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**Review Article**

# Biomechanical and Biological Performance of Next-Generation Materials in Implant-Supported Prosthetic Restorations

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**Abstract:** The evolution of implant-supported prosthetic restorations has been driven strongly by the pursuit of improved biomechanical stability, biological compatibility, and aesthetic integration. While titanium and cobalt-chromium alloys remain the conventional choice due to their proven strength and corrosion resistance, limitations related to soft tissue interaction and esthetics have accelerated the transition toward advanced ceramic alternatives, particularly zirconia. Zirconia implants and abutments demonstrate favorable biological responses and excellent esthetics; however, their inherent brittleness and reduced fracture resistance under functional loading remain critical concerns. To overcome these challenges, zirconia–titanium hybrid abutments have emerged as a promising solution, uniting the strength of titanium with the soft-tissue and esthetic advantages of zirconia. Parallel to these developments, additive manufacturing (AM) techniques, such as selective laser melting (SLM) and direct metal laser sintering (DMLS), have enabled the fabrication of highly precise and patient-specific prosthetic frameworks. Evidence indicates that AM-produced titanium infrastructures exhibit mechanical properties equal to or superior to those of conventional casting, while additively manufactured zirconia, despite having lower flexural strength compared to subtractively manufactured zirconia, demonstrates promising clinical applicability. Clinical outcomes highlight restoration-type-specific complication patterns, with screw loosening, veneer chipping, and peri-implant inflammation being the most frequently observed. Furthermore, advances in surface optimization, digital workflows, and artificial intelligence–assisted planning are contributing to enhanced long-term clinical performance. Despite these innovations, limitations persist regarding the standardization of AM protocols, the availability of long-term clinical data, and comprehensive patient-specific risk assessment. Future directions should prioritize multicenter longitudinal studies, advanced biomechanical simulations, and the integration of next-generation materials with digital technologies to optimize both biomechanical and biological outcomes of implant-supported prosthetic restorations.

**Keywords:** Dental İmplantology, İmplant-Supported Prostheses, Zirconia, Titanium, Hybrid Abutments, Additive Manufacturing, Biomechanical Performance, Biological Response.

## INTRODUCTION

In recent decades, dental implantology has undergone a significant transformation in dental practice, and implant-supported prosthetic treatments have created high expectations in terms of esthetics, function, and patient satisfaction. While osseointegration of implants with bone is the first stage of success, factors such as the mechanical load-bearing capacity of the restoration, connection details, the biocompatibility of the material used, and the impact on peri-implant tissues are also critical for long-term outcomes. For conventional prosthetic frameworks, titanium and cobalt-chromium alloys have been preferred due to their long-term durability, corrosion resistance, and mechanical performance. However, especially in the anterior region, esthetic demands and disadvantages such as the grayish hue of titanium causing pigmentation in patients with thin gingival biotypes have strengthened the shift toward ceramic alternatives. For instance, in the systematic review titled "Esthetic, mechanical, and biological outcomes of various implant abutments", it was reported that ceramic abutments are particularly advantageous in terms of color matching compared to titanium or gold



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abutments; nevertheless, certain limitations remain regarding brittleness and material-connection stability [1]. Zirconia implants and abutments, particularly with their white color, provide esthetic advantages and offer a favorable biological response in terms of low plaque accumulation and soft tissue adaptation. When comparing the long-term survival and success rates of titanium and zirconia implants, it is emphasized that zirconia represents a suitable alternative, especially in cases with high esthetic demands [2].

At the same time, in recent years, the use of 3D printing/additive manufacturing techniques for metal infrastructures and frameworks has been increasingly observed. Bars and frameworks produced for metal alloys using methods such as SLM and DMLS provide design flexibility and the advantage of patient-specific fabrication. However, the effects of manufacturing parameters (e.g., layer orientation, surface roughness, heat treatments) on mechanical strength and fatigue performance remain an ongoing subject of research. While metal AM techniques offer clear advantages, uncertainties regarding surface finishing and post-processing requirements persist [3]. Another recent study reported that, after a one-year follow-up period, titanium implants demonstrated lower marginal bone loss and higher survival rates compared to zirconia; however, no significant differences were found in specific biological indicators (e.g., plaque index, bleeding measures) [4].

