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Microbial Corrosion in Titanium-Based Dental Implants: How Tiny Bacteria Can Create a Big Problem?

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Abstract

Microbiologically induced corrosion plays a key role in implanted materials survival, especially those exposed to the oral environment. Despite considerable progress in this field, a consensus is still missing due to contradictory findings regarding the role of oral biofilms in the electrochemical behavior of titanium (Ti) implant surfaces. This scoping review comprehensively reviews and discusses the current evidence and new perspectives on microbial corrosion. The main focus is understanding oral biofilm formation and its synergistic effect under the corrosion/tribocorrosion phenomenon. We critically revisited the literature to refine key concepts and mechanisms involved in polymicrobial biofilm formation on implant devices, microbial corrosion phenomenon, and its consequence for surrounding tissues. To summarize what is currently known about this topic, we have conducted a scoping review. Data of eligible in vitro studies suggest that oral biofilm and bacterial metabolites products can affect negatively the electrochemical behavior of Ti material and promote implant surface deterioration. Relevant experimental strategies to practically approach the field of microbial corrosion mechanisms are outlined. Finally, new approaches to enhance biomaterial development should consider improved corrosion resistance to promote higher implant survival.

Keywords Titanium · Dental implant · Corrosion · Wear · Biofilm

1 Introduction

Dental implants are some of the most successful implantable devices with long-term predictability and clinical performance [1]. Titanium (Ti) has been a commonly employed material used for dental implants with high success rates (90.9% to 97.7%) after 15 years of post-implantation [2, 3]. The success of these Ti-based implants is mainly due to a combination of suitable biomaterial properties and the ability to spontaneously form a passive titanium oxide layer when in contact with atmosphere O_2 (named as TiO_2) [4, 5]. However, albeit TiO_2 film protects the metal surface against oxidative degradation processes from biological fluids [6], dental implants are inserted in a challenging and humid environment in which they are constantly exposed to corrosion and microbial colonization starting from the moment of the implantation and lasting for the entire implant lifetime [7]. Consequently, implant failures can be induced by several individuals or synergistic events related to the mechanical, chemical, biological, and microbiologically induced degradation processes [8].

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Polymicrobial biofilm formation on the Ti surface is the primary etiologic factor in the etiopathogenesis of implant-related infections [9, 10]. Since the implantation, dental implants, like all oral surfaces, are a substrate for microbial adhesion and accumulation [11]. Therefore, polymicrobial infection induced by biofilms is the main reason for dental implant failures [10], as oral biofilms can mitigate the electrochemical stability of implanted material, leading to faster corrosion processes and deterioration [12]. Some studies have hypothesized that biofilm-covered implant surfaces undergo accelerated corrosion due to an acidic environment generated by bacterial cell metabolism and products released [12–15]. The microbiologically induced corrosion—as this deleterious phenomenon is called—promotes surface deterioration, including discoloration, pitting, cracking, scratches, and an increase of surface roughness [2]. Microbial corrosion results in the release of metallic ions or even particles (when associated with the fretting process) into the surrounding tissues that can stimulate an exacerbated inflammatory response, peri-implant bone reabsorption [16], and microbiological dysbiosis [17]. Ex vivo studies [18, 19] proved that the dissemination of Ti wear debris in the peri-implant tissues is strongly associated with implant device failure. Therefore, microbial corrosion has been considered a key issue on whether the implant will survive or fail.

Facing the boost growth in the implant market and patients seeking Ti-based implants for oral rehabilitation (https://www.grandviewresearch.com/industry-analysis/dental-implants-market), microbial corrosion concerns might increase. Here, we attempt to summarize what is currently known on this topic, identify gaps, refine key concepts, mechanisms involved, and report the types of evidence that guide practice in the field. For this, we conducted a scoping review to evaluate the main experimental findings in terms of the corrosion/tribocorrosion process, considering the synergistic interactions of oral biofilms with the Ti surface. This review gathers knowledge from materials sciences, microbiology, and dentistry, contributing to a better understanding of microbial corrosion phenomenon and points the way forward towards the rational design of safer and enhanced dental implant surfaces.

2 Oral Biofilms: A Powerful Microbiologically Influenced Corrosion Force

In the oral environment, indigenous microorganisms from the oral microbiome live in a symbiotic state with the host by adhering to any biotic [20] or abiotic surfaces [21] present in this environment. Microbial accumulation and biofilm formation on implanted materials can trigger different biological and chemical processes, such as polymicrobial infections [22] and material deterioration [14, 15]. Microbiologically induced corrosion has been defined and widely accepted as corrosion damage initiated or aggravated due to the direct or indirect activities of microorganisms colonizing materials surfaces [23]. The impact of biofilms on the TiO_2 layer breakdown depends on the synergic effect of microenvironmental conditions and microbial activity [8]. Previously, research investigating the failed dental implants caused by Ti corrosion raises the possibility of oral bacteria having a relative contribution to this purpose [24]. Thus, it has to be emphasized that the role of oral microorganisms in the corrosion process is complex in that they can either accelerate corrosion or induce corrosion alone (i.e., microbiologically induced corrosion), and the latter is the central topic of this review and will be discussed in detail.

2.1 Biofilm Development on Implant Surfaces

It is essential to know the biofilm formation process to understand the unique effect of surface-attached biofilms in terms of the corrosion phenomenon. Theoretically, the main stages of oral biofilm formation may include the following: protein adsorption, microbial adhesion, followed by co-aggregation processes, biofilm formation, maturation, and dispersal [11, 25]. The temporal sequence of in vitro polymicrobial biofilm development on the Ti surface can be visualized in Fig. 1.

Immediately after implant insertion in the oral cavity, Ti material is rapidly exposed to protein-rich fluids, such as saliva or blood plasma, forming a protein layer on the Ti surface [11]. In this way, protein adsorption represents the first biological response in the human body to implanted materials [26]. Typically, the serum protein layer formed by blood plasma comprises fibronectin, serum albumin, apolipoprotein, and fibrinogen, facilitating the biological interactions between the material and host cellular response [27, 28]. On the other hand, salivary pellicle composition mainly includes organic and inorganic components, such as aminoacids, proteins, glycoproteins, carbohydrates, lipids and sodium, chloride, calcium, phosphate, and bicarbonate, respectively, which could prevent corrosion of Ti material by a buffering mechanism [8]. However, the buffering mechanism can be limited considering the high density of bacterial cells or a low salivary flow rate [29]. Moreover, in the long term, several salivary proteins show a remarkable specificity in their ability to promote the adhesion of some prominent oral bacteria to these surfaces, which can favor bacterial colonization [30]. Another theory is that protein layers could protect surfaces against wear due to the viscoelastic and lubricating effect on the Ti and counterbody surfaces [31]. In fact, previous studies have shown lower friction and wear of Ti surfaces in the presence of whole human saliva [32], mucin [29], and albumin [33].

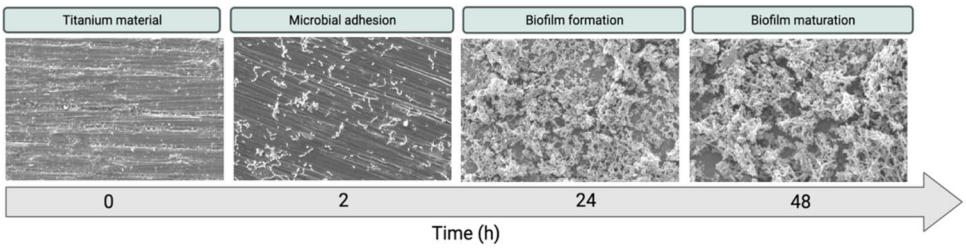

Fig. 1 The temporal sequence of in vitro polymicrobial biofilm development on titanium surface using scanning electron microscopy images (15 kV, 1000 × magnification). To mimic the dental implant material, machined titanium samples were used as a substrate for biofilm formation from human saliva. After 2 h of in vitro bacterial incubation, it is possible to see bacteria (cocci species) attachment on the surface, representing the early-colonizer bacteria. After 24 h, polymicrobial biofilm with higher biovolume and complex 3D structure due to extracellular biofilm matrix can also be observed. These micrographs suggest that biofilm growth changes the microenvironment on the titanium surface and leads to biofilm maturation (48 h). Reprinted (adapted) from Costa et al. [5], Copyright (2020), with permission from Elsevier (license number 5078840308928)

Bacteria–surface interactions can occur in different ways, including electrostatic forces, hydrogen bonding, and Van der Waals forces [34]. After initial saliva or blood plasma coating, followed by bacterial adhesion, interactions among different species known as a co-aggregation drive towards a highly organized microbial accumulation and biofilm formation [35]. For instance, *Streptococcus* and *Actinomyces* spp. are considered primary colonizers, binding to salivary agglutinins and proline-rich proteins, and capable of providing additional sites for late colonizers adhesion, such as *Aggregatibacter actinomycetemcomitans*, *Porphyromonas gingivalis*, and *Fusobacterium nucleatum*, favoring biofilm development and increased pathogenicity over time [22, 36]. Conceptually, oral biofilms are complex and highly organized polymicrobial communities embedded in a self-produced extracellular matrix [37, 38]. Extracellular polymeric substances (EPS) in the biofilm matrix are responsible for the three-dimensional biofilm architecture [38]. They provide a unique environment, improve microbial adhesion, nutrient richness, and create an acidic microenvironment [38]. In addition, EPS diminishes the mechanical biofilm removal [25] and reduces biofilm susceptibility to antimicrobials drugs [39] on Ti surfaces. Figure 2 shows a schematic illustration of biofilm formation on dental implants and their effect under clinical progression of implant-related diseases.

