Multimodal Surface Characterization of Implant Failure in Peri-Implant Disease: SEM, EDX, and AFM-Based Study

Abstract

Background
Peri-implantitis is a progressive inflammatory disease affecting the tissues surrounding dental implants, often leading to implant failure and compromising oral health and patient wellbeing. Surface characteristics of implants play a critical role in osseointegration, disease prevention, and long-term clinical success. Understanding surface alterations in failed implants can provide valuable insight into disease mechanisms and support the development of improved implant designs and treatment strategies, contributing to better health outcomes and quality of life.

Aim
This study aimed to analyze and compare the surface morphology, elemental composition, and topographical features of failed dental implants retrieved from peri-implantitis patients with those of unused implants using scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), and atomic force microscopy (AFM).

Methods
Five failed implants were retrieved from patients diagnosed with peri-implantitis and compared with five unused implants. Surface morphology was evaluated using SEM, elemental composition through EDX, and nanoscale surface topography via AFM. Quantitative data were statistically analyzed using an unpaired t-test, with significance set at $p < 0.05$.

Results
SEM analysis revealed substantial surface degradation and debris accumulation on failed implants, while controls showed intact, well-defined surfaces. EDX spectra indicated increased levels of oxygen, carbon, calcium, and phosphorus on failed implants, suggesting corrosion and contamination. AFM analysis showed significantly higher surface roughness in failed implants across all parameters ($p = 0.000$).

Conclusion
Failed implants exhibited pronounced morphological damage, elemental contamination, and increased nanoscale roughness, highlighting the role of surface deterioration in peri-implantitis-related failures. These findings underscore the importance of surface optimization for implant longevity.

Authors

Anuja Patil[1]
Arvina Rajasekar[2*]

1
Postgraduate, Department of Implantology, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai, India

2
Associate Professor, Department of Periodontology, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai, India

* Corresponding Author

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INTRODUCTION

Dental implants have revolutionized modern dentistry by offering a durable and functional solution for the replacement of missing teeth. Unlike conventional dentures or bridges, implants restore not only aesthetics but also replicate the biomechanical function of natural teeth (1-3). Their ability to achieve osseointegration—direct structural and functional connection with the jawbone—ensures long-term stability, supports bone preservation, and enhances overall oral health (4-6).

The success of osseointegration is profoundly influenced by the implant's surface characteristics, including topography, chemical composition, wettability (hydrophilicity), and surface coatings (7,8). These features affect cellular responses such as osteoblast adhesion, protein adsorption, and bone remodeling. Surface modifications, such as micro-roughening or texturing, are designed to enhance bone-to-implant contact, while hydrophilic surfaces promote early wound healing by facilitating blood and protein interactions. Additionally, bioactive coatings have been shown to accelerate osseointegration and bone regeneration (9,10).

Despite these advancements, implant failure remains a clinical challenge. Failures are broadly categorized into early (within three months of placement) and late (beyond three months). Early failures are typically associated with surgical trauma, overheating of bone, or insufficient primary stability, whereas late failures are predominantly linked to biological complications, notably peri-implantitis (11). Peri-implantitis is a progressive inflammatory condition affecting the peri-implant mucosa, characterized by mucosal inflammation and alveolar bone loss, largely driven by bacterial biofilm accumulation. Clinically, it presents as increased probing depth, bleeding on probing, and radiographic evidence of crestal bone loss. Several factors, including implant design, surface roughness, and the health of peri-implant tissues, influence the risk and progression of peri-implant infections (12). However, the precise role of surface characteristics in the pathogenesis of peri-implantitis remains insufficiently explored.

In recent years, the analysis of retrieved or failed implants has emerged as a valuable approach for elucidating the mechanisms underlying implant failure. Surface degradation, biofilm adherence, and mechanical wear can significantly alter the implant's surface morphology and chemistry, thereby affecting its biological performance. Advanced surface characterization techniques such as scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), and atomic force microscopy (AFM) provide detailed insights into microstructural and elemental changes (13,14).

This study aims to investigate and compare the surface characteristics of failed implants retrieved from patients diagnosed with peri-implantitis against unused control implants using SEM, EDS, and AFM. By identifying specific surface alterations associated with implant failure, the study seeks to contribute to the understanding of peri-implant disease mechanisms and support the development of optimized implant surfaces.