Taken together, these findings underscore the importance of material selection, prosthetic design, and manufacturing techniques in achieving both esthetic and functional success in implant-supported restorations. While titanium remains a gold standard in terms of long-term survival and mechanical reliability, zirconia offers distinct advantages in esthetic outcomes and soft tissue compatibility. Concurrently, the advent of additive manufacturing techniques opens new possibilities for patient-specific and complex prosthetic designs, although further research is necessary to optimize mechanical performance and post-processing protocols. Therefore, a comprehensive understanding of material properties, biological responses, and manufacturing parameters is essential to maximize the longevity and clinical success of modern implant-supported restorations.

**1. Zirconia–Titanium Hybrid Structures**

Among the framework materials used in dental implantology, titanium has long been considered the “gold standard” due to its biocompatibility, corrosion resistance, and high mechanical strength. However, especially in the anterior region, increasing esthetic demands and the gray metallic hue of titanium becoming visible through soft tissue translucency have highlighted certain disadvantages. In this context, zirconia has emerged as an essential alternative, offering high esthetic compatibility, low plaque accumulation, and good soft tissue integration due to its white color. Nevertheless, the brittleness and low fracture toughness of zirconia can limit its use under high occlusal loads, particularly in the posterior region. Therefore, in recent years, hybrid structures combining zirconia and titanium have been developed. In these hybrid systems, the implant–abutment connection region is made of titanium, while the superstructure or visible portions are fabricated from zirconia. In this way, the mechanical strength of titanium is combined with the esthetic advantages of zirconia, providing more balanced solutions in terms of clinical performance [1]. For example, a systematic review highlighted that hybrid abutments have favorable biological effects on peri-implant tissues and provide a more natural soft tissue esthetics compared to titanium; however, they may fall short of fully titanium abutments in terms of mechanical durability [5].

Moreover, the advancement of CAD/CAM 82lümina82onal has made it possible to fabricate individualized hybrid abutments. Using this approach, the zirconia superstructure can be customized according to the patient’s gingival contours and tooth morphology, while the titanium base ensures stability at the implant–abutment connection. This approach stands out in meeting both aesthetic and functional expectations [6].

In conclusion, zirconia–titanium hybrid structures are increasingly preferred, particularly in esthetic regions, to enhance long-term stability. However, long-term clinical follow-up studies remain limited, and issues such as fracture risk and connection success continue to be investigated.

**2. Implant-Supported Prostheses Fabricated Using 3D Printing (Additive Manufacturing)**

In dentistry, additive manufacturing (AM), also known as 3D printing technology, has introduced groundbreaking innovations in prosthetic treatments over the past decade. Particularly in the fabrication of frameworks, bars, and abutments used in implant-supported prostheses, AM provides faster, more precise, and patient-specific solutions compared to conventional casting and milling techniques [7].

**2.1 Technologies Used**

Among the most commonly used methods in 3D Printing are:

- Selective Laser Melting (SLM)
- Direct Metal Laser Sintering (DMLS)
- Electron Beam Melting (EBM)

These methods allow biocompatible metals such as titanium and cobalt-chromium alloys to be processed layer by layer into implant-supported structures. Studies have shown that titanium frameworks produced using SLM exhibit a more homogeneous microstructure and lower porosity compared to those fabricated by conventional casting methods [8].

### 2.2 Biomechanical Performance

3D printing technologies have shown promising results, particularly in terms of load distribution and fatigue resistance. Some in vitro studies indicate that implant bars produced using SLM exhibit similar or even higher mechanical strength compared to conventionally cast bars. However, surface roughness and manufacturing parameters play a critical role in these outcomes [9].

### 2.3 Clinical Applications

One of the most significant advantages of 3D Printing is the ability to design patient-specific restorations. Using CAD files derived from digital scanning data, individualized implant-supported bars, bridges, and prosthetic frameworks can be fabricated. This approach is particularly beneficial in full-arch rehabilitations, such as All-on-Four and All-on-Six treatments, as it shortens treatment time and improves cost-effectiveness [10].

### 2.4 Limitations and Future Perspectives

Although 3D printing technologies are rapidly advancing, certain limitations remain. The surface roughness and microstructural variations of metal frameworks produced by SLM and DMLS can negatively affect long-term fatigue resistance. Additionally, the lack of standardization in these methods can result in variations in clinical success from one center to another. Nevertheless, it is anticipated that these limitations can be overcome by optimizing parameters such as powder particle size, laser power, and layer thickness [11].