From a clinical standpoint, the microbial colonization of dental implants begins at supragingival area exposed to the oral environment, and initial biofilm formation depends on the surface properties, implant topography, oral microbiota, and environmental conditions, such as pH, oxygen level, fermentable carbohydrate exposed, and poor oral hygiene [40]. An area of particular interest is the implant–abutment connection region, in which microgaps (2.5–60 µm) can compromise the sealing performance, favoring the penetration of bacteria and microbial colonization of the inner threads of the implants [41, 42]. Interestingly, once inside the implant–abutment connections, biofilm can act as lubricants, decreasing friction between contacting prosthetic surfaces [43]. Such protection is attributed to the viscoelastic property of microbial cells provided by the presence of polysaccharides, proteins, phospholipids, and nucleic acids [44]. Notably, a loss of mechanical integrity of dental implant

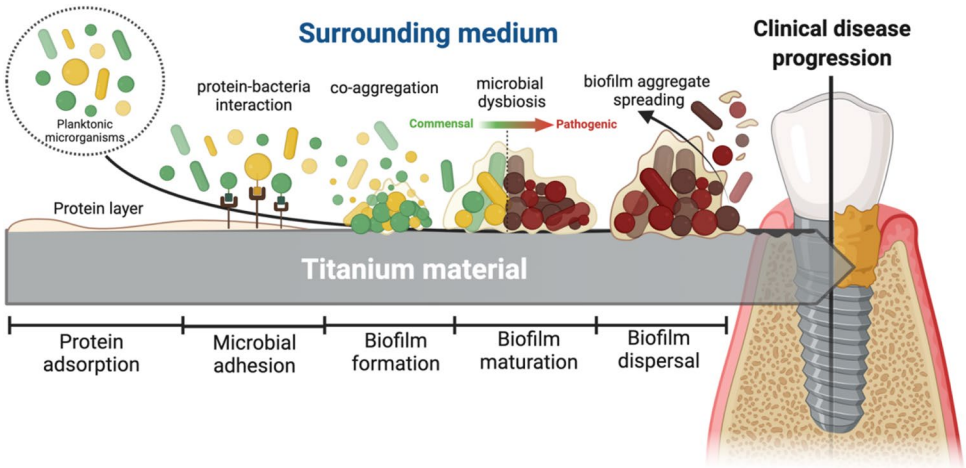

Fig. 2 Schematic representation for the steps of biofilm formation on titanium biomaterial. The schematic drawing depicts the five main steps for forming and spreading biofilms such as protein adsorption, microbial adhesion, biofilm formation, maturation, and dispersal. The clinical disease progression is dependent on biofilm accumulation (created with BioRender.com; License number: KL22UL22JY)

internal connections may occur due to the decrease in friction caused by biofilm formation, leading to screw loosening and other prosthetic complications [12]. Oppositely, biofilms can also detach from the surface as shear stress increases and no longer provide the protective lubricating effect on the surface [45]. Another relevant point is that corroded Ti surfaces may promote increased bacterial attachment and higher biofilm biovolume because of surface deterioration and increased roughness [46]. Thus, corroded implant surfaces can promote bacterial recolonization, impair regeneration procedures, and reduce the ability of host cells to reattach and proliferate [47].

2.2 Microbial Corrosion Mechanisms

Oral biofilms are assumed to change the implant's electrochemical environment, leading to disruption of the TiO_2 layer [48]. This is hypothesized based on two main mechanisms: (1) bacteria can significantly reduce the peri-implant microenvironment pH by producing organic acids during fermentable carbohydrate catabolism [49]. This low pH creates a favorable environment for pitting attacks [13]. (2) Microbial accumulation on the dental implant can promote differential oxygen exposure on the Ti surface [23]. As a result, the less aerated zones act as the anode and undergo crevice corrosion, thereby mitigating the reformation of the oxide layer [14]. Both unfavorable conditions initiate metal dissolution and surface deterioration [15], as shown in Fig. 3.

As the biofilms develop, oral bacteria produce and release various corrosive agents such as lactic acid, methyl mercaptan, hydrogen sulfide, and dimethyl sulfide [50, 51]. In addition, it is well documented that several modulatory factors related to saliva can accelerate the metal electrochemical degradation by acidification around the implant, as follows: fluoride concentration [52], mouthwashes [53], teeth bleaching agents [54], chronic diseases, and medications [55]. Moreover, hydrogen peroxide (H_2O_2) synthesis during the peri-implant inflammation process negatively affects Ti corrosion resistance [51].

The biofilm composition is influenced by the local pH values and environmental conditions, considering the release and tolerance of bacteria to acids, nutritional factors, and how aerobic or anaerobic the microenvironment is [56, 57]. Among the several bacteria present in the oral cavity, *Streptococcus mutans* is a powerful corrosive microorganism because of its capacity to release lactic acid and grow in acidic environments [48]. Although *S. mutans* is not directly responsible for implant-related infections [58], this key pathogen promotes quick co-aggregation with periodontopathogens bacteria due to reduced oxygen content related to the biofilm accumulation and EPS formation [20]. Some studies have also appointed the role of bacterial components of periodontopathogens such as lipopolysaccharide (LPS) [59], dextrose [60], and sulfides [61] to change the Ti electrochemical behavior. Indeed, the biofilm structure can pick up external acidic substances from diet, caffeine, cotinine, or nicotine [62], as well as acidic substances produced from microbial metabolism [63]. Interestingly, although *S. mutans* has a high ability to produce acids, we have shown that *S. mutans* in vitro biofilms exposed to higher carbohydrate (sucrose) concentration did not affect the electrochemical

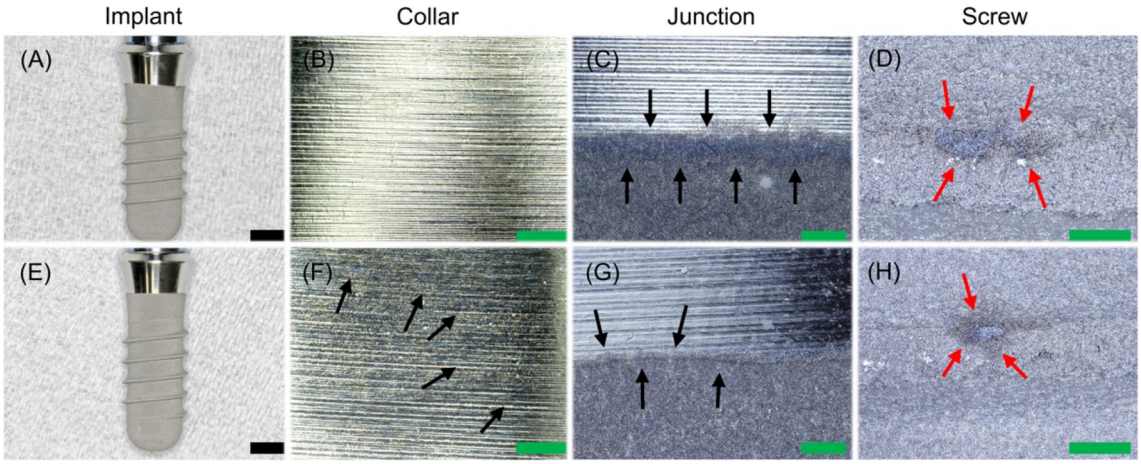

Fig. 3 In vitro microbial corrosion in titanium dental implants with sandblasted and acid-etched (SLA) surface after immersion in bacterial polyculture. In this panel it is possible to see the **A**–**E** whole-view of implant samples (×20), **B**–**F** smooth collar (×300), **C**–**G** collar–screw junction (×500), and **D**–**H** implant screw (×700). Black and red arrows indicate surface discoloration/pitting attack and crevice corrosion features, respectively. Apparently, the type of bacteria/growth conditions may modulate the surface damage. The black bars correspond to a length of 2000 µm and green bars to 100 µm. Reprinted from Siddiqui et al. [15], Copyright (2021), with permission from John Wiley and Sons (license number 5079500517450) (Color figure online)

behavior of Ti, which may be explained by the short time that the surface was exposed to the biofilm, knowing microbial corrosion is a chronic process a long-term acidic exposure might be needed for microbiologically induced corrosion [21].

The biofilm-covered implant surface is a cathodic area, and the exposed Ti is an anodic area, which forms galvanic corrosion [49]. In other words, these anodic and cathodic regions are produced by converting the biofilm-covered implant surface into an electrode, which increases the corrosion rate due to the high chemical reactivity of the Ti material [20]. Therefore, the Ti oxidation reaction can be summarized as follows:

(1) $TiO_2 + H_2O + H^+ = Ti(OH)^{3+}$ (exposed surface)
(2) $4H^+ + O_2 + 4e = 2H_2O$ (cathode region)
(3) $Ti + H_2O = TiO^{2+} + 2H^+ + 4e$ (anode region)

Consequently, this electrochemical reaction promotes pitting-like features, peaks, and valleys on the surface, releasing corrosion products into the surrounding tissues [63]. Interestingly, a previous ex vivo study [24] has suggested that aerobic bacteria could induce microbial corrosion primarily concentrated in the pits. In contrast, anaerobic bacteria are associated with crevicular corrosion due to decreased oxygen levels in the microenvironment. Furthermore, a unique pattern of surface discoloration also appears to be associated with the microbial profile [15]. However, the role of specific bacterial species in the microbial corrosion of Ti and how different factors affecting biofilm growth can also change this electrochemical behavior needs to be further evaluated. Overall, the microbial corrosion mechanisms are illustrated in Fig. 4.

