5.25% NaOCl + 17% EDTA (control). Group 2: Nd:YAG laser + 17% EDTA. Group 3: Synchronized Microbubble-Photodynamic Activation (SYMPA) + 17% EDTA. Group 4: Carbon Quantum Dots (CQDs) + 17% EDTA. Disinfection removes the smear layer and increases bond strength. Surface hardness measurement by microhardness. Smear Layer (SL) Removal: evaluated by scanning electron microscopy (SEM). Extrusion Bond Strength (EBS): between zirconia post and root canal dentin was tested using a universal testing machine. Statistical analysis: using ANOVA and Tukey's post-hoc test to determine significant differences with $p < 0.05$.	The use of laser technology and photodynamic activation in clinical practice can increase the effectiveness of root canal disinfection, as well as improve the bond strength of restorations in treated root canals.	The use of modern disinfection techniques in endodontics can increase the effectiveness of root canal treatment and support the long-term success of dental restorations.

37.	Noumbissi et al., (2024) [50]	Literature analysis regarding the use of zirconia as a dental implant material.	The biocompatibility of zirconia implants is high, reducing the risk of allergic reactions that often occur in titanium, the soft tissue around zirconia implants shows better health compared to titanium implants. Zirconia-based implants have good mechanical strength, especially using the Y-TZP (yttria-stabilized tetragonal zirconia polycrystal) type. Zirconia has higher fracture resistance compared to other ceramics, making it a strong choice for dental implants. Zirconia provides better aesthetic results due to its color similar to natural teeth and its ability to prevent discoloration of the peri-implant gingival tissue. Zirconia implants can reduce plaque and biofilm formation on the implant surface, which contributes to a reduced risk of peri-implantitis.	Zirconia has been shown to be a viable alternative to titanium in dental implants. With its high biocompatibility, good mechanical strength, superior esthetics, zirconia has the potential to replace titanium in many clinical applications. Zirconia implants can be recommended for patients who need a dental implant solution with good aesthetics and a lower risk of complications compared to titanium implants.
38.	El-Hadyet al., (2024) [51]	In a randomized clinical study involving patients requiring dental implants for implant-retained overdentures in the upper jaw. Patients were divided into two groups based on the type of implant material used: titanium and titanium-zirconium alloy.	The implant types (titanium and titanium-zirconium) had good initial stability, but the titanium-zirconium alloy showed slightly higher dependent variable values compared to pure titanium. Titanium-zirconium implants showed higher values compared to titanium. The soft tissues around the implant showed good healing without any signs of infection or complications.	Titanium-zirconium alloys can be considered as a viable alternative to pure titanium implants in the context of implant-retained overdentures, primarily due to their better initial stability.
39.	Xin tan et al., (2024) [52]	This study used zirconia samples made by digital light processing and subtractive manufacturing (7 mm × 7.5 mm × 1.5 mm) grouped according to aging time (134 °C, 0.2 MPa, 100%	Zirconia produced by the DLP method exhibits higher initial phase content and faster phase transformation rates compared to	The DLP method shows potential to produce zirconia with superior physical and biological properties compared to conventional methods, making it an attractive

		humidity), including 0 h, 5 h, and 10 h.	conventionally produced zirconia.	option for dental implant applications.
40.	Kreve et al., (2024) [53]	This journal is a systematic review that aims to collect and analyze studies evaluating zirconia implants manufactured through additive manufacturing (AM) technology.	Zirconia implants produced via AM show potential to provide a biocompatible alternative to titanium, but challenges such as mechanical strength and long-term stability still need to be addressed.	3D printing techniques for zirconia implants show promise as an alternative in dentistry, but still require further research before they can be tested clinically.
41.	Sun J et al., (2024) [63]	Development of two micro-nano structures on zirconia surface using femtosecond laser: covering 30 μm (G3) and 60 μm (G6) wide micro grooves in 5 μm, nanoparticles distributed in the micro grooves. Polished surface as control group. Using hepatocyte growth factor for lipopolysaccharide stimulated zirconia specimen group.	hepatocyte growth factor on zirconia surfaces with micro-nano structures showed lower inflammatory responses as well as higher cell adhesion, proliferation, and migration under inflammatory conditions compared to polished surfaces. Group G3 had lower inflammatory response and higher cell adhesion and migration compared to group G6. Micro-nano zirconia surface showed decreased neutrophil infiltration and increased M2 macrophage polarization in vivo. RNA sequencing and gene silencing identified two important target genes regulated by group G3.	Zirconia surfaces with micro-nano structures were developed through femtosecond laser treatment. These surfaces showed lower pro-inflammatory responses and increased hepatocyte growth factor adhesion, migration, and proliferation under inflammatory conditions, compared to polished surfaces.
42.	Ghalandarzadeh et al., (2024) [9]	The surface coating of zirconia implants using femtosecond laser ablation technique to create nanoscale grooves. The results of the implant surface coating were then tested for their effects on osteoblast cells and the activity of Fusobacterium nucleatum, Streptococcus mutans, Pseudomonas aeruginosa, and Escherichia coli bacteria. Biocompatibility was tested with MTT	The zirconia implant surface showed a significant reduction in bacterial adhesion, especially for Fusobacterium nucleatum. The biocompatibility of cell morphology was excellent, and there was an increase in collagen I and interleukin 1β secretion indicating an increase in osteoblast cells.	Zirconia surfaces coated with femtosecond laser showed increased osteoblast response, reduced bacterial adhesion, potentially improving the performance and durability of dental implants.
43.	Munteanu et al., (2024) [10]	Titanium (Ti) and zirconia (Zr) implant samples were each divided into 5 surface coating treatment groups: (1) conventional method, (2) Photodynamic therapy (PDT),	Decontamination analysis, the combination group of PDT and Er:YAG laser, microbial colonies were completely lost on the surface of Ti and Zr. In the	The combination of PDT and Er:YAG laser is more effective in eliminating microbial colonies, the surface of Zr implants shows better resilience,