MATERIALS AND METHODS

Study Design and Sample Selection

Five failed dental implants (Dio®, Busan, Korea) were retrieved from five patients diagnosed with peri-implantitis, who had previously undergone implant placement at Saveetha Dental College and Hospital, Chennai, between April and June 2023. Ethical approval was obtained from the Institutional and Ethical Review Board, and informed consent was secured from all participants, ensuring anonymity. For comparative evaluation, five unused implants of the same brand served as the control group.

Inclusion and Exclusion Criteria

Participants were periodontally healthy individuals aged 30–60 years, presenting with functional implants for at least one year and exhibiting clinical signs of peri-implantitis with implant mobility. All implants were commercially available, bone-level, platform-switched designs, and were restored with cement-retained porcelain-fused-to-metal prostheses following a three-month healing period. Exclusion criteria included smoking, prolonged antibiotic use, systemic diseases, bone metabolism disorders, and a history of periodontitis.

Sample Collection and Preparation

Failed implants were retrieved from both maxillary and mandibular arches, with failure attributed to peri-implantitis as confirmed through clinical (bleeding on probing, suppuration, mobility) and radiographic examination. Immediately after retrieval, specimens were placed in sterile containers to prevent contamination. To remove organic residues, implants were immersed in 3% sodium hypochlorite for 10 minutes, followed by 30 minutes in pure acetone. Ultrasonic agitation in a hot water bath was used to enhance cleaning efficacy. Between steps, implants were thoroughly rinsed with ethyl alcohol to prevent cross-contamination and preserve the inorganic layer for subsequent surface analysis.

Scanning Electron Microscopy (SEM)

Surface topography of both failed and control implants was analyzed using a Carl Zeiss Sigma SEM (UK) equipped with a Gemini column (resolution: 1.5 nm). To enhance conductivity and reduce charging effects, implants were coated with a 5–10 nm layer of gold (Au) using a vacuum sputter coater (chamber pressure ~0.05 mbar, 20 mA, 30–60 seconds). Imaging was conducted in high vacuum mode at 10.00 kV (EHT), with a working distance of 15.1 mm and a magnification of 85X. Surface morphology was captured using an SE2 detector.

Energy Dispersive X-ray Spectroscopy (EDX)

Elemental composition was assessed using a Bruker Nano XFlash EDX detector (Germany). Spectra were recorded at an accelerating voltage of 15–20 kV, working distance of 11.5 mm, and magnification of 200X. The analysis identified the elemental constituents and quantified them in terms of atomic percentages.

Atomic Force Microscopy (AFM)

AFM analysis was performed using a Nanosurf C3000 (USA) in static force mode under ambient conditions. A ContAl-G cantilever was used with scan head type SH_B. Surface scans were conducted in the downward direction over a 20 µm area, with a line scan time of 780 ms. The Z-axis scan range extended up to 4.88 µm, and deflection values ranged from -28.2 nN to 165 nN. The system operated in free-run feedback mode using a standard PID algorithm, with an error range of 2.4 µN. Tip voltage was 0 V and amplitude control was maintained in constant drive mode. AFM offered comprehensive three-dimensional nanoscale surface characterization, including parameters such as Sa (average surface roughness), Sq (root mean square surface roughness), Ra (line average roughness), Rq (line root mean square roughness), and Ry (maximum peak-to-valley roughness). The software and firmware versions used were 3.8.8.13, with controller serial number 096-20-010.

Statistical Analysis

The data were processed using the Statistical Package for the Social Sciences (SPSS Software, Version 23.0; IBM Corp., Armonk, NY, USA). Quantitative data obtained from AFM analysis was compiled and expressed as mean ± standard deviation (SD). The Shapiro-Wilk and Kolmogorov-Smirnov tests confirmed a parametric distribution. Intergroup comparisons between failed and control implants were performed using an unpaired t-test. A p-value < 0.05 was considered statistically significant.