3 Titanium Corrosion Products and Peri-implant Diseases: An Overview

Microbial corrosion may induce accelerated, and localized Ti dissolution, contributing to the burden of particles released surrounding the implant site [15, 48]. In addition, these particles can be dissolved in contact with biological fluids, generating Ti ions [64]. However, emerging researches have demonstrated that Ti corrosion products are not entirely bioinert materials [65, 66]. To further support this claim, multiple systematic reviews have confirmed that Ti corrosion products can induce peri-implant inflammation and decrease the long-term success rate of dental implants [16, 67, 68].

Although the cause–effect relationship between Ti dissolution and peri-implant diseases is not fully comprehended, higher Ti particles/ions concentrations have been found in peri-implantitis sites [16]. These Ti particles released may have different sizes and morphologies (0.5–54 µm) and direct contact with bone tissue, as demonstrated in post-mortem human jawbone (HE et al. 2016) in Fig. 5A, B. Animal models have also been shown that Ti particles enhance pro-inflammatory cytokines release, infiltration of

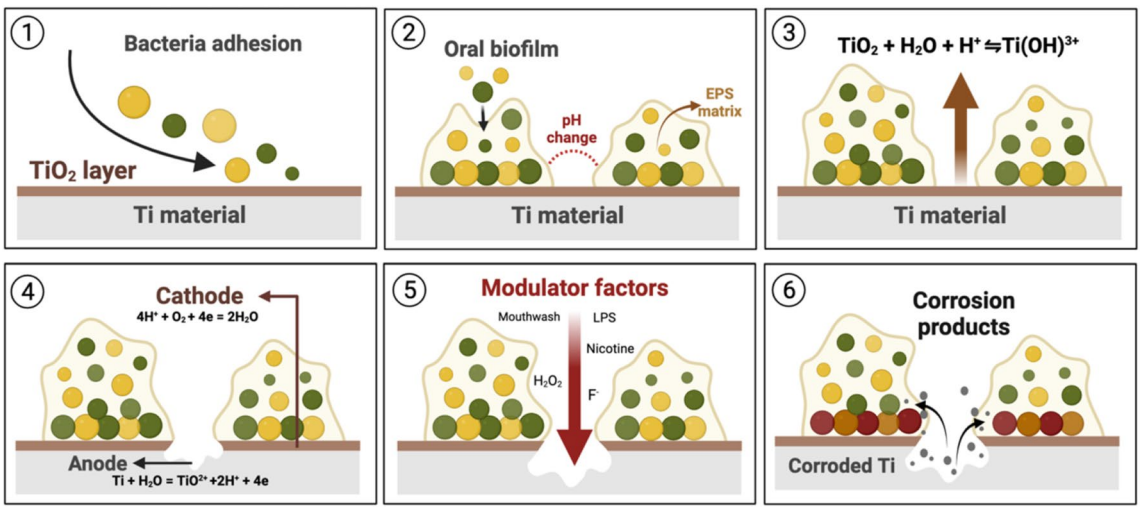

Fig. 4 Representative proposed mechanisms of microbial corrosion in titanium-based dental implants. **1** Titanium material in contact with biological fluids leads to passive TiO_2 layer formation and, subsequently, bacterial adhesion on the surface. **2** Biofilm formation promotes a drop in the pH (acidification) of the microenvironment around the implant due to bacterial metabolism. **3** The exposed titanium surface is susceptible to material corrosion trigger by human saliva (biological electrolyte). **4** The biofilm-covered implant surface is a cathodic area, and the exposed titanium is an anodic area. **5** Several modulator factors may also accelerate the corrosion process. **6** Finally, the TiO_2 breakdown reactions with the environment induce titanium particles/ions release and corrosion products accumulation (created with BioRender.com; License number: YE22UL1A3B)

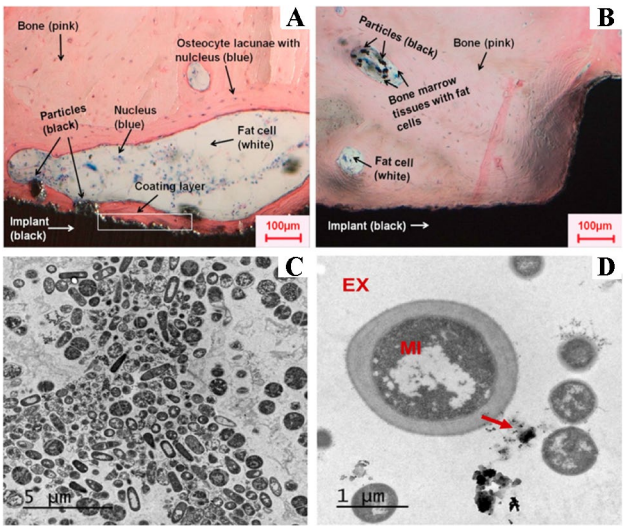

Fig. 5 Effect of titanium corrosion products on peri-implant tissues and oral biofilms. **A** and **B** Histological images of bone slices with a dental implant (300 µm thick, Giemsa-Eosin stained; light microscopy analysis) show that the primary location of Ti particles is in the bone marrow tissue at a distance of 60–700 µm from the implant, with particle sizes < 40 µm, confirming the corrosion products release in post-mortem human jawbone. **C** and **D** Transmission electron microscopy (80 kV, 5 and 1 µm magnification) showed biofilms formed in situ (oral cavity) on Ti surface and exposed to the treatment of Ti particles. Red arrows indicate Ti particles agglomerated and precipitated Ti ions on extracellular sites around microorganism cells. *EX* extracellular environment, *MI* microorganism. Reprinted (adapted) from He et al. [18] and Souza et al. [11], Copyright (2021), with permission from Elsevier and John Wiley and Sons (license numbers 5079491368023, 5074931356473) (Color figure online)

immune-inflammatory cells, and activation of osteoclast activity, resulting in unfavorable healing and osseointegration outcomes [69, 70]. From a microbiological point of view, our group recently demonstrated that Ti particle/ions interaction with bacterial cells, as visualized in Fig. 5C, D. This interaction can potentially change the microbiological composition of biofilms formed on Ti surfaces in the oral cavity leading to a composition similar to polymicrobial infections with higher pathogenicity [17]. Therefore, the presence of Ti products around dental implants may contribute to peri-implant bone resorption, microbial dysbiosis and, consequently, enhance the risk of peri-implantitis development [65].

4 The Current Weight of Evidence of the Microbial Corrosion in Dental Implants

In this section, we strive to offer an overview of the scientific evidence on microbial corrosion in dental implants, regardless of the methodological quality of the studies. For this, we followed the guidelines of Preferred Reporting Items for Systematic reviews or Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) [71]. The orientated research question was: *"What is the current state of knowledge regarding microbial corrosion in titanium-based dental implants?"* In this review, only studies with electrochemical data related to biofilm-covered Ti surfaces were considered. For full methodological details, see Supplementary Methods (available online). To explore differences among each study design, data from biofilm models (Table 1), electrochemical assays (Table 2), and corrosion/tribocorrosion outcomes (Table 3) were outlined. cpTi

4.1 State-of-Art in Microbial Corrosion Science

The initial search identified a total of 1643 records from all electronic databases and manual searches. Following the scoping review strategy, 15 eligible studies were included in the quantitative synthesis (please see Supplemental Results; Fig. S1). Six pre-eligible studies [61, 72–76] were excluded during the studies selection because they only performed surface characterization tests after biofilm exposure without referring to electrochemical assays. Furthermore, two studies [77, 78] that evaluated the microbiological effect and corrosion behavior independently and two studies [79, 80] that did not use titanium material as a substrate for biofilm growth were also excluded.

All eligible studies ($n = 15$) were published between 2003 [49] and 2021 [81] in nine different countries (United States of America, Taiwan, Brazil, Mexico, Spain, Portugal, Japan, China, and Chile), showing a progressive increase in the rate of publication in this field. Medical-grade pure titanium, titanium–aluminum–vanadium (Ti–6Al–4V), and titanium–zirconia (Ti–Zr) alloys were used among the implant materials. In terms of surface treatment, only five studies considered SLA [7, 15, 20, 75], modified SLA (modSLA) [15], anodized [7] or porous [82] surfaces, while the others used machined surfaces. The surface feature before electrochemical tests was impossible to summarize due to the lack of information in most studies. Considering that roughness and surface area have an essential role in Ti material's electrochemical behavior [4], this lack of data represents a significant scientific barrier to overcome in future studies to ensure better interpreting of microbial corrosion results and comparison among different studies.