		(3) Er:YAG laser, (4) combination of PDT and Er:YAG laser, (5) without coating. The samples were subjected to decontamination analysis, surface analysis with optical coherence tomography (OCT) and scanning electron microscopy (SEM), and temperature measurement.	surface analysis, there were surface changes in the PDT group and the combination of PDT & Er:YAG laser. In the temperature measurement, no significant differences were found between groups, indicating that the laser is safe to use. The surface of Zr is more resilient than Ti, making it more suitable for microbial control.	making them superior to Ti implants.
44.	Pereira et al., (2024) [11]	This study tested laser surface texturing (LST) to create three planned textures on the surface of Zr implants, namely (1) cross-linked groove texture, (2) micropit texture, and (3) combined texture (a combination of the first and second patterns). In addition, this study also tested surface coating with bioactive biphasic calcium phosphate (70HaP/30β-TCP) using a laser.	LST is capable of producing three textures, namely cross-linked groove texture with 100 µm squared ridges, 30 µm groove width, and 100 µm depth; micropit texture with aligned spots of 35 µm diameter, 15 µm spacing, and 30 µm depth; and combined texture that produces 6 spots per squared ridge. Surface coating with biphasic calcium phosphate shows a smoother and more consistent surface, indicating improved quality.	LST can be a promising alternative to improve the surface quality of Zr implants.
45.	Sathish et al., (2024) [12]	The surface of the Zr implant was coated with S53P4 bioactive glass using a laser. The laser used was set with several parameters, namely laser power (1 kW, 2 kW, 3 kW, 4 kW), beam diameter (2 mm, 3 mm, 4 mm, 5 mm), powder feed rate (10 g/min, 15 g/min, 20 g/min, 25 g/min), and scanning speed (3 mm/s, 4 mm/s, 5 mm/s, 6 mm/s). All of these parameters were tested for compressive strength, microhardness, and wear resistance.	Compression strength: reaches a value of 373 MPa. Micro hardness: up to 898.37 HV0.2. Wear resistance: shows a minimum wear volume of 0.148 mm^3.	Coating S53P4 bioactive glass on Zr using laser coating process improves mechanical properties: compression strength, microhardness, and wear resistance. Optimal parameters produce strong and durable materials.
46.	Vohra et al., (2024) [13]	Thirty endosseous implants consisting of 10 titanium implants, 10 Yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) implants, and 10 selective laser melting Co-Cr (SLM-CoCr) implants were analyzed for micro-roughness	The micro-roughness (Ra) of SLM-CoCr implants was lower than Y-TZP implants, higher than Ti implants. The micro-gap of SLM-CoCr implants and Ti implants showed no significant difference, while Y-TZP implants	The SLM technique has the potential to be used to make abutments, but further research is still needed to improve the suitability of surface topography.

		(Ra) by 3D microscopy and micro-gap by Bruker micro-CT.	showed a higher micro-gap.	
47.	Zhong et al., (2024) [14]	Forty 40 selective laser melting (SLM) Zr abutments were fabricated and divided into 3 groups: SLM Zr (A), Zr (B), and polished SLM Zr (C), 20 abutments each. Surface roughness tests were performed by laser microscopy, mechanical by micro-gap. Data were analyzed using LSD and Tamhane's T2 tests ($\alpha=0.05$).	The surface roughness of abutment C (6.86±0.64 µm) was lower than A (26.52±7.12µm), the torque loss ratio in A (24.16%) was lower than B (58.26%). The micro-gap in C (2.38±1.39 µm) was significantly lower than A (8.69±5.30 µm) and similar to B (1.87±0.81 µm). There was a significant positive correlation between surface roughness values, torque loss ratio, and micro-gap ($r=0.903$, $P<0.01$ and $r=0.800$, $P<0.01$).	Polishing on SLM Zr significantly improves the roughness of the abutment interface, optimal implant-abutment fit. This method has increased the potential clinical use of SLM Zr abutments.
48	Okutan et al. (2024) [39]	Eighty zirconia samples were divided into eight groups based on different treatment protocols, including a control group without treatment, as well as air abrasion and femtosecond laser treatments both before and after the sintering process. The air abrasion process used alumina particles to increase the surface roughness, ultrashort pulse laser treatment to create micro patterns on the zirconia surface. The surface roughness was tested using a profilometer, the shear resin bond strength was tested using a universal testing machine. The results of each group were compared to determine the effectiveness of each method in increasing the surface roughness and resin bond strength.	The control group had the lowest Ra value and bond strength, the femtosecond laser group showed the highest Ra value and bond strength. Laser treatment before sintering (FBS) and the combination of FBS with air abrasion after sintering (FBS + AAS) significantly increased both parameters. Air abrasion after laser treatment did not show any significant changes compared to laser treatment alone.	The results showed that the group receiving femtosecond laser treatment, especially before sintering, produced the highest surface roughness and better resin bond strength compared to the control group. This treatment significantly increased the Ra (surface roughness) value, which contributed to the enhancement of the interaction between the resin and zirconia.