## 3. Additively Manufactured (AM) Zirconia: New Horizons

Traditionally, zirconia ceramics have been fabricated using subtractive manufacturing (SM) methods such as milling and sintering. However, recent advancements in 3D printing and additive manufacturing (AM) techniques have garnered increased interest due to their advantages, including geometric freedom, reduced material waste, the ability to create personalized structures, and potential cost benefits. This section examines the mechanical, surface, and clinical performance of AM zirconia, as well as its advantages and limitations, in light of recent studies [12].

### 3.1 Mechanical and Surface Properties

- Lee-Gang Yoo *et al*., Compared the flexural strength (FS), Vickers hardness, and surface roughness parameters of additively manufactured (AM) zirconia and subtractively manufactured (SM) zirconia. The results indicated that zirconia produced using SM methods generally exhibited higher flexural strength compared to AM zirconia; however, AM zirconia also provided clinically acceptable FS values. Surface treatments (e.g., alümina sandblasting) were found to affect both FS and surface roughness [13].
- The review titled "3D printed zirconia used as dental materials: a critical review" comprehensively examines the physical and adhesive properties, accuracy, biocompatibility, and clinical applications of AM zirconia materials. The review indicates that AM zirconia can potentially exhibit properties comparable to SM zirconia; however, it emphasizes the importance of optimizing manufacturing parameters and surface treatments [12].
- The study titled "Mechanical and surface properties of additive manufactured zirconia …" investigated specimens produced using a stereolithography (SLA)-based AM system with zirconia paste, examining the effects of build orientation (parallel, diagonal, perpendicular) on flexural strength, hardness, fracture toughness, elastic modulus, and surface characteristics. The study found that orientation had a significant impact on these properties [14].
- The study titled "Mechanical properties and crown accuracy of additively manufactured zirconia restorations" compared AM-fabricated zirconia crowns with SM crowns in terms of marginal fit and crown accuracy. The results indicated that the measured parameters were at clinically acceptable levels [15].

### 3.2 Clinical Performance and Applications

- The study *"Clinical outcomes of zirconia implants: a systematic review and meta-analysis"* examined the long-term clinical outcomes of zirconia implants (success/survival rates, complications), highlighting that these implant systems may be a good alternative to titanium implants in esthetic regions; however, it emphasized that the number of studies and follow-up periods remains limited [16].
- The systematic review *"The Use of Zirconia for ISFCDPs (implant-supported fixed complete dental prostheses)"* reported survival rates ranging from 88% to 100% for zirconia in full-arch fixed prosthetic restorations. Prosthetic complications were mostly related tossues such as veneer fractures or chipping [17].
- Clinical trial records under the title *"Monolithic Zirconia Full-Mouth Implant Supported Rehabilitation Behavior"* (ClinicalTrials.gov) indicated that in zirconia-implant prosthetic rehabilitations, both AM and SM crowns are being monitored for full-mouth restorations [17].

- The in vitro study *"Fracture Resistance of Additively Manufactured Monolithic vs Bi-Layered Alumina-Toughened Zirconia Crowns…"* compared AM monolithic zirconia crowns with bi-layered (alümina-toughened) zirconia crowns; no statistically significant difference in fracture resistance was found, and both groups demonstrated performance levels sufficient to meet clinical requirements [18].
- The study *"Analysis of 3D-Printed Zirconia Implant Overdenture Bars"* emphasized the cost and weight advantages of 3D-printed zirconia bars, underlining the importance of thermal and structural design in relation to the effects of heavy prostheses on bone microstrain [19].

### 3.3 Advantages & Limitations

**Advantages:**

- **Geometric complexity:** Lattice structures, lightweight bars, and complex crown inner geometries can be more easily fabricated through AM. This provides advantages in terms of both weight reduction and material utilization [19].
- **Customization**: Optimization can be achieved through parameters such as build orientation, sintering time, paste properties, and structural design, facilitating the fulfillment of both functional and esthetic expectations [12].
- **Meeting clinical esthetic expectations**: Studies have shown that AM zirconia crowns and prostheses achieve satisfactory results in terms of marginal fit, appearance, and patient satisfaction, when compared with SM crowns [15].

**Limitations**:

- **Mechanical strength disadvantages compared to SM zirconia:** Parameters such as flexural strength and fracture toughness have sometimes been reported to be lower in the AM group. These differences are closely related to manufacturing parameters such as layer thickness, orientation, and sintering temperature/speed [13].
- **Surface roughness, microcrack formation, and phase transformations (tetragonal ↔ monoclinic):** These are critical factors influencing the brittleness of ceramics, making surface treatments (air abrasion, polishing, etc.) essential [13].
- **Limitations in clinical data:** Current studies often have short follow-up durations, small patient cohorts, aö ölümina predominantly single-center. Additionally, for AM zirconia implant systems, factors such as screw connection design and crown attachment type may influence performance. In particular, pilot clinical studies on "two-piece zirconia implant systems" have reported 12-month survival rates lower than expected [20].