4.2 Oral Biofilm Models to Test Microbial Corrosion

Regarding the biofilm model used on the selected studies (Table 1), mono-species [7, 13, 20, 21, 48, 49, 63, 82–85], dual-species [12, 85], and polymicrobial [15, 81, 86] were used. *S. mutans* is the preferred pathogen used to test microbial corrosion in aerobic conditions (37 °C, 5% CO_2),

Table 1 Summary of in vitro biofilm models used to test microbial corrosion in titanium implant materials

Author (year)	Biofilm model	Microbial species	Supplementation of medium (concentration)	Decontamination method	Incubation		Bacterial cell density	
					Conditions	Time[a]	Initial	Final
Chang et al. (2003) [49]	Monospecies	*Streptococcus mutans* (A32-2; CS2)	NA	NA	Aerobic (37 °C, 5% CO_2)	NR	OD_{540nm} = NR CFU/mL	NR
Díaz et al. (2017) [7]	Monospecies	*Streptococcus mutans* (ATCC 25175)	NA	NA	Aerobic (37 °C, 5% CO_2)	2, 7, 15, 21, 28 d	10^8 CFU/mL	NR
Figueiredo-Pina et al. (2018) [63]	Monospecies	*Streptococcus salivarius* (NR)	Glucose (0.05 g/L) Meat extract (0.05 g/L) Urea (0.05 g/L)	NA	Aerobic (37 °C, 5% CO_2)	9 h	$OD_{600nm} = 10^6$ CFU/mL	NR
Fukushima et al. (2014) [13]	Monospecies	*Streptococcus mutans* (NCTC10449)	Glucose (1%, w/v)	NA	Aerobic (37 °C, 5% CO_2)	0, 90 min	10^8 CFU/mL	NR
Li et al. (2017) [83]	Monospecies	*Streptococcus sanguinis* (CGMCC No. 1.2497)	Hydrochloric acid (HCl 0.1 M)	NA	Aerobic (37 °C, 5% CO_2)	336 h	OD_{580nm} = NR CFU/mL	NR
Silva et al. (2020) [82]	Monospecies	*Staphylococcus aureus* (ATCC BAA 977)	NA	NA	Aerobic (37 °C, 5% CO_2)	21 d	$OD_{600nm} = 10^6$ CFU/mL	NR
Souza et al. (2013) [48]	Monospecies	*Streptococcus mutans* (ATCC 25175)	Mucin (2.5 g/L) Peptone (5 g/L) Urea (1 g/L) Yeast extract (2 g/L) Sucrose (200 g/L)	NA	Aerobic (37 °C, 5% CO_2, 150 rpm)	24, 48, 168 h	$OD_{630nm} = 10^8$ CFU/mL *(2 mL used for test, 10^{16} CFU/mL)*	NR
Souza et al. (2018) [21]	Monospecies	*Streptococcus mutans* (UA159)	Glucose (1%; w/v)	Sucrose (0%, 1%, 10%, 40%; w/v)	Aerobic (37 °C, 5% CO_2)	144 h	$OD_{600nm} = 10^6$ CFU/mL	0% = 9.3 $\log_{10}$ CFU 1% = 7.9 $\log_{10}$ CFU 10% = 8.3 $\log_{10}$ CFU 40% = 7.7 $\log_{10}$ CFU
Xu et al. (2020) [20]	Monospecies	*Porphyromonas gingivalis* (ATCC 33277)	Hemin (0.001%) Vitamin K1 (0.0001%)	NA	Anaerobic (37 °C, 85% N_2, 5% H_2, 10% CO_2)	7 d	10^8 CFU/mL	NR
Zhang et al. (2013) [84]	Monospecies	*Actinomyces naeslundii* (ATCC12104)	Mucin (2.5 g/L) Peptone (5 g/L) Urea (1 g/L) Yeast extract (2 g/L) Sucrose (200 g/L)	NA	NR	1, 3, 7 d	10^8 CFU/mL	NR
Garza-Ramos et al. (2020) [85]	Monospecies Dual-species	*Streptococcus gordonii* (NR) *Fusobacterium nucleatum* (NR)	NA	NA	Aerobic (37 °C, 5% CO_2)	0, 48, 96 h	10^6 CFU/mL	NR

Table 1 (continued)

Author (year)	Biofilm model	Microbial species	Supplementation of medium (concentration)	Decontamination method	Incubation		Bacterial cell density	
					Conditions	Time[a]	Initial	Final
Souza et al. (2010) [12]	Dual-species	*Streptococcus mutans* (ATCC 25175) *Candida albicans* (clinical strain)	Mucin (2.5 g/L) Peptone (5 g/L) Urea (1 g/L) Yeast extract (2 g/L) Sucrose (200 g/L)	NA	Aerobic (37 °C, 5% CO_2, 150 rpm)	216 h	*S. mutans* 10^8 CFU/mL *C. albicans* 10^9 CFU/mL	*S. mutan:* 8.1×10^7 ($\pm 4.7 \times 10^6$) CFU/cm^2 *C. albicans* 1.1×10^8 ($\pm 7.6 \times 10^6$) CFU/cm^2
Chandrashekar et al. (2021) [81]	Multispecies	*Streptococcus mutans* (ATCC 700610) *Streptococcus sanguinis* (ATCCC 10556) *Streptococcus salivarius* (ATCC 13419) *Aggregatibacter actinomycetemcomitans* (ATCC 43718) *Fusobacterium nucleatum* (ATCC 25586) *Porphyromonas gingivalis* (ATCC BAA-1703)	Hemin (5 mg/L) Vitamin K (0.01 mg/L)	Citric acid (40%; v/v)	Aerobic (37 °C, 5% CO_2) Anaerobic (37 °C, 85% N_2, 5% H_2, 10% CO_2)	4 h and 7 d (for each condition)	$OD_{600nm} = 10^6$ CFU/mL (all strains)	NR
Siddiqui et al. (2019) [15]	Multispecies	*Streptococcus mutans* (NR) *Streptococcus sanguinis* (NR) *Streptococcus salivarius* (NR)	NA	NA	Aerobic (37 °C, 5% CO_2)	30 d	$OD_{600nm} = 10^6$ CFU/mL	0.8–0.9 (adherent bacterial colony-forming units)
Sridhar et al. (2019) [86]	Multispecies	*Streptococcus mutans* (UA 159) *Streptococcus sanguinis* (10556) *Aggregatibacter actinomycetemcomitans* (VT 1169)	NA	NA	Aerobic (37 °C, 5% CO_2)	144 h	10^5–10^7 CFU/mL	NR

ATCC American Type Culture Collection, *NR* not reported, *NA* not applied, *h* hour, *d* days, *min* minutes, *OD* optical density

[a]Incubation time was considered for corrosion and tribocorrosion tests, not for bacterial inoculum growth

Table 2 Summary of methods used to evaluate the corrosion and tribocorrosion behavior

Author (year)	Electrochemical analysis	Equipment	Reference electrode	Counter electrode	Work electrode	Electrochemical solutions		Working parameters	Sliding mode	Counter-body
						Composition	Conditions			
Figueiredo-Pina et al. (2018) [63]	Tribocorrosion	Tribometer (Gamry 600)	Saturated calomel electrode	NR	Ti–6Al–4V ball	(1) *AS* artificial saliva (composition: NR) (2) *AS* + *G* artificial saliva + glucose (3) *AS* + *G* + *Ss* artificial saliva + glucose + *S. salivarius*	37 (± 1) °C 2 h	1.20 N 1 Hz	Linear reciprocating (2 mm)	Ti–6Al–4V ball (∅ 6 mm)
Souza et al. (2010) [12]	Tribocorrosion	Tribometer (Solartron electrochemical interface model 1287)	Ag/AgCl	Platinum	NR	Fusayama's artificial saliva[a]	pH 5.5	100 and 200 mN 1 Hz	Linear reciprocating (0.5 mm)	Al_2O_3 ball (∅ 5 mm)
Souza et al. (2013) [48]	Corrosion	Potentiostat (Voltalab PGZ 100)	Saturated calomel electrode	Platinum		Fusayama's artificial saliva[a]	NR	NA	NA	
Chang et al. (2003) [49]	Corrosion	Potentiostat (Stern Gamry)	NR	NR	NR	Ringer's solution[b] *Streptococcus mutans* + Ringer's solution Tryptic soy broth Byproducts of *Streptococcus mutans* + tryptic soy broth	NR	Potential range: − 250 mV up to 250 mV Scan rate: 5 mV/5 s	NA	NA
Díaz et al. (2017) [7]	Corrosion	Potentiostat (Gamry Instruments-Reference 600)	Ag/AgCl (saturated KCl)	NR	cpTi	Aqueous solution of 0.9% NaCl	7 days pH 6.18 15 mL NaCl, 37 (± 1) °C	Potential range: 200 mV up to 1 mA Scan rate: 1 mV/s	NA	NA
Fukushima et al. (2014) [13]	Corrosion	Potentiostat (VersaSTAT4, Princeton Applied Research)	Ag/AgCl	Platinum	cpTi	2 mM PBS containing 5 mM $MgCl_2$ and 150 mM KCl	Room temperature, pH 7	Potential range: − 250 mV up to 250 mV Scan rate: 5 mV/5 s	NA	NA

Table 2 (continued)