4. Discussion

Zirconia (ZrO_2) has become one of the most widely used materials in medical applications, especially in dentistry, due to its many outstanding advantages. The main advantages of zirconia include excellent biocompatibility, high mechanical strength, corrosion resistance, and esthetics close to natural teeth, making it an ideal choice for various implant applications. Research conducted by Yanget al., [57] revealed that zirconia can interact with body tissues without causing inflammatory reactions or rejection, making it very suitable for dental implants. This material has shown the ability to enhance osseointegration, which is the process of union between the implant and bone tissue. This makes it very effective in supporting the adhesion of osteoblasts, which are cells that are important in the process of bone repair and formation.

The high biocompatibility of zirconia, which can be used in the human body for a long time without significant risk of side effects, makes it a safe and effective material choice in medical applications. The mechanical strength of zirconia is also one of the main factors attracting its use. This material is known for its very high tensile strength and bending strength, much better than other ceramic materials used in dentistry such as porcelain. The results of the study that Santos et al., [58] that zirconia shows better corrosion resistance compared to other metal materials such as titanium, more durable in the corrosive environment of the human body. This is very important in increasing the durability of implants and long-term restorations, as well as reducing the potential for complications that can arise from material corrosion. Unlike other metal or composite materials, zirconia has very high transparency properties, so it can imitate the appearance of natural teeth better. This is very important in dental applications, aesthetics being one of the main factors considered by patients.

Several major problems arise in the use of zirconia prostheses in the oral cavity. One of them is the limited ability of zirconia to control plaque, which increases the risk of peri-implantitis in dentures. The oral microflora and its dynamic interaction with zirconia implants cause strong bacterial adhesion, which can eventually lead to peri-implantitis or even loss of supporting bone. Although zirconia is known as a chemically neutral material, it cannot form a direct bond with natural tissues, so it has no cohesion with bone, which causes incompatibility between the implant and the surrounding environment.

Animal studies have shown that dental zirconia implants can successfully heal bone, both under non-loading and loading conditions. However, because conventional zirconia stem fabrication generally results in a smooth surface, few studies have explored the role of surface roughness in enhancing protein adsorption and osteoblast adhesion, which in turn may improve osseointegration [13].

Surface treatment is a proper surface modification that can improve the contact between the implant and bone tissue, as well as increase the proliferation of osteoblast cells, which is important for the long-term success of the implant. By improving the physicochemical properties of the surface, surface treatment contributes to improving the quality and quantity of tissue formed around the implant, thus supporting the clinical success of the use of zirconia implants [59].

Several types of lasers used for surface treatment include femtosecond laser. This laser is used to improve the surface roughness and biological response of zirconia implants. Research shows that femtosecond laser with 10 nJ energy and 80 MHz frequency can increase adhesion, spreading, proliferation, and differentiation of osteogenic cells after laser irradiation. These results indicate that femtosecond laser is effective in modifying the zirconia surface to improve osseointegration [60]. In addition, there is also Nd: YAG Laser, this laser is also used for zirconia surface texture. Research shows that texturing with Nd: YAG laser can produce patterns that increase the interaction of osteoblasts and fibroblasts with the implant surface. Although the results show increased osteoblast cell viability, there is no significant advantage over other texturization methods such as sandblasting [61]. There is also Fiber Laser, Fiber laser is able to create micro grooves on the zirconia surface, which has been shown to increase surface roughness and support new bone formation and mechanical strength at the implant-bone interface [62].

Laser surface treatment of zirconia implants can inhibit bacterial adhesion and biofilm clustering through the mechanism of modifying the topography and surface properties of the material. Laser technology creates nanoscale microstructures or grooves that precision thereby reducing the contact area for bacteria to adhere and form biofilms [18, 47]. The hydrophobic surface produced by laser treatment makes bacterial adhesion more difficult due to reduced interaction between the bacterial cell wall and the implant surface. In addition, the resulting microstructure can interfere with biofilm formation by preventing bacteria from colonizing effectively and disrupting bacterial cell communication (quorum sensing) which are required for biofilm formation [13].

Laser surface modification of zirconia implants physically and chemically creates an environment that is not conducive to bacterial and biofilm growth, thereby increasing the potential of the implant to control infection and prolong its clinical success. However, the surface treatment method using laser technology must take into account the type of topography produced [13] found that hydrophobic surface treatment with a nanosecond laser effectively inhibited bacterial growth.Porphyromonas gingivalis(Pg), but some other types of bacteria still showed significant growth at certain times. This indicates the need for further optimization of the laser-generated surface patterns on zirconia implants.

The general impact of laser application on zirconia implants shows that laser surface treatment can significantly improve the topographic properties and biological response of the implant. Laser irradiation, especially using a femtosecond laser, has been shown to be effective in increasing surface roughness at the micro and nano scales. This increase in roughness contributes to increased wettability, which in turn supports adhesion, spreading, proliferation, and differentiation of osteogenic cells [60].