RESULTS

SEM Analysis

SEM analysis (Figure 1) revealed distinct differences between the control and failed implant surfaces. The first image, representing control (unused) implant, shows well-defined and clean threads with a uniform micro-roughened surface, indicating preserved surface integrity and the absence of microbial contamination. In contrast, the second image of the failed implant demonstrated significant surface degradation, with irregular, damaged threads and extensive deposition of debris and amorphous material. These features are indicative of biofilm accumulation, possible corrosion, and peri-implant tissue breakdown. The disrupted surface topography, loss of definition, and signs of structural compromise reflect advanced peri-implant pathology, likely due to peri-implantitis.

EDX Analysis

The EDX spectrum (Figure 2) revealed the presence of several elements—Titanium (Ti), Potassium (K), Oxygen (O), Chlorine (Cl), Carbon (C), Calcium (Ca), Sodium (Na), Aluminium (Al), and Phosphorus (P). These elements were found in significantly higher concentrations on the surface of the failed implant. In contrast, the unused (control) implant exhibited a dominant peak for Ti, indicating an intact and uncontaminated surface with minimal elemental interference. O and C levels were relatively low, reflecting a clean and stable surface. However, the failed implant showed complete loss of the Ti signal, with marked elevations in O, C, Ca and P. This elemental profile is indicative of surface corrosion, biofilm accumulation, and possible deposition of inflammatory or necrotic tissue. The heightened presence of Ca and P may also reflect mineralized debris or remnants of peri-implant bone resorption.

AFM Analysis

The AFM analysis (Figure 3) revealed that the surface roughness of failed dental implants was significantly greater across all measured parameters when compared to unused implants. For instance, Sa in the test group