Author (year)	Electrochemical analysis	Equipment	Reference electrode	Counter electrode	Work electrode	Electrochemical solutions		Working parameters	Sliding mode	Counter-body
						Composition	Conditions			
Li et al. (2017) [83]	Corrosion	Potentiostat (PARSTAT 2263)	Saturated calomel electrode	NR	cpTi	Enriched artificial saliva solution	37 (±1) °C pH 6.7	Potential range: − 250 mV up to + 250 mV Scan rate: 1 mV/5 s	NA	NA
Silva et al. (2020) [82]	Corrosion	Potentiostat (OrigaTrod, Origalys)	Saturated calomel electrode	Platinum	Ti–6Al–4V(Bulk and porous)	Hank's solution%	37 (±1) °C, 150 rpm	Potential range: − 100 mV up to + 300 mV Scan rate: 1 mV/s	NA	NA
Souza et al. (2018) [21]	Corrosion	Potentiostat (Interface 1000 Gamry Instruments)	Saturated calomel electrode	Graphite	cpTi	Artificial saliva[d]	37 (± 1)°C, pH 7.0 10 mL	Potential range: − 8 V to + 8 V Scan rate: 2 mV/s	NA	NA
Xu et al. (2020) [20]	Corrosion	Potentiostat (CS310 Cortest Instruments)	Ag/AgCl	Platinum	cpTi	Hank's solution%	37 (±0.5)°C	Potential range: − 800 mV to + 3000 V Scan rate: 2 mV/s	NA	NA
Zhang et al. (2013) [84]	Corrosion	Potentiostat (PARSTAT 2263)	Ag/AgCl	Platinum	cpTi	Fusayama's artificial saliva[a]	pH 5.0	Potential range: 1000 kHz to 10 mHz Scan rate: NR	NA	NA
Garza-Ramos et al. (2020) [85]	Corrosion	Potentiostat (NR)	Saturated calomel electrode	Platinum	Ti–6Al–4V	Bacterial solution *Streptococcus gordonii* + *Fusobacterium nucleatum* *Streptococcus gordonii* Ringer's solution[b]	37 °C 5 h	Potential range: − 0.20 V to 1.5 V Scan rate: NR	NA	NA
Chandrashekar et al. (2021) [81]	Corrosion	Potentiostat (Interface 1000 Gamry Instruments)	Saturated calomel electrode	Graphite	cpTi	1 × Phosphate-buffered saline (PBS) + gaseous nitrogen (only anaerobic condition)	37 °C	Potential range: NR Scan rate: 1 mV/s	NA	NA
Siddiqui et al. (2019) [15]	Corrosion	Potentiostat (ASTM F2129-15)	Saturated calomel electrode	NR	NR	1 × Phosphate-buffered saline (PBS)	37 °C 30 days	Potential range: 0 to 250 mV Scan rate: 1 mV/s	NA	NA

Table 2 (continued)

Author (year)	Electrochemical analysis	Equipment	Reference electrode	Counter electrode	Work electrode	Electrochemical solutions		Working parameters	Sliding mode	Counter-body
						Composition	Conditions			
Sridhar et al. (2019) [86]	Corrosion	Potentiostat (NR)	Saturated calomel electrode	Graphite	TiZr	1 × Phosphate-buffered saline (PBS)	pH 7.4	Potential range :– 10 to 10 mV Scan rate: 1 mV/s	NA	NA

NR not reported, *NA* not applied, *h* hour, *d* day, *cpTi* commercial pure titanium

[a]Fusayama's artificial saliva: NaCl 0.4 (g/L), KCl 0.4 (g/L), $CaCl_2{\cdot}2H_2O$ 0.795 (g/L), $Na_2S{\cdot}9H_2O$ 0.005 (g/L), $NaH_2PO_4{\cdot}2H_2O$ 0.69 (g/L), urea 1 (g/L)

[b]Ringer's solution: NaCl 425 mg, KCl 15 mg, $CaCl_2$ 10 mg, 2.58 sodium lactate 60% in 500 mL of distilled water

[c]Enriched artificial saliva solution: NR, Hank's solution: NR

[d]Artificial saliva: NR

possibly due to its high acidogenic ability [7, 12, 13, 15, 21, 48, 49, 81, 86]. Despite the well-known ability of *S. mutans* to adversely lower the electrochemical behavior of Ti surfaces [48, 74], this oral pathogen is not directly associated with the pathogenesis of the peri-implant diseases [58]. Similarly, *Staphylococcus aureus*, the main bacterium related to a bone infection in orthopedic implants [86], was investigated in one study for dental purposes [82]. To date, only one study [81] provided experimental results of microbial corrosion using a polymicrobial biofilm model with key periodontopathogens, such as *P. gingivalis*, *A. actinomycetemcomitans*, and *F. nucleatum* in anaerobic condition (37 °C, 85% N_2, 5% H_2, 10% CO_2). Thus, biofilm models considering the wide microbial diversity of oral cavity and environmental conditions (i.e., anaerobiosis, pH, temperature, carbohydrate exposure), which mimics the in vivo implant site, should be considered further in vitro and in vivo tests for better translating these findings into clinical situations and generate more clinically significant results.

Another relevant point is related to in vitro bacteria supplementation. Several solutions have been used to stimulate bacterial growth (e.g., glucose, sucrose, mucin, peptone, urea, hydrochloric acid, yeast extract, hemin, and vitamin K). However, some solutions may change the pH of the medium, as hydrochloric acid with a pH ~ 6.7 [83]. Additionally, carbohydrate supplementation, as the combination of sucrose and *S. mutans*, may drastically decrease the pH due to the acid production in the bacteria inoculum even before the biofilm formation, which does not mimic an in vivo process. Moreover, we found a broad range of bacterium inoculum concentrations (10^3–10^9 CFU/mL) with incubation time from 90 min up to 30 days for biofilm formation. Considering that deterioration of the oxide layer by acids produced by bacteria might be a slow and chronic process and dependent on the presence of viable bacteria, the electrochemical analysis can be performed during biofilm development [7, 12, 13, 15, 48, 49, 63, 81–85] or after biofilm removal of the surface [20, 21, 86]. When electrochemical tests are performed after the biofilm removal, it is possible to eliminate the acids' direct effect produced in the biofilm present in the medium. Meanwhile, biofilm elimination in the electrochemical test allows an estimation of the actual surface conditions and the direct effect of microbial accumulation in the electrochemical behavior of the surface after biofilm formation, being a better model alternative overall [21]. The currently published microbiological methodologies used are illustrated in Fig. 6.

4.3 Unraveling the Role of Oral Biofilm in Corrosion and Tribocorrosion Properties

Corrosion is an electrochemical process; therefore, electrochemical techniques have been frequently employed to

Table 3 Summary of electrochemical behavior on the titanium surfaces after the exposure microbial biofilm

Author (year)	Titanium biomaterial	Surface treatment	Electrical parameters			Electrochemical parameters					Main findings
			Polarization resistance (R_p)	Capacitance (Q)	p value	Corrosion potential (E_{corr})	Corrosion current density (i_{corr})	Passivation current density (i_{pass})	Corrosion rate	p value	
Chang et al. (—2003) [49]	cpTi Ti–6Al–4V	NA	Without biofilm: (NR) With biofilm cpTi (Ω cm^2): R 4.75E−05 (±4.04E−05) M 9.41E06 (±1.03E05) C: 5.44E−09 (±1.22–09) B 2.65E−06 (±2.08E−06) Without biofilm: (NR) With biofilm Ti–6Al–4V (Ω cm^2): R: 8.75E−05 (±5.96E−05) M: 5.21E−06 (±4.37E−06) C: 7.64E−07 (±2.63E−07) B: 1.07E−06 (±9.70E−07)	NR	*S. mutans* increased the i_{corr}, reduced the E_{corr}, and increased i_{pass} parameters	Without biofilm (NR) With biofilm cpTi (mV): R: − 76.7 (±5.37) M: 322.6 (±18.81) C: − 340.3 (±0.25) B: − 250.53 (±18.54) Without biofilm: (NR) With biofilm Ti–6Al4V (mV): R: − 144.97 (±38.39) M: − 187.93 (±20.06) C: − 179.40 (±20.35) B: − 176.53 (±8.79)	Without biofilm: (NR) With biofilm cpTi (A/cm^2): R: 8.95E−06 (±2.32E−07) M: 2.33E−07 (±1.20E−07) C: 5.44E−08 (±6.44E−09) B: 3.48E−07 (±1.53E−07) Without biofilm (NR) With biofilm Ti-6Al-4V (A/cm^2): R: 2.23E−06 (±8.93E−07) M: 2.48E−07 (±1.56E−07) C: 2.33E−08 (±1.03E−08) B: 2.87E−08 (±9.84E−09)	Without biofilm: (NR) With biofilm cpTi (A/cm^2): R: 1.26E−05 (±6.54E−06) M: 4.10E−05 (±2.16E−05) C: 6.45E−10 (±4.15E−09) B: 7.64E−06 (±1.21E−06) Without biofilm: (NR) With biofilm Ti-6Al-4V (A/cm^2): R: 3.56E−05 (±1.30E−05) M: 3.26E−05 (±2.20E−05) C: 6.45E−06 (±2.24E−05) B: 6.23E−06 (±2.33E−06)	NR	NR	*S. mutans* increased the i_{corr}, and reduced the E_{corr} and increased i_{pass} parameters.
Díaz et al. (2017) [7]	cpTi	(1) Machined (2) SLA (3) Anodized	NR	Without biofilm: (NR) With biofilm (mC): (1) 38.65 (NR) (2) NR (3) 0.25 (NR)	NR	Without biofilm: (NR) With biofilm (mV): (1) − 0.32 (±0.62) (2) NR (3) − 0.25 (±0.69)	Without biofilm: (NR) With biofilm (nA/cm^2): (1) 6.04 (±0.31) (2) 4.36 (±0.23) (3) 5.80 (±0.04)	Without biofilm: (NR) With biofilm (A/cm^2): (1) 1.80E−06 (NR) (2) NR (3) 2.19E−09 (NR)	NR	NR	*S. mutans* negatively affected the corrosion resistance of the titanium for the immersion periods studied.
Figueiredo-Pina et al. (2018) [63]	Ti–6Al–4V	NA	NR	NR	NR	NR	NR	NR	NR	NR	The presence of *S. salivarius* alters Ti6Al4V.
Fukushima et al. (2014) [13]	cpTi	NA	Without biofilm (0 min; MΩ): (1) VC-G$^+$: 54.2 (±16.3) (2) VC-G$^-$: 66.0 (±13.8) (3) KC: 78.5 (±11.6) With biofilm (90 min; MΩ): (1) VC-G$^+$: 9.0 (±4.0) (2) VC-G$^-$: 3.0 (±0.1) (3) KC: 73.9 (±6.2)	NR	R_p: $p < 0.05$ (only 1 and 2 groups after biofilm developed)	NR	Without biofilm (0 min; nA): (1) VC-G$^+$: 4.4 (±4.0) (2) VC-G: 0.9 (±0.5) (3) KC: 0.3 (±0.1) With biofilm (90 min; nA): (1) VC-G$^+$: 36.6 (±9.1) (2) VC-G: 52.0 (±5.1) (3) KC: 0.3 (±0.2)	Without biofilm (0 min; nA): (1) VC-G$^+$: 0.9 (±0.4) (2) VC-G$^-$: 0.8 (±0.3) (3) KC: 0.2 (±0.1) With biofilm (90 min; nA): (1) VC-G$^+$:32.8 (±4.0) (2) VC-G$^-$: 34.2 (±2.3) (3) KC: 0.2 (±0.0)	NR	i_{corr}: $p < 0.05$ (Only 1 and 2 groups after biofilm developed) i_{pass}: $p < 0.05$ (Only 1 and 2 groups after biofilm developed)	Viable bacterial cells on the titanium surface modified the corrosive properties of titanium.