Dental implants have become a priority and reliable treatment option for patients with missing teeth [54], providing many advantages, including comfort, improved aesthetics, no damage to adjacent teeth, and significant clinical effects. With the development of material science, zirconia implants have been used to overcome the problems of metal allergy and gray color of titanium implants, providing patients with new choices for dental implant materials. In the process of implant repair, mechanical properties and osseointegration are key factors that ensure the success and long-term stability of the implant. [55].

Zirconia (Zr)-based implants provide osseointegration equivalent to other implants, thus having advantages in terms of better biocompatibility and soft tissue response [10]. Osseointegration refers to the formation of a direct connection between the implant surface and the bone tissue, without any fibrous tissue in between. This process is an important element to ensure the long-term success of the implant. The success of the implant also depends on effective tissue adhesion and is also influenced by the topography and basicity of the implant [13].

One of the main challenges in the use of zirconia for implants is its ability to achieve osseointegration, the process by which the implant fuses with the bone tissue. Several studies have shown that although zirconia has a high level of biocompatibility, the osseointegration process can be hampered by microbial colonization, which can lead to chronic inflammation or infection. and also showed that reducing the number of microbes on the surface of zirconia implants can accelerate osseointegration and reduce infection-related complications [56]. The study also showed that after three months of osseointegration, the percentage of bone-to-implant contact (BIC) on laser-modified zirconia surfaces did not show any significant difference compared to standard titanium implants. This suggests that laser-treated zirconia implants can achieve osseointegration results comparable to titanium, making them an attractive option in dentistry. In addition, parameters such as irradiation intensity, time, and frequency can be optimized to achieve the desired surface morphology and better biological response in the process. osseointegration [60]. Thus it has been proven that osseointegration between the implant surface and human bone plays an important role in the success of dental implants [18].

The relationship between zirconia implants and microbes can be seen from several studies that show the impact of surface treatment and material properties on the interaction with microorganisms around the implant. Studies have shown that zirconia implants have a lower plaque affinity than titanium implants. This means that the surface of zirconia implants tends to reduce the formation of biofilms, which are collections of microbes that can cause infections and complications such as peri-implantitis. In the study, the prevalence and quantity of periodontal bacteria around zirconia implants and natural teeth were measured. The results showed that despite the presence of bacteria, the condition of the soft tissue around zirconia implants remained healthy, with lower probing pocket depths (PPD) and minimal bleeding on probing (BOP) percentages.

Zirconia implants showed better soft tissue stability, which contributed to overall periodontal health. This study emphasized that zirconia implants are not only effective in terms of osseointegration but also in maintaining the health of the surrounding soft tissues. With the ability to reduce plaque and biofilm formation, zirconia implants can reduce the risk of infectious complications, making them an attractive option in clinical practice for patients concerned about periodontal health [71].

Recent studies have shown that zirconia surfaces, despite their biocompatible properties, are still susceptible to bacterial adhesion.Streptococcus mutans, Staphylococcus aureus, AndEscherichia coliare some bacteria that are often found attached to the surface of zirconia. This interaction has the potential to cause infection in implants, especially in areas such as the mouth and other body cavities where bacteria can easily grow. Research by [9] shows that surface modification of zirconia using femtosecond laser technology can reduce bacterial adhesion to the surface by creating micro and nanoscale structures that inhibit microbial colonization [9].

The use of laser technology in zirconia implant surface coating shows great potential to increase implant durability. Laser technology can provide significant advantages in increasing the bond strength between the coating layer and the zirconia surface, improving mechanical properties, and increasing implant biocompatibility. In addition, the application of laser technology can also optimize the production process, reduce the time required, and produce implants with more consistent and reliable quality. Thus, the application of laser technology in zirconia implant surface coating has the potential to be an innovative solution in the field of dentistry

Further research is recommended to study more deeply the variation of laser parameters that can affect the results of zirconia implant surface coating. Further research also needs to be focused on long-term testing to evaluate the durability and effectiveness of implants coated with laser technology in human body conditions, both from a mechanical and biological perspective. In addition, the development of better coating materials that are compatible with zirconia and testing against various clinical conditions also need to be considered in order to provide optimal solutions for patients. This study has several limitations that need to be noted. One of them is the limitation in testing the variation of laser types and operational parameters used in surface coating. therefore, further research is needed to overcome these limitations.

5. Conclusion

Laser technology has been proven to effectively improve the mechanical and biological properties of zirconia dental implants to prevent peri-implantitis and increase stability.

Compliance with ethical standards

Disclosure of conflict of interest

No Conflict of interest to be disclosed.

References

[1] Mahesh, K. P., Iyer, M. S., Raghavendra, S., Patil, K., & Raghunath, N. Biomaterials and Their Applications in Dentistry–A Literature Review. *J Evolution Med Dent Sci*. 2021; *10*(26) : 1940-1947.

[2] López-Píriz, R., Sevillano, D., Fernández Domínguez, M., Alou, L., González, N., Goyos-Ball, L.,Torrecillas, R. Peri-Implant Microbial Signature Shifts in Titanium, Zirconia and Ceria-Stabilized Zirconia Reinforced with Alumina Sites Subjected to Experimental Peri-Implantitis: A Preclinical Study in Dogs. *Antibiotics*. 2024; *13*(8): 690.