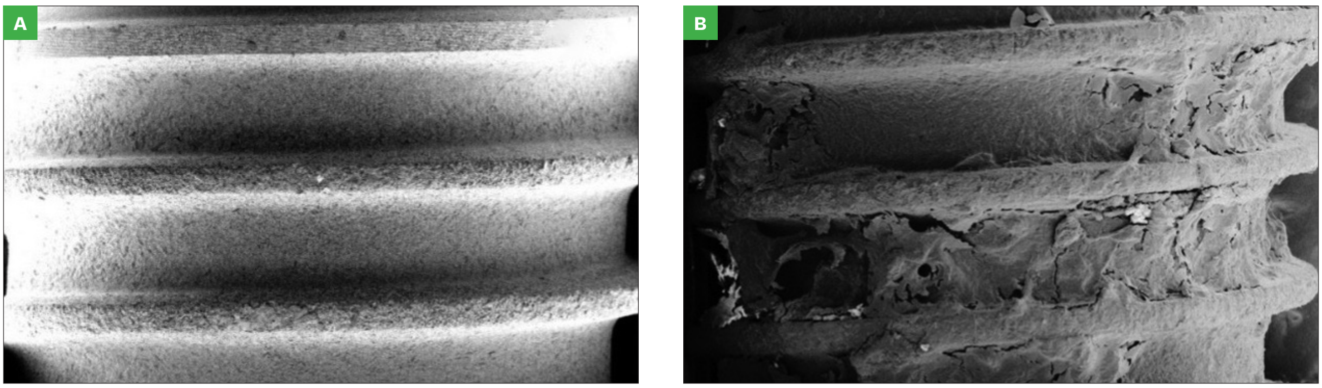

Fig. 1 SEM image of control **(A)** and failed **(B)** implant surfaces

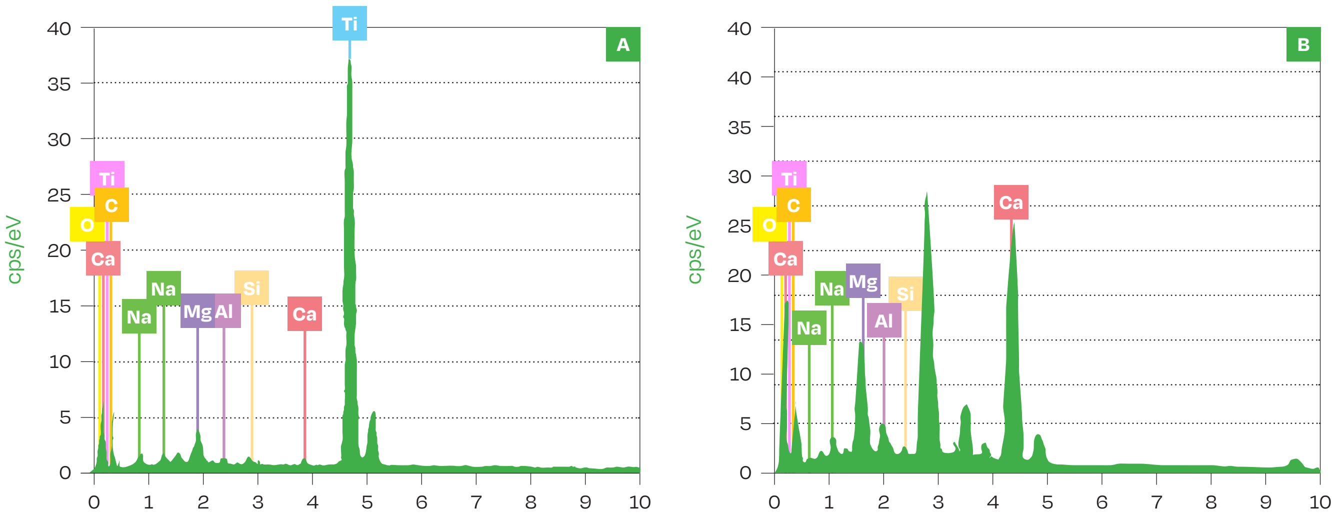

Fig. 2 EDX spectrum of control **(A)** and failed **(B)** implant surfaces

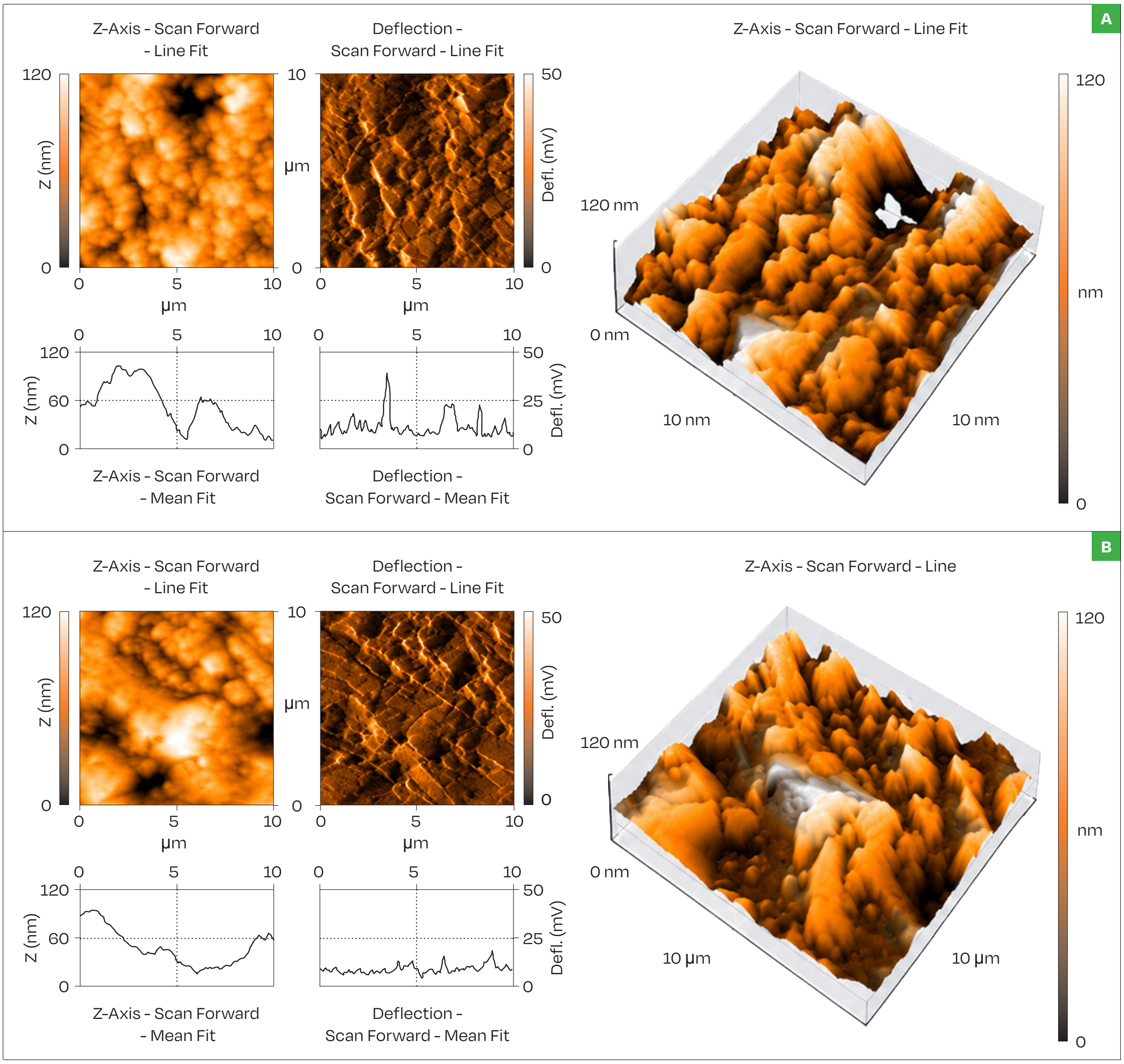

Fig. 3 AFM image of control **(A)**and failed **(B)** implant surfaces

was 695.48 ± 14.46 nm, whereas in the control group it was only 526.66 ± 10.38 nm, yielding a highly significant t-value of 29.9964 (p = 0.000). Similarly, Ra was markedly elevated in failed implants (832.20 ± 24.42 nm) compared to unused implants (384.38 ± 6.04 nm), showing an even higher statistical difference (t = 56.2990, p = 0.000). Other parameters such as Sq, Rq and Ry followed the same trend, with all p-values equal to 0.000 (Table 1). These pronounced differences quantitatively affirm that implant failure is associated with increased surface irregularities.

DISCUSSION

Peri-implantitis is a multifactorial and challenging condition that necessitates a comprehensive and multidisciplinary approach for effective management. Although its prevalence varies, affecting approximately 20% of patients with implants, its clinical significance is profound due to the potential for rapid progression and unpredictable treatment outcomes (15). The complexity of its etiology, which includes microbial colonization, host immune responses, and implant-related factors, has driven ongoing efforts to improve preventive and therapeutic strategies. Among these, innovations in implant surface engineering—such as topographical modifications and antimicrobial coatings—have been pivotal. These modifications aim to reduce bacterial adhesion, limit biofilm development, and enhance the biological integration of implants. When employed in conjunction with optimal surgical protocols, appropriate patient selection, and strict maintenance regimens, such advances contribute substantially to reducing peri-implant disease incidence (16).

Understanding the surface alterations associated with failed implants is essential for elucidating the pathophysiological mechanisms underlying peri-implantitis. Surface characterization techniques such as SEM, EDX, and AFM offer valuable insights into how changes in surface integrity, composition, and roughness may predispose implants to microbial colonization and inflammatory responses. The present study sought to compare failed implants retrieved due to peri-implantitis with unused control implants using these methods to delineate surface degradation patterns and their potential etiological role in implant failure.

SEM and EDX analyses revealed marked differences in both surface topography and elemental composition between failed and unused implants. Failed implants demonstrated extensive surface irregularities, including pitting and the presence of foreign deposits, likely indicative of chronic inflammatory insult. Elemental mapping via EDX highlighted significantly increased levels of carbon and oxygen on failed implant surfaces, suggestive of biofilm accumulation and oxidative degradation. These findings are in concordance with the observations of Dhaliwal JS et al. (17), who noted that organic and inorganic contaminants on titanium surfaces can hinder osseointegration and contribute to implant failure. Similarly, Daubert DM et al. (18), emphasized the central role of biofilm-induced surface changes in the onset and progression of peri-implant disease.