Table 3 (continued)

Author (year)	Titanium biomaterial	Surface treatment	Electrical parameters			Electrochemical parameters					Main findings
			Polarization resistance (R_p)	Capacitance (Q)	p value	Corrosion potential (E_{corr})	Corrosion current density (i_{corr})	Passivation current density (i_{pass})	Corrosion rate	p value	
Li et al. (2017) [83]	cpTi	NA	Without biofilm: (NR) With biofilm (Ω $cm^2 \times 10^5$): 24h: 3.24 (NR) 48h: 2.27 (NR) 72h: 1.13 (NR) 120h: 0.41 (NR) 168h: 0.35 (NR) 336h: 0.23 (NR)	Without biofilm: (NR) With biofilm (Ω^{-1}/c m^2 S^n): 24 h: 91.97 (NR) 48 h: 99.36 (NR) 72 h: 102.40 (NR) 120 h: 107.99 (NR) 168 h: 119.10 (NR) 336 h: 122.54 (NR)	NR	Without biofilm: (NR) With biofilm (mV vs. SCE): 24h: − 395 (NR) 48h: − 425 (NR) 72h: − 434 (NR) 120h: − 524 (NR) 168h: − 533 (NR) 336h: − 550 (NR)	Without biofilm :(NR) With biofilm ($\mu A/cm^2$) 24h: 0.55 (NR) 48h: 0.99 (NR) 72h: 1.21 (NR) 120h: 1.74 (NR) 168h: 2.02 (NR) 336h: 4.01 (NR)	NR	NR	NR	Adsorption of *S. sanguinis* on titanium, especially when growing as biofilm, promotes the localized corrosion.
Silva et al. (2020) [82]	Ti–6Al–4V	Porous	Without biofilm: (Ω) 1d: 183 (NR) 3d: 154 (NR) 7d: 279 (NR) 21d: 134 (NR) With biofilm: (Ω): 1d: 64 ($\pm$3.8) 3d: 67 ($\pm$6.5) 7d: 68 ($\pm$6.8) 21d: 72 ($\pm$7.0)	NR	NR	NR	NR	NR	NR	NR	Polarization curves showed that the passivity potential range decreased, and the anodic current increased slightly in the inoculated medium with bacteria.
Souza et al. (2013) [48]	cpTi	NA	Without biofilm (Ω cm^2) 48h: 6.5E−09 ($\pm$0.2E−09) With biofilm (Ω cm^2): 48h: 4.9E−09 ($\pm$0.2E−09)	Without biofilm (F cm^2) 48h: 1.6E−05 ($\pm$0.1E−05) With biofilm (F cm^2): 48h: 2.6E−05 ($\pm$0.1E−05)	NR	NR	NR	NR	NR	NR	The decrease of pH caused by acidic substances released from *S. mutans* metabolism can induce the corrosion of titanium during a prolonged period at high sucrose concentration or in association with other acidic substances and fluorides in the oral cavity.

Table 3 (continued)

Author (year)	Titanium biomaterial	Surface treatment	Electrical parameters			Electrochemical parameters					Main findings
			Polarization resistance (R_p)	Capacitance (Q)	p value	Corrosion potential (E_{corr})	Corrosion current density (i_{corr})	Passivation current density (i_{pass})	Corrosion rate	p value	
Souza et al. (2013) [21]	cpTi	NA	Without biofilm: (NR) With biofilm (MΩ cm^2): Control: 23.56 (±30.54) Group0%: 22.24(± 10.70) Group1%: 12.28(±5.56) Group10%: 14.73(±6.50) Group40%: 14.05(±9.08)	Without biofilm: (NR) With biofilm ($\mu\Omega^{-1}$ S^n/cm^2): Control: 11.36 (±5.58) Group0%: 13.43 (±3.51) Group1%: 12.77 (±4.41) Group10%: 12.50 (±3.06) Group40%: 13.12 (±2.17)	NR	NR	Without biofilm: (NR) With biofilm (nA/cm^2): Control: 17.26 (± 8.21) Group0%: 17.69 (±5.47) Group1%: 15.02 (±4.41) Group10%: 14.26 (±4.32) Group40%: 14.42 (−±3.37)	NR	(mpy)× 10^{-3}: Control: 5.90 (±2.24) Group0%: 6.09 (±1.63) Group1%: 5.43 (±1.15) Group10%: 4.96 (±1.17) Group40%: 5.12 (±1.11)	NR	The biofilm formed over 144 h could not reduce the corrosion resistance of titanium regardless of sucrose concentration.
Xu et al. (2020) [20]	cpTi	SLA	Without biofilm: (NR) With biofilm (MΩ cm^2): Ti: 2.24 (±0.05) Ti-pg: 1.43 (±0.17) SLA: 8.60 (±1.48) SLA-pg: 6.65 (±0.18)	Without biofilm: (NR) With biofilm (μF cm^2 ($\times 10^{-5}$)): Ti: 5.18 (NR) Ti-pg: 4.16 (NR) SLA: 5.96 (NR) SLA-pg: 5.73 (NR)	$R_p = p < 0.05$ (Ti-pg and SLA-pg × controls) $Q = p < 0.05$ (Ti-pg and SLA-pg × controls)	Without biofilm: (NR) With biofilm (mV): Ti: − 0.32 (±0.009) Ti-pg: − 0.41 (±0.003) SLA: − 0.38 (±0.075) SLA-pg: − 0.35 (±0.060)	Without biofilm: (NR) With biofilm (μA /cm^2): Ti: 1.23×10^{-8} (2.12×10^{-9}) Ti-pg: 2.26×10^{-8} (3.68×10^{-9}) SLA: 1.11×10^{-8} (6.25×10^{-10}) SLA-pg: 1.55×10^{-8} (1.54×10^{-9})	NR	Without biofilm: (NR) With biofilm (mm/A): Ti: 1.45×10^{-4} (2.50×10^{-5}) Ti-pg: 2.66×10^{-4} (4.33×10^{-5})* SLA: 1.31×10^{-4} (7.34×10^{-6}) SLA-pg: 1.83×10^{-4} (1.82×10^{-5})	$E_{corr} = p < 0.05$ (Ti-pg x controls) i_{corr} = pTi-pg and SLA-pg × controls) Corrosion rate = $p < 0.05$ (Ti-pg and SLA-pg × controls)	*P. gingivalis* was able to weaken their surface properties, especially a decrease in the protective TiO_2 film, which caused a decline in the corrosion resistance and further induced the biocorrosion.

Table 3 (continued)