[3] Heboyan, A., & Bennardo, F. New biomaterials for modern dentistry. *BMC Oral Health*. 2023; *23*(1): 817.

[4] Toscano, R. A., Barbosa, S., Campos, L. G., de Sousa, C. A., Dallazen, E., Mourão, C. F., Assunção, W. G. The addition of hydroxyapatite nanoparticles on implant surfaces modified by zirconia blasting and acid etching to enhance peri-implant bone healing. *International Journal of Molecular Sciences*. 2024; 25.13: 7321.

[5] Jin HW, Noumbissi S, Wiedemann TG. Comparison of Zirconia Implant Surface Modifications for Optimal Osseointegration. *Journal of Functional Biomaterials*. 2024; 15(4):91. https://doi.org/10.3390/jfb15040091

[6] Sun L, Hong G. Surface Modifications for Zirconia Dental Implants: A Review. *Frontiers in Dental Medicine*. 2021;2:733242. doi: 10.3389/fdmed.2021.733242

[7] Romanos GE. *Laser fundamental principles*. In: Romanos GE, editor. Advanced laser surgery in dentistry. Hoboken (NJ): Wiley Blackwell; 2021. p. 3–11.

[8] Labunet A, Tonea A, Kui A, Sava S. The Use of Laser Energy for Etching Enamel Surfaces in Dentistry-A Scoping Review. *Materials* (Basel). 2022 Mar 8;15(6):1988. doi: 10.3390/ma15061988. PMID: 35329440; PMCID: PMC8949169.

[9] Ghalandarzadeh A, Ganjali M, Hosseini M. Tailoring zirconia surface topography via femtosecond laser-induced nanoscale features: effects on osteoblast cells and antibacterial properties. *Biomed Mater*. 2024 Jul 17;19(5). doi: 10.1088/1748-605X/ad606f. PMID: 39016135.

[10] Munteanu I-R, Luca R-E, Hogea E, Erdelyi R-A, Duma V-F, Marsavina L, Globasu A-L, Constantin G-D, Todea DC. Microbiological and Imaging-Based Evaluations of Photodynamic Therapy Combined with Er:YAG Laser Therapy in the In Vitro Decontamination of Titanium and Zirconia Surfaces. *Microorganisms*. 2024; 12(7):1345. https://doi.org/10.3390/microorganisms12071345

[11] Pereira, L.M. Santos R, Pereira, A.B. Ferreira, N.M. J. Mesquita-Guimarães. Double-size texturisation and biphasic calcium phosphate coatings obtained via laser technologies for bioactive zirconia dental implant surfaces. *Open Ceramics*. 2024; Vol.18: 100583. ISSN 2666-5395. https://doi.org/10.1016/j.oceram.2024.100583.

[12] Sathish, T., Giri, J., Saravanan R. Optimizing laser cladding powder injection parameters to shape bioactive glass nano-coated zirconium oxide for biomedical application. *Heliyon*. 2024 Jan 26;10(3):e25277. doi: 10.1016/j.heliyon.2024.e25277. PMID: 38318026; PMCID: PMC10839605.

[13] Vohra, F., Alsaif, R., Khan, R. Bukhari I A. Comparison of misfit and roughness of CAD-CAM ZrO, selective laser sintered CoCr and preformed Ti implant abutment crowns. *BMC Oral Health* 24, (2024) : 999. https://doi.org/10.1186/s12903-024-04735-3.

[14] Zhong P, Deng L, Xu S, Cao Y. Effect of polishing process on torque loss ratio and microgap of selective laser melting abutment: an in vitro study. *BMC Oral Health*. 2024 Sep 9;24(1):1055. doi: 10.1186/s12903-024-04829-y. PMID: 39251975; PMCID: PMC11386349.

[15] Bihn SK, Son K, Son Y-T, Dahal RH, Kim S, Kim J, Hwang JH, Kwon S-M, Lee JH, Kim HD, et al. In Vitro Biofilm Formation on Zirconia Implant Surfaces Treated with Femtosecond and Nanosecond Lasers. *Journal of Functional Biomaterials*. 2023; 14(10):486. https://doi.org/10.3390/jfb14100486

[16] Garcia-de-Albeniz N, Ginebra MP, Jimenez-Piqué E, Roa JJ, Mas-Moruno C. Influence of nanosecond laser surface patterning on dental 3Y-TZP: Effects on the topography, hydrothermal degradation and cell response. *Dent Mater*. 2024 Jan;40(1):139-150. doi: 10.1016/j.dental.2023.10.026. Epub 2023 Nov 10. PMID: 37951750.

[17] Li W, Ding Q, Sun F, Liu B, Yuan F, Zhang L, Bao R, Gu J, Lin Y. Fatigue behavior of zirconia with microgrooved surfaces produced using femtosecond laser. *Lasers Med Sci.* 2023 Jan 4;38(1):33. doi: 10.1007/s10103-022-03679-w. PMID: 36598586.

[18] Majidian H, Ghalandarzadeh A, Kaboosi M, Nikzad L, Ganjali M. Influence of laser intensity and $BaTiO_3$ content on the surface properties of 3YSZ. *Odontology*. 2024 Apr;112(2):408-427. doi: 10.1007/s10266-023-00853-6. Epub 2023 Oct 4. PMID: 37792126.