### 3.4 Future Directions and Recommendations

- Standardization of manufacturing protocols: Control and optimization of factors such as layer thickness, sintering parameters, and structural orientation.
- Long-term clinical follow-up studies: Especially those with observation periods of ≥5 years, including various implant systems and loading protocols.
- Biomechanical modeling and finite element analyses: To evaluate stress distribution and document which design parameters are critical at crown–abutment and abutment–implant interfaces.
- Surface treatments and biocompatibility studies: Further research on non-mechanical effects (cell behavior, plaque accumulation, soft tissue adaptation), along with more data on patient satisfaction and the perception of functional outcomes.

Additively manufactured (AM) zirconia has emerged as a promising material supported by numerous laboratory studies, in vitro tests, and early clinical data. Although its mechanical properties may be lower than those of subtractively manufactured (SM) zirconia in certain aspects, they have been found adequate for many clinical applications. Its potential use is particularly high in anterior regions where esthetic demands are critical, as well as in full-arch prosthetic rehabilitations. However, achieving reliable long-term clinical outcomes and establishing control over manufacturing and delivery parameters remain essential for realizing this potential.

## 4. Clinical Application Areas and Complication Profiles

### 4.1 Full-Arch Fixed Restorations (All-on-4 / All-on-6, etc.)

Full-arch implant-supported fixed restorations (protocols such as All-on-4/6) are widely applied due to their ability to rapidly restore function and esthetics in complete edentulism. Although the literature reports high survival rates for full-arch prosthetics, both mechanical complications (framework fractures, porcelain chipping, screw-related issues) and biological complications (peri-implantitis, marginal bone loss, soft tissue problems) are frequently documented (Vozzo *et al*., 2023). For instance, large cohort studies such as those by Papaspyridakos *et al*., have demonstrated high survival rates at 5-year follow-up; however, they also reported minor but clinically relevant complications related to porcelain chipping and framework integrity [21]. The magnitude and direction of occlusal loading in full-arch cases directly influence the choice of a rigid framework and connection design (screw-retained vs. cement-retained, framework thickness, number and position of supporting implants). Improper design may increase the risk of screw loosening and framework fractures caused by sled-like loading patterns [22].

**4.2 Implant-Supported Overdentures (Locator, Bar, Ball, etc.)**

Removable overdentures supported by two or more implants are particularly favored in the mandibular arch due to their ability to improve patient satisfaction and function. The complication profiles differ among attachment systems (Locator, bar, ball). Locator systems have generally been reported to require less maintenance and to exhibit fewer complications, whereas bar systems are more frequently associated with mechanical component wear, splint/framework fractures, and soft tissue irritations. The most common problems in overdenture systems include loss of retention (retentive element wear), the need for locator cap replacement, attachment misalignment, and fractures or abrasion of prosthetic plastic/acrylic components. In addition, the 5-year cost and maintenance burden can be significant, particularly in the elderly population [23].

**4.3 Implant-Supported Single Crowns and Short-Span Fixed Dental Prostheses (FDPs)**

For single implant-supported crowns, the most frequently reported technical complications are screw/abutment loosening and screw fracture, while biological complications include peri-implant mucosal lesions and peri-implantitis. Systematic reviews have reported rates of screw loosening and the incidence of peri-implant mucosal problems over 5-year periods [24]. Proper torque application, adherence to manufacturer guidelines in screw and abutment selection, adequate oxidation and surface fit, and ensuring preload stability help reduce loosening. Furthermore, the choice of retention type (screw-retained vs. cement-retained) influences the technical complication profile [25].

**4.4 Classification of Complications — Mechanical vs. Biological**
**Mechanical / Prosthetic Complications**

- **Screw/abutment loosening:** One of the most frequently encountered technical complications. Systematic reviews have reported loosening rates within 5-year intervals [26].
- **Screw or implant fractures**: These may occur particularly in narrow-diameter 85lümina85ona inadequately designed implant–abutment connections [27].
- **Framework/bar fractures and porcelain (veneer) chipping**: Frequently reported, especially in metal-ceramic or zirconia-veneered restorations. Chipping is particularly common in full-arch prostheses [28].
- **Wear of retentive elements (e.g., locator caps, O-rings):** Common in overdentures and often requires periodic component replacement [29].
- **Biological Complications**
- **Peri-implant mucositis and peri-implantitis:** Typically associated with plaque accumulation, poor oral hygiene, systemic conditions, and smoking. Several reports have demonstrated a significant incidence of peri-implantitis in clinical series [30].
- **Marginal bone loss:** Can result from overloading, micromovement, biological reactions, or improper connection design. Some studies have shown that marginal bone loss varies depending on implant type and prosthetic design [30].