Author (year)	Titanium biomaterial	Surface treatment	Electrical parameters			Electrochemical parameters					Main findings
			Polarization resistance (R_p)	Capacitance (Q)	p value	Corrosion potential (E_{corr})	Corrosion current density (i_{corr})	Passivation current density (i_{pass})	Corrosion rate	p value	
Zhang et al. (2013) [84]	cpTi	NA	Without biofilm (MΩ/cm^2): Control1: 6.47 (±3.27) Control2: 5.54 (±1.60) With biofilm: 1d: 4.15 (±1.26) 3d: 0.70 (±0.02) 7d: 0.38 (0.0±8)	Without biofilm (μF/cm^2): Control 1: 25.91 (±3.02) Control 2: 23.36 (±1.91) With biofilm: 1d: 23.71 (±0.97) 3d: 18.30 (±0.09) 7d: 29.64 (±0.61)	R_p and $Q = p < 0.05$ (controls/1 day × 3 and 7 days)	NR	NR	NR	NR	NR	Oral bacteria such as *A. naeslundii* can induce titanium corrosion.
Garza-Ramos et al. (2020) [85]	Ti–6Al–4V	NA	NR	NR	NR	Without biofilm 0h: − 309 (±15) 48h: −187 (±9) With biofilm: (1) *S. gordonii* 0h: − 586 (±29) 48h: − 473 (±24) (2) *S. gordonii* + *F. nucleatum*: 0h: − 417 (±21) 48h: − 461 (±23 2)	Without biofilm 0h: 120 (±4) 48h: 107 (±3) With biofilm: (1) *S. gordonii* 0h: 122 (±6) 48h: 214 (±11) (2) *S. gordonii* + *F. nucleatum*: 0h: 140 (±7) 48h: 79 (±4 2)	Without biofilm: 0h: 2.05×10^{-6} ($\pm1\times10^{-7}$) 48h: 1.71×10^{-6}($\pm9\times10^{-8}$) With biofilm: (1) *S. gordonii* 0h: 1.52×10^{-6}($\pm8\times10^{-8}$) 48h: 4.46×10^{-6} ($\pm2\times10^{-7}$) (2) *S. gordonii* + *F. nucleatum*: 0h: 1.70×10^{-6} ($\pm9\times10^{-8}$) 48h: 1.37×10^{-6} ($\pm7\times10^{-8}$)	Without biofilm: 0h: 1.95×10^{-3} ($\pm10\times10^{-5}$) 48h: $1.74\times10^{-3}\pm10^{-5}$) With biofilm: (1) *S. gordonii* 0h: 1.99×10^{-3} ($\pm10\times10^{-5}$) 48h: 3.49×10^{-6} ($\pm2\times10^{-4}$) (2) *S. gordonii* + *F. nucleatum*: 0h: 2.28×10^{-3} ($\pm1\times10^{-4}$) 48 h: 1.29×10^{-3} ($\pm6\times10^{-5}$)	NR	Ti6Al4V alloy in three solutions (*Fusobacterium nucleatum* + *Streptococcus gordonii*, *Streptococcus gordonii*, and Ringer's lactate) presents a uniform corrosion behavior at different exposure times.
Souza et al. (2010) [12]	cpTi	NA	NR	NR	NR	NR	NR	NR	NR	NR	The presence of lactic acid-producing bacteria such as *S. mutans* can increase the corrosion of Ti-based systems used for oral rehabilitation.

Table 3 (continued)

Author (year)	Titanium biomaterial	Surface treatment	Electrical parameters			Electrochemical parameters					Main findings
			Polarization resistance (R_p)	Capacitance (Q)	p value	Corrosion potential (E_{corr})	Corrosion current density (i_{corr})	Passivation current density (i_{pass})	Corrosion rate	p value	
Chandrashekar et al. (2021) [81]	cpTi	NA	Without biofilm(kΩ cm^2) (1) Aerobic: 4h: 6371 (±4343) 7d: 6604 (±4079) (2) Anaerobic: 4 h: 10,351 (±2500) 7d: 10,506 (±2500) With biofilm (kΩ cm^2) (1) Aerobic: 4h: 6593 (±2499) 7d: 3722 (±2236) (2) Anaerobic: 4h: 5758 (±1842) 7d: 5781 (±1316)	NR	NR	Without biofilm(mV) (1) Aerobic: 4h: − 167.8 (±43.1) 7d: − 163.9 (±50.9) (2) Anaerobic: 4h: − 116.0 (±22.7) 7d: − 112.1 (±22.7) With biofilm (mV) (1) Aerobic: 4h: − 82.4 (±22.7) 7d: − 63.3 (±53.0) (2) Anaerobic: 4h: − 61.0 (±0.3) 7d: 11.06 (±30.2)	NR	NR	Without biofilm(µmpy) (1) Aerobic: 4h: 0.07 (±0.01) 7d: 0.07 (±0.01) (2) Anaerobic: 4h: 0.05 (±0.01) 7d: 0.05 (±0.01) With biofilm (µmpy) (1) Aerobic: 4h: 0.1 (±0.1) 7d: 0.1 (±0.2) (2) Anaerobic: 4h: 0.1 (±0.1) 7d: 0.1 (±0.1)	NR	Bacterial exposure inflicted surface damage.
Siddiqui et al. (2019) [15]	cpTi TiZr	SLA	Without biofilm (NR) With biofilm (kΩ cm^2): (1) Ti-SLA: 10,521 (±1874) (2) Ti-modSLA: 9767 (±3402) (3) TiZr-SLA: 9234 (±741)	NR	NR	Without biofilm (NR) With biofilm (mV): (1) Ti-SLA: 3.5 (±11.3) (2) Ti-modSLA: 21.7 (±28.3) (3) TiZr-SLA: − 122.3 (±11.3)	NR	NR	Without biofilm (NR) With biofilm (nm/year): (1) Ti-SLA: 48.2 (±10.5) (2) Ti-modSLA: 43.8 (±3.1) (3) TiZr-SLA: 55.6 (±5.6)	NR	TiZr exhibits statistically similar corrosion resistance as pureTi after exposure to *Streptococcus* polyculture
Sridhar et al. (2019) [86]	cpTi	SLA	Without biofilm(MΩ cm^2) 3.2 (±0.2) With biofilm (MΩ cm^2) 5.0 (±3.5)	NR	NR	Without biofilm (mV) 13.9 (±32.9) With biofilm (mV) − 45.0 (±21.7)	NR	NR	Without biofilm (nm/year) 0.09 (±0.01) With biofilm (nm/year) 0.06 (±0.01)	NR	The potentiodynamic electrochemical experiments showed that the surface damage did not affect corrosion resistance of the material

R Ringer's solution, *M* Ringer's solution + *S. mutans*, *C* tryptic soy broth, *B* products of *S. mutans* mixed with sterilized tryptic soy broth, *VC-G*$^+$ viable cells addition of 1% glucose, *VC-G*$^-$ viable cells addition of deionized water, *KC* killed cells, *SLA* sandblasted, large grit, acid-etched, *cpTi* commercial pure titanium, *NR* not reported, *NA* not applied, *h* hour, *d* day, *min* minutes

**Only OCP values and wear characterizations

determine and measure the Ti corrosion rate in static or dynamic conditions [55]. The vast majority of studies have used a standardized method of three-electrode cells coupled in a potentiostat system (Table 2), following the standard ANSI/AAMI/ISO 10993-15:2000 applicable for implantable devices or ASTM International (American Society for Testing and Materials, G61-86 and G31-72). A saturated calomel electrode was commonly used as the reference electrode, a platinum rod as the counter electrode, and the exposed surface of the sample as the working electrode. The working parameters employed to test the electrochemical stability of Ti material during or after biofilm exposure differ across the studies.

Regarding the electrolyte solution, inert solutions such as phosphate-buffered saline (PBS), NaCl 0.9%, Hank's, and Ringer's solutions were the most considered in corrosion tests. Nevertheless, six studies [12, 21, 48, 63, 83, 84] choose artificial saliva with different compositions and bacterial medium solution as the electrolyte to mimic the oral situation. Additionally, we observed that the pH range of solutions used in all studies varied from 5 (acidic) [84] to 7.4 (neutral/physiologic) [86]. This key information is not reported by some authors [15, 20, 48, 49, 63, 81, 82, 85]. The choice of electrolyte is a relevant factor because the effect of oral biofilm can overlap with solution characteristics, as pH level [4] and ionic exchange trigger by electrolyte composition [21].

Among the 15 eligible studies, only 2 research groups [12, 63] used a linear reciprocating tribometer to investigate the synergic interaction between wear and corrosion in the presence of oral biofilms. The main difference between corrosion and tribocorrosion systems can be seen in Fig. 7. Nowadays, electrochemical and tribological synergic analyses have been suggested to translate the tribocorrosion phenomenon in the oral environment to the bench [8, 29, 55]. However, considering that these studies focused on the specific effect of *Streptococcus salivarius* [63] or *S. mutans* + *Candida albicans* [12] on the Ti corrosion/wear, in-depth analysis of the tribocorrosion kinetics using a polymicrobial biofilm model lack in the literature. Moreover, similar to corrosion assays, different working parameters (e.g., load, time, frequency) were employed in tribocorrosion systems. Therefore, guidelines and standardized protocols are also needed to improve the quality of electrochemical data obtained and allow direct comparison between the studies outcomes in the future.

Regardless of the type of electrochemical assay, the oral biofilm developed on the Ti surface negatively affected the material's corrosion resistance (Table 3). In terms of electrical parameters, higher polarization resistance (R_p) and lower capacitance/constant phase element (C_{dl}, Q) values indicate higher corrosion resistance [87]. The available corrosion results revealed that the polarization resistance (R_p) and capacitance (Q) values shifted to lower and higher levels in biofilm-covered surfaces, respectively. Even studies that not considered groups without biofilms [7, 12, 15, 20, 21, 63, 81, 83, 85, 86], this trend was confirmed along the time points evaluated for the group with biofilms [7, 13, 15, 20, 21, 48, 49, 81–84, 86]. This fact supports the disadvantageous electrochemical properties of Ti material when it is exposed to different oral microorganisms (*Streptococcus* spp., *Actinomyces* spp., *P. gingivalis*, *F. nucleatum*, and *C. albicans*) since higher capacitance values indicate an increase in the ionic exchange between the material and the electrolyte/biofilm structure [53]. Moreover, a lower R_p suggests higher corrosion rates since this parameter is considered a measure of the barrier effect of the passive film against charge transfer [4]. Consequently, biofilm-covered surface may be more susceptible to Ti deterioration and material loss over time.

The electrochemical parameters, including corrosion potential (E_{corr}), corrosion current density (i_{corr}), and passive current density (i_{pass}), also were negatively influenced by biofilm presence. Conceptually, nobler E_{corr} values are associated with more remarkable passivity and lower corrosion tendency, while i_{corr} indicates the current flow at an open circuit potential as a result of oxidation or reduction reactions, and i_{pass} corresponds to the current value in the transition from the active region to the passive state of Ti [4, 53]. In other words, higher E_{corr} and lower i_{corr} and i_{pass} values reflect low electrochemical activity and high corrosion resistance properties. Most studies found lower E_{corr} [20, 49, 81, 83, 85], with higher i_{corr} [13, 83, 85] and i_{pass} [49, 85] values, demonstrating unfavorable electrochemical properties of Ti in the presence of biofilm.