[19] Ghalandarzadeh A, Javadpour J, Majidian H, Ganjali M. The evaluation of prepared microstructure pattern by carbon-dioxide laser on zirconia-based ceramics for dental implant application: an in vitro study. *Odontology*. 2023 Jul;111(3):580-599. doi: 10.1007/s10266-022-00781-x. Epub 2022 Dec 22. PMID: 36547737.

[20] Li Q, Li C, Wang Y. Effect of femtosecond laser ablate ultra-fine microgrooves on surface properties of dental zirconia materials. *J Mech Behav Biomed Mater*. 2022 Oct;134:105361. doi: 10.1016/j.jmbbm.2022.105361. Epub 2022 Jul 21. PMID: 35939951.

[21] Li M, Komasa S, Hontsu S, Hashimoto Y, Okazaki J. Structural Characterization and Osseointegrative Properties of Pulsed Laser-Deposited Fluorinated Hydroxyapatite Films on Nano-Zirconia for Implant Applications. *Int J Mol Sci*. 2022 Feb 22;23(5):2416. doi: 10.3390/ijms23052416. PMID: 35269557; PMCID: PMC8910007.

[22] Moura CG, Dinis H, Carvalho O, Mendes PM, Nascimento RM, Silva FS. A Novel Approach for Micro-Antenna Fabrication on ZrO_2 Substrate Assisted by Laser Printing for Smart Implants. *Applied Sciences*. 2022; 12(18):9333. https://doi.org/10.3390/app12189333

[23] Staehlke S, Oster P, Seemann S, Kruse F, Brief J, Nebe B. Laser Structured Dental Zirconium for Soft Tissue Cell Occupation-Importance of Wettability Modulation. *Materials* (Basel). 2022 Jan 19;15(3):732. doi: 10.3390/ma15030732. PMID: 35160678; PMCID: PMC8836786.

[24] Garófalo SA, Wehner M, Dohrn A, Bilandžić MD, Roos C, Wierichs RJ, Meyer-Lueckel H, Aranha ACC, Esteves-Oliveira M. Increasing dental zirconia micro-retentive aspect through ultra-short pulsed laser microstructuring: study on flexural strength and crystal phase characterization. *Clin Oral Investig*. 2022 Jan;26(1):939-955. doi: 10.1007/s00784-021-04077-2. Epub 2021 Aug 17. PMID: 34402980; PMCID: PMC8791917.

[25] Li WJ, Ding Q, Yuan FS, Sun FB, Zheng JQ, Bao R, Zhang L. Effects of femtosecond laser treatment on surface characteristics and flexural strength of zirconia. Beijing Da Xue Xue Bao Yi Xue Ban. 2021 Aug 18;53(4):770-775. *Chinese*. doi: 10.19723/j.issn.1671-167X.2021.04.025. PMID: 34393243; PMCID: PMC8365050.

[26] Wawrzyk A, Łobacz M, Adamczuk A, Sofińska-Chmiel W, Wilczyński S, Rahnama M. The Use of a Diode Laser for Removal of Microorganisms from the Surfaces of Zirconia and Porcelain Applied to Superstructure Dental Implants. *Microorganisms*. 2021 Nov 15;9(11):2359. doi: 10.3390/microorganisms9112359. PMID: 34835484; PMCID: PMC8625943.

[27] Faria D, Madeira S, Buciumeanu M, Silva FS, Carvalho O. Novel laser textured surface designs for improved zirconia implants performance. *Mater Sci Eng C Mater Biol Appl*. 2020 Mar;108:110390. doi: 10.1016/j.msec.2019.110390. Epub 2019 Nov 7. PMID: 31923937.

[28] Moura, D. Faria, O. Carvalho, RSF. Pereira, MF. Cerqueira, RM. Nascimento, FS. Silva. Laser printing of silver-based micro-wires in ZrO2 substrate for smart implant applications. *Optics & Laser Technology*. 2020; 131 : 106416.

[29] Kitajima H, Komatsu K, Matsuura T, Ozawa R, Saruta J, Taleghani SR, Cheng J, Ogawa T. Impact of nano-scale trabecula size on osteoblastic behavior and function in a meso-nano hybrid rough biomimetic zirconia model. *J Prosthodont Res*. 2023 Apr 12;67(2):288-299. doi: 10.2186/jpr.JPR_D_22_00015. Epub 2022 Jul 21. PMID: 35858802.

[30] Cano-Velázquez MS, Bon J, Llamazares M, Camacho-López S, Aguilar G, Hernández-Cordero J, Trujillo M. Experimental and computational model approach to assess the photothermal effects in transparent nanocrystalline yttria stabilized zirconia cranial implant. *Comput Methods Programs Biomed*. 2022 Jun;221:106896. doi: 10.1016/j.cmpb.2022.106896. Epub 2022 May 16. PMID: 35617809.

[31] Tzanakakis E, Kontonasaki E, Voyiatzis G, Andrikopoulos K, Tzoutzas I. Surface characterization of monolithic zirconia submitted to different surface treatments applying optical interferometry and raman spectrometry. *Dent Mater J*. 2020 Jan 31;39(1):111-117. doi: 10.4012/dmj.2018-358. Epub 2019 Oct 12. PMID: 31611497.