**4.5 Risk Factors for Complications**

- **Design & manufacturing factors:** Inadequate framework thickness, weak connection details, improper torque application, poor prosthetic fit, 3D printing parameters, or casting errors can all increase the likelihood of mechanical failure [31].
- **Patient-related factors:** Bruxism, high occlusal forces, low bone volume, poor oral hygiene, uncontrolled systemic diseases, and smoking increase the risk of implant failure and complications [28].
- **Attachment type**: In overdenture cases, the choice of attachment (bar vs. locator vs. ball) influences maintenance requirements, risk of retention loss, and soft tissue reactions [29].

**4.6 Complication Management and Prevention Strategies**

1. **Planning & design:** Digital planning and adequate biomechanical analysis (e.g., FEA) to reinforce critical sections; optimizing implant number/position according to load distribution [28].
2. **Appropriate material selection**: In anterior esthetic cases, zirconia-based hybrid solutions may be considered; in posterior regions or in patients with heavy occlusion, the durability of titanium may be preferred [17].
3. **Proper torque and connection protocols**: Adhering to manufacturer torque recommendations and performing torque re-checks (within the first week/month) reduces loosening [32].
4. **Periodic maintenance & patient education**: Regular monitoring/replacement of overdenture retentive components, professional cleaning, plaque control, and smoking cessation counseling are essential [33].
5. **Early intervention:** Timely detection of screw loosening or small cracks can prevent more severe fractures; regular follow-ups are crucial [26].

**4.7 Summary and Clinical Implications**

- The most common technical complications in implant-supported restorations are screw loosening, retentive element wear, and porcelain chipping, while the primary biological complications are peri-implant mucositis and peri-implantitis [26].
- The complication profile depends on multiple factors, including the type, material, design, and number of implants, as well as patient-specific characteristics. Therefore, patient-specific planning, appropriate material selection, and regular maintenance significantly enhance long-term success [28].

**5. Biocompatibility, Plaque Accumulation, and Peri-implant Tissue Health**

The long-term success of implant-supported prostheses is influenced not only by mechanical stability and esthetic integration but also by biocompatibility, plaque control, and the health of peri-implant tissues. Therefore, both the choice of material and prosthesis design directly affect peri-implant tissue conditions.

**5.1 Biocompatibility**

Biocompatibility refers to the ability of a material to function in the body without eliciting toxic or immunological responses. The primary materials used in implant-supported prostheses include:

**Titanium:**

Long considered the gold standard, titanium exhibits high biocompatibility. Its surfaces support osseointegration and elicit a low inflammatory response [34].

**Zirconia:**

In addition to esthetic advantages, zirconia demonstrates a lower tendency for plaque accumulation and good soft tissue adaptation. Studies have shown that zirconia surfaces promote less bacterial colonization compared to titanium [35].

Surface roughness and chemical coatings also influence biocompatibility; excessively rough or irregular surfaces can increase microbial accumulation and peri-implant inflammation [36].

**5.2 Plaque Accumulation**

Plaque accumulation is a primary risk factor for peri-implant tissue inflammation and long-term failure. Prosthesis design, attachment type, and material play a decisive role in plaque control:

**Zirconia Prostheses:**

Especially monolithic designs, reduce plaque accumulation due to smaller surface area and lower roughness [35].

**Titanium Frameworks:**

Particularly in open-surfaced bar systems, plaque accumulation may be higher. Regular cleaning and proper oral hygiene instruction are essential [36].

**3D-Printed Prostheses:**

Microgeometry and production orientation can optimize surface roughness, thereby reducing bacterial colonization [37].

Moreover, prosthetic design that accommodates the patient's own oral hygiene routine, with appropriate spacing and contours, is critical in minimizing plaque accumulation and peri-implant tissue inflammation.