The complete absence or marked reduction of titanium peaks in failed implants, coupled with elevated concentrations of calcium, phosphorus, and carbon, further supports the hypothesis of mineralized biofilm deposits and surface corrosion. Hayashi R et al. (19), observed that high surface carbon levels negatively affect osteoblast attachment and differentiation, thereby impairing osseointegration. Dias FJ et al. (20), also demonstrated the heterogeneity of implant surface compositions and morphologies using EDX, underscoring how material-specific characteristics can influence clinical outcomes. Moreover, studies by Secgin-Atar A et al. (21), and Nejem Wakim R et al. (22), demonstrated a relative increase in titanium and oxygen levels post-debridement, indicating that biofilm removal restores surface purity. Takagi T et al. (23), reported reductions in calcium and carbon following laser decontamination, with corresponding increases in titanium visibility, reinforcing the importance of maintaining surface integrity.

AFM analysis further substantiated the degradation of failed implants by revealing significantly higher surface roughness values—specifically in average surface roughness (Sa), root mean square roughness (Sq), and line roughness parameters (Ra, Rq)—compared to the control group. These findings suggest that peri-implantitis-induced surface deterioration may potentiate bacterial adherence and biofilm maturation, thereby perpetuating the inflammatory cycle. De Bruyn H et al. (24), noted that although moderately rough surfaces are favorable for initial osseointegration, excessive roughness may predispose to increased peri-implant bone loss in the long term. Supporting this, Doornewaard R et al. (25), and Qui-

Roughness Parameter	Test Group (Failed) (Mean ± SD) [nm]	Control Group (Unused) (Mean ± SD) [nm]	t-value	p-value
Sa	695.48 ± 14.46	526.66 ± 10.38	29.9964	0.000*
Sq	834.32 ± 18.88	678.40 ± 11.83	22.1273	0.000*
Ra	832.20 ± 24.42	384.38 ± 6.04	56.2990	0.000*
Rq	938.56 ± 40.08	471.71 ± 5.68	36.4651	0.000*
Ry	3035.56 ± 45.03	2143.16 ± 25.68	54.4365	0.000*
*Statistically Significant (unpaired t-test)				

Tab. 1 Comparison of surface roughness parameters between test and control dental implants

rynen M et al. (26), emphasized the association between highly roughened surfaces and greater marginal bone loss, particularly in susceptible patients. Interestingly, Esposito M et al. (27), in a comprehensive review of 27 randomized controlled trials, found no definitive evidence linking implant surface type to long-term success. However, some studies included in the review indicated that implants with machined surfaces might be less prone to peri-implantitis-related bone loss compared to rougher surfaces. This supports the notion that while rough surfaces may initially promote bone contact, they can become detrimental in inflammatory scenarios.

One of the key strengths of this study lies in its multimodal analytical approach—integrating SEM, EDX, and AFM—which allowed for a comprehensive evaluation of both topographical and compositional differences between failed and unused implants. This triangulated methodology offers robust insights into the role of surface degradation in peri-implantitis-related failures. However, certain limitations must be acknowledged. It was not possible to correlate clinical parameters such as duration of implant function, patient-specific systemic factors, or oral hygiene status with the extent of surface degradation. Future studies should correlate clinical, microbiological, and immunological data with surface characteristics, which would offer a more holistic understanding of peri-implant disease progression. There is also scope for evaluating the impact of different decontamination strategies on restoring surface integrity and minimizing re-infection risk. Ultimately, insights from such comprehensive studies could guide the development of next-generation implants with optimized surfaces that are both biologically favorable and resistant to microbial colonization, thereby enhancing long-term treatment outcomes.

In summary, the comparative analysis of failed versus unused implants underscores the pivotal role of surface integrity in implant longevity. Surface degradation, compositional changes, and increased roughness not only reflect the severity of peri-implantitis but may also serve as contributing factors in the failure process. These findings reinforce the importance of material selection, surface modification, and maintenance protocols in mitigating peri-implant disease progression. Future implant designs should aim to balance surface characteristics that support osseointegration without predisposing to microbial colonization or inflammatory breakdown.

CONCLUSION

This study revealed that failed implants affected by peri-implantitis exhibited significant surface degradation, elemental contamination, and increased roughness compared to unused controls. SEM, EDX, and AFM analyses collectively showed morphological damage, corrosive elemental deposits, and elevated nanoscale irregularities, highlighting the role of surface alterations in implant failure. These findings emphasized the importance of optimizing implant surface properties to improve long-term clinical outcomes.

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