[32] Sun, Y., Sun, J., Wu, X., Li, Y., Li, X., Li, R., & Yu, Y. Mechanism of zirconia microgroove surface structure for osseointegration. *Materials Today Advances*. 2021; 12 : 100159.

[33] Li, Y., Liang, H., Xie, D., Shen, L., Tian, Z., Ahsan, N., & Xiao, M. Study on properties and biocompatibility of ZrO 2/Ti composites prepared by selective laser melting. In *2020 17th International Bhurban Conference on Applied Sciences and Technology (IBCAST)*. 2020 : pp. 5-11.

[34] da Cruz MB, Marques JF, Fernandes BF, Pinto P, Madeira S, Carvalho Ó, Silva FS, Caramês JMM, da Mata ADSP. Laser surface treatment on Yttria-stabilized zirconia dental implants: Influence on cell behavior. *J Biomed Mater Res B Appl Biomater*. 2022 Jan;110(1):249-258. doi: 10.1002/jbm.b.34909. Epub 2021 Jul 18. PMID: 34278714.

[35] Henriques, B., Fabris, D., Voisiat, B., Boccaccini, A. R., & Lasagni, A. F. Direct Laser Interference Patterning of Zirconia Using Infra-Red Picosecond Pulsed Laser: Effect of Laser Processing Parameters on the Surface Topography and Microstructure. *Advanced Functional Materials*, 2024; 34.2: 2307894.

[36] da Silva BTF, Trevelin LT, Schroeter AC, Willers AE, Cesar PF, Matos AB. Effect of silica coating and laser treatment on the flexural strength, surface characteristics, and bond strength of a dental zirconia. *Eur J Oral Sci*. 2021 Feb;129(1):e12754. doi: 10.1111/eos.12754. Epub 2021 Jan 27. PMID: 33501718.

[37] Henriques, B., Fabris, D., Voisiat, B., & Lasagni, A. F. Fabrication of Multiscale and Periodically Structured Zirconia Surfaces Using Direct Laser Interference Patterning. *Advanced Functional Materials*, 2024, 34.49: 2408949.

[38] Pu, Z., Jing, X., Yang, C., Wang, F., & Ehmann, K. F. Wettability modification of zirconia by laser surface texturing and silanization. *International Journal of Applied Ceramic Technology*, 2020, 17.5: 2182-2192.

[39] Okutan, Y., Kandemir, B., Gundogdu, Y., Kilic, H. S., & Yucel, M. T. Combined application of femtosecond laser and air-abrasion protocols to monolithic zirconia at different sintering stages: Effects on surface roughness and resin bond strength. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*. 2021; *109*(4): 596-605.

[40] Cai P, Zhuo Y, Lin J, Zheng Z. Er:YAG laser removal of zirconia crowns on titanium abutment of dental implants: an in vitro study. *BMC Oral Health*. 2022 Sep 12;22(1):396. doi: 10.1186/s12903-022-02427-4. PMID: 36096836; PMCID: PMC9469558.

[41] Ji, Y., Zhang, J., Hou, M., Jin, M., Chen, S., Tan, J.,Wang, T. osseointegration of titanium-based and zirconia implants: novel perspective on features, influencing factors and improvements. *Journal of Materials Science*, 2024, 59.34: 16020-16037.

[42] Birand C, Kurtulmus-Yilmaz S. Evaluation of Er,Cr:YSGG laser irradiation for debonding of zirconia hybrid abutment crowns from titanium bases. *Lasers Med Sci*. 2022 Aug;37(6):2675-2685. doi: 10.1007/s10103-022-03539-7. Epub 2022 Mar 7. PMID: 35254569.

[43] Dikicier S, Korkmaz C, Atay A. Surface roughness and characteristics of CAD/CAM zirconia and glass ceramics after combined treatment procedures. *BMC Oral Health*. 2022 Nov 23;22(1):524. doi: 10.1186/s12903-022-02389-7. PMID: 36419112; PMCID: PMC9685924.

[44] Okutan Y, Gundogdu Y, Donmez MB, Seker H, Kilic HS. Effect of femtosecond laser induced surface patterns on the flexural strength of monolithic zirconia. *J Biomed Mater Res B Appl Biomater*. 2024 Jun;112(6):e35432. doi: 10.1002/jbm.b.35432. PMID: 38817034.

[45] Suliman S, Sulaiman T, Deeb JG, Abdulmajeed A, Abdulmajeed A, Närhi T. Effect of Er:YAG laser on debonding zirconia and lithium disilicate crowns bonded with 2- and 1-bottle adhesive resin cements. *J Esthet Restor Dent*. 2024 Dec;36(12):1687-1692. doi: 10.1111/jerd.13274. Epub 2024 Jun 25. PMID: 38923782.

[46] Silva, N.,Marques, J., Caramês, J.,Silva, F., Mata, A., da Cruz, M.B. The Impact of Using Laser and Milling Techniques to Create Zirconia Patterns on *Streptococcus oralis* Biofilm Formation. *Ceramics*. *7*. 2024 ; 1855-1866. https://doi.org/10.3390/ceramics7040116

[47] Alkhudhairy F. Canal disinfection using Nd: YAG Laser, synchronized microbubble-photodynamic activation, and carbon quantum dots on microhardness, smear layer removal, and extrusion bond strength of zirconia post to canal dentin. An invitro scanning electron microscopic analysis. *Microsc Res Tech*. 2024 Sep;87(9):2043-2052. doi: 10.1002/jemt.24584. Epub 2024 Apr 22. PMID: 38646819.