**5.3 Peri-implant Tissue Health**

The health of peri-implant tissues is critical for the long-term functionality of implants. Clinically, peri-implant mucositis and peri-implantitis are the primary biological complications:

**Peri-İmplant Mucositis:**

Characterized solely by inflammation of the soft tissues; it is reversible if detected early [36-38].

**Peri-İmplantitis:**

Involves both soft tissue inflammation and bone loss; if it progresses, it may result in implant failure [39].

Material selection, prosthesis design, surface roughness, and patient-related factors (smoking, diabetes, oral hygiene) influence peri-implant tissue health. For example, zirconia prostheses provide better soft tissue adaptation and lower inflammation, whereas titanium bars and open-surfaced systems require regular 86lümina86onal maintenance [38].

**5.4 Clinical Recommendations**

1. **Material selection:** Zirconia may be preferred in anterior esthetic zones, whereas titanium or hybrid structures are suitable for posterior load-bearing regions.
2. **Surface control:** Polished, low-roughness prostheses reduce plaque accumulation.
3. **Patient education:** Regular brushing, interdental cleaning, and scheduled periods of professional care should be established.
4. **Regular monitoring:** Early detection of peri-implant tissue inflammation is essential; mechanical or biological intervention should be performed as needed.

Biocompatibility, plaque accumulation, and peri-implant tissue health directly affect the long-term success of implant-supported prostheses. Selection of materials such as zirconia and titanium, production method (SM vs. AM), and surface optimization help minimize plaque accumulation and inflammation, thereby protecting peri-implant tissues.

**6. Future Directions and Research Areas**

Despite recent technological advancements in prosthetic dentistry, particularly in implant-supported restorations and zirconia/titanium hybrid structures, several critical gaps and areas for future research remain.

**6.1 Emerging Technological Trends**

1. **Additive Manufacturing (3D Printing) and Hybrid Fabrication Techniques:** 3D Printing enables personalized design for zirconia and titanium frameworks, allowing rapid and cost-effective production of patient-specific prostheses. However, long-term clinical performance data for AM zirconia and titanium structures remain limited [40].
2. **Digital Dentistry and AI-Supported Planning:** CAD/CAM and AI-based design systems are increasingly used for implant placement, framework thickness, and occlusal load distribution optimization. AI can predict potential complications and support patient-specific treatment protocols [41].
3. **Material İnnovations:** New ceramic–metal combinations, such as hybrid zirconia–titanium or alumina-reinforced zirconia, are being developed with the aim of optimizing both esthetic and mechanical performance [42].

**6.1 Research Shortcomings**

1. **Long-Term Clinical Data:** There is limited 10-year follow-up data for AM zirconia and hybrid titanium prostheses. Most studies cover only 1–5 years, which is insufficient to assess long-term complication rates fully [7].
2. **Lack of Standardization:** 3D printing and sintering parameters vary across laboratories. Factors such as layer thickness, sintering temperature, build orientation, and surface roughness have not been fully standardized or evaluated regarding mechanical and biological performance [43].
3. **Biomechanical Optimization:** The long-term effects of framework thickness, implant number/position, and load distribution on full-arch restorations remain under investigation. Finite element analyses are essentially in vitro and have limited clinical validation [44].
4. **Peri-İmplant Biology and Material İnteraction:** Long-term effects of new hybrid materials on soft tissue adaptation, inflammatory response, and microbial colonization are supported by only a few clinical studies [45].

**Patient-Specific Factors:**

Smoking, systemic diseases, and bruxism effects on new AM or hybrid prostheses have not been sufficiently evaluated with long-term data [46].

**6.3 Recommended Future Research Directions**

- Conduct long-term (>10 years), multicenter clinical studies to assess survival and complication rates of AM zirconia and hybrid prostheses [16].
- Optimize manufacturing parameters: Evaluate the effects of layer thickness, sintering temperature, and build orientation on biomechanical performance and surface roughness under standardized protocols [47].
- Develop and validate AI-supported planning algorithms and complication prediction models [48].
- Perform long-term in vivo studies on biocompatibility and microflora interactions [2].
- Model patient-specific risk factors to develop personalized treatment protocols that reduce complication risk in AM and hybrid restorations [46-49].

## Conclusion

Future prosthetic dentistry will focus on personalized restorations, long-term biomechanical and biological success, the prediction of complications in advance, and standardized manufacturing parameters. Current research gaps are concentrated particularly in the areas of limited long-term data for AM and hybrid prostheses, a lack of standardization, and insufficient evaluation of patient-specific parameters. Addressing these gaps will be critical for guiding future research.

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