[48] Hassouna M, Al-Zordk W, Aboshilib M, Ghazy M. Clinical and radiographic prospective study of customized one-piece titanium and one-piece fusion-sputtered zirconia implants: five-year mean follow-up. *BMC Oral Health*. 2022 Nov 24;22(1):531. doi: 10.1186/s12903-022-02600-9. PMID: 36424624; PMCID: PMC9685929.

[49] Elkharashi A, Grzech-Leśniak K, Deeb JG, Abdulmajeed AA, Bencharit S. Exploring the use of pulsed erbium lasers to retrieve a zirconia crown from a zirconia implant abutment. *PLoS One*. 2020 Jun 1;15(6):e0233536. doi: 10.1371/journal.pone.0233536. PMID: 32479553; PMCID: PMC7263620.

[50] Noumbissi, S. and Gupta, S. Zirconia as a Viable Implant Material in Implant Dentistry. In Implant Dentistry. *Saving Dental Implants*. 2024 ; 483-502. https://doi.org/10.1002/9781119807049.ch25

[51] El-Hady, A. I. A., Eid, H. I., Mohamed, S. L., & Fadl, S. M. Influence of titanium and titanium-zirconium alloy as implant materials on implant stability of maxillary implant retained overdenture: a randomized clinical trial. *BMC Oral Health*, 2024, 24.1: 902.

[52] Tan X, Zhao Y, Lu Y, Yu P, Mei Z, Yu H. Physical and biological implications of accelerated aging on stereolithographic additive-manufactured zirconia for dental implant abutment. *J Prosthodont Res*. 2022 Oct 7;66(4):600-609. doi: 10.2186/jpr.JPR_D_21_00240. Epub 2021 Dec 17. PMID: 34924492.

[53] Kreve S, Ferreira I, Dos Reis AC. Zirconia Implants Produced by Additive Manufacturing - A Scoping Review. *Eur J Prosthodont Restor Dent.* 2024 Feb 29;32(1):9-19. doi: 10.1922/EJPRD_2513Kreve11. PMID: 37721549.

[54] Yamamuro, Y., Shimoyama, T., & Yan, J. Microscale surface patterning of zirconia by femtosecond pulsed laser irradiation. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 2022, 9.2: 619-632.

[55] Balmer M, Spies BC, Kohal RJ, Hämmerle CH, Vach K, Jung RE. Zirconia implants restored with single crowns or fixed dental prostheses: 5-year results of a prospective cohort investigation. *Clin Oral Implants Res*. 2020 May;31(5):452-462. doi: 10.1111/clr.13581. Epub 2020 Feb 5. PMID: 31981374.

[56] Feng, J., Zhang, L., & Zhao, Y. Effects of surface modification on the osseointegration and antibacterial properties of zirconia implants. *Journal of Materials Science: Materials in Medicine*. 2021; 32(6): 67. https://doi.org/10.1007/s10856-021-06435-7

[57] Yang, J., Zhang, H., & Wang, Y. Biocompatibility and osteointegration of zirconia implants in the oral cavity: a systematic review. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*. 2020 ; 108(1) : 157-167. https://doi.org/10.1002/jbm.b.34102

[58] Santos, D., Silva, D., & Garcia, L. Corrosion resistance of zirconia in oral environment: A systematic review. *Journal of Dental Research*. 2022 ; 101(3) : 298-305. https://doi.org/10.1177/00220345211062409

[59] Li J, Jiang CD, Ye H, Wang Y, Zhu YC, Wang DL. Research progress on surface treatment technology of zirconia implant. Zhonghua Kou Qiang Yi Xue Za Zhi. 2020 Sep 9;55(9):691-695. *Chinese*. doi: 10.3760/cma.j.cn112144-20200409-00201. PMID: 32878408.

[60] Cunha W, Carvalho O, Henriques B, Silva FS, Özcan M, jia JCM. Surface modification of zirconia dental implants by laser texturing. *Lasers Med Sci*. 2022 Feb;37(1):77-93. doi: 10.1007/s10103-021-03475-y. Epub 2022 Jan 13. PMID: 35022871.

[61] da Cruz MB, Marques JF, Fernandes BF, Pinto P, Madeira S, Carvalho Ó, Silva FS, Caramês JMM, da Mata ADSP. Laser surface treatment on Yttria-stabilized zirconia dental implants: Influence on cell behavior. *J Biomed Mater Res B Appl Biomater*. 2022 Jan;110(1):249-258. doi: 10.1002/jbm.b.34909. Epub 2021 Jul 18. PMID: 34278714.

[62] Sun L and Hong G. Surface Modifications for Zirconia Dental Implants: A Review. *Front. Dent. Med.* 2021; 2:733242. doi: 10.3389/fdmed.2021.733242

[63] Sun J, Ding Q, Chen Y, Li J, Wang Z, Wei Z, Ge X, Zhang L. Effects and underlying mechanism of micro-nano-structured zirconia surfaces on biological behaviors of human gingival fibroblasts under inflammatory conditions. Acta Biomater. 2024 Jul 15;183:356-370. doi: 10.1016/j.actbio.2024.05.031. Epub 2024 May 18. PMID: 38768742.