Although it is difficult to estimate how much changes in the electrical and electrochemical parameters would have clinical relevance, it is known that reduced electrochemical properties of Ti have a direct relationship with surface deterioration. Microscopy analysis investigated this correlation in 12 studies [12, 15, 20, 21, 48, 63, 81–86]. To understand the whole kinetics of corrosion, inductively coupled plasma mass spectrometry should also be used to investigate Ti ions' content in the electrolyte solution after microbial corrosion tests, as conducted in two studies [7, 13]. Surprisingly, one study [21] showed the absence of pitting corrosion and no clear evidence of changes in the Ti surface after biofilm removal. Therefore, one may assume a threshold between the time/condition of biofilm growth and the risk of pitting corrosion, which needs further investigation. Additionally, only five studies [7, 20, 82, 86] evaluated the microbial corrosion on commercial surface treatment (i.e., SLA, anodized, or porous), representing one condition closer to clinical settings. Finally, preclinical and clinical studies investigating the influence of microbial corrosion on the longevity of Ti-based dental implants are lacking.

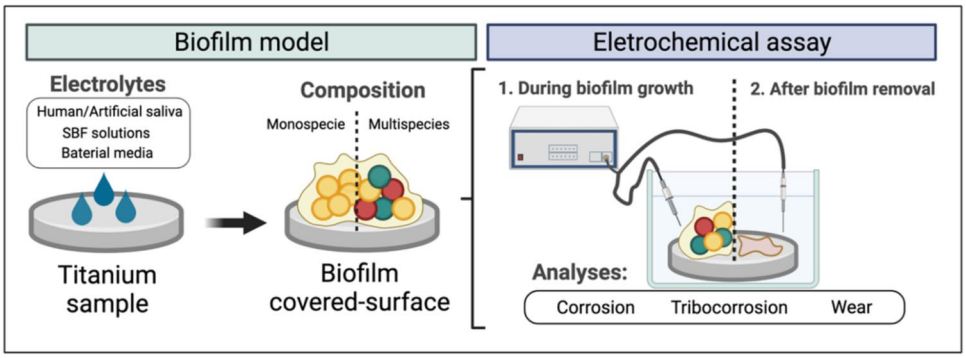

Fig. 6 The summarized sequence of in vitro biofilm model to test microbial corrosion on titanium material. Titanium discs can be exposed to different electrolyte solutions [human/artificial saliva, simulated body fluid (SBF) solution, and bacteria media] to spontaneously form a TiO_2 layer on the surface. Next, mono or multispecies bacterial inoculum can promote biofilm-covered surface in a specific time. Then, the electrochemical assay can be performed during biofilm growth or after biofilm removal to check the microbial corrosion process. Finally, simultaneous corrosion, tribocorrosion, and wear characterizations can be obtained (created with BioRender.com; License number: DV22UL3LDQ)

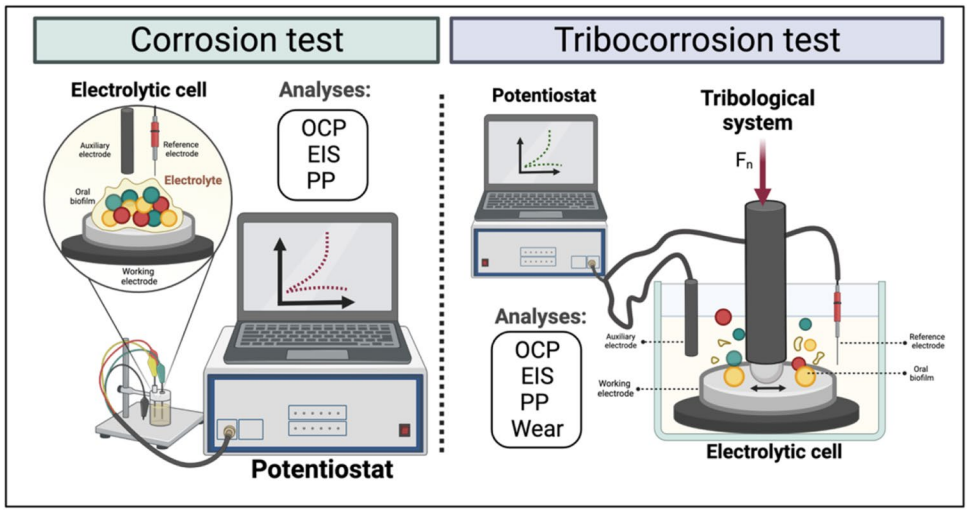

Fig. 7 Schematic diagram of corrosion and tribocorrosion testing systems. Static (corrosion) and dynamic (tribocorrosion) conditions can be considered to evaluate the microbial corrosion in Ti material. In addition to electrical and electrochemical outcomes, the tricorrosion systems can provide the samples' wear features and weight loss. Specific working parameters are recommended for each system. *OCP* open circuit potential, *EIS* electrochemical impedance spectroscopy, *PP* potentiodynamic polarization (created by Biorender®; License number AA22UL1R54)

5 Preventing Microbial Corrosion in Implant Dentistry

Microbial corrosion is rarely linked to a single mechanism but is considered a complex reaction in which bacterial metabolites trigger or enhance the corrosion process [8, 29]. Therefore, there is an outstanding effort to prevent microbial corrosion using methods to inhibit biofilm formation or antimicrobial approaches or improve surface mechanical and chemical properties [88]. For this purpose, surface modification development to enhance the electrochemical behavior of Ti material for long-term dental implant clinical applications has been widely investigated [5]. Newly developed strategies have been focused mainly on surface properties dedicated to non-fouling abilities to prevent bacteria attachment and improve corrosion resistance [11, 89]. Nowadays, it is known that topographic patterns with different shapes and sizes have been shown to inhibit biofilm formation compared to flat surfaces [90]. In addition to the early-mentioned surfaces, antibacterial, anti-corrosive, and biocompatible coatings have also been indicated as strategies to improved implant survival and, consequently, decrease the harmful effect of microbial corrosion [39, 53]. Thus, since microorganisms can adhere directly to surfaces and lead to corrosion, inhibiting bacterial attachment or biofilm formation is a promising strategy to reduce microbial corrosion in the long term.

Another relevant strategy consists of dual-targeting therapies to disrupt the extracellular biofilm matrix without promoting implant surface damages. In mature biofilms with high bacterial cell density, the EPS-matrix forms a transport barrier, which may maintain the bacteria metabolites in

contact with the surface and impeded saliva penetration to lixiviate these acidic [83]. Consequently, a higher deterioration of the TiO_2 layer with increasing the time of biofilm development is expected. Recently, our group has shown that the iodopovidone (pre-treatment) may enhance the antibiofilm efficacy of antibiotics (second treatment) by dismantling the EPS matrix, amplifying the killing of pathogenic bacteria on Ti surfaces [39]. However, further studies are needed to check the effect of iodopovidone on Ti surface as a possible way to control peri-implant diseases and synergically microbial corrosion.

In a nutshell, these alternatives strategies mentioned above are promising approaches to control microbial corrosion. However, future preclinical and clinical studies need to consider some challenges, such as prolong effectiveness, enhanced surface properties, and effect on comprehensive microbial composition. Furthermore, this scoping review focused only on titanium-based dental implants, but other biomaterials (such as zirconium and its alloys) should also be considered in others research. Additionally, with greater reliability, the well-documented tribocorrosion assay can provide answers regarding titanium degradation against corrosive environments, including polymicrobial biofilms. Lastly, this review is a guide for researchers and materials scientists in developing new investigations and clinicians to understand the mechanisms involved in microbiologically induced corrosion in dental implants.

6 Conclusion and Outlook

In this scoping review, we reinforced that the microbial corrosion phenomenon can be considered one of the emerging areas of interest and research in implant dentistry and biomaterial fields. Considering the loss of passivity potential on titanium material and the corrosion of implant devices due to acidic metabolites produced from oral biofilms, this research topic is a concerning issue. To predict the microbial corrosion effects in in vitro conditions, corrosion/tribocorrosion tests can be used as suitable tools during biofilm formation or after biofilm removal from the titanium surface. Notably, the polymicrobial biofilm model represents a more clinical reliable condition to evaluate the changes in the electrochemical behavior of titanium but still is under-investigated. Additionally, the cause–effect relationship between biofilm formation and titanium deterioration is not fully understood due to its chronic long-term effect. The direct effect of microbial accumulation on the specific chemical, physical, and mechanical properties of the implant surface and its mechanism needs to be further investigated. Moreover, a feedback loop is expected in this process since biofilm leads to surface deterioration, and particles and ions released promote microbial accumulation and microbiological shift. Therefore, in the future, it is necessary for preclinical and clinical studies to investigate the influence of microbiologically induced corrosion on the survival of Ti-based dental implants. Additionally, to prevent this deleterious phenomenal, anti-fouling, antibacterial, and anti-corrosive coatings from preventing bacterial attachment or biofilm formation are encouraged to reduce microbial load and consequently corrosion. For instance, surface coatings—even without antimicrobial ability—may act as a protective film improving the material's corrosion resistance and can be a promising approach for implant device manufacturing.

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Author Contributions RCC, VLA, PHCM, and IMV collected the data and led the writing. MB, MTM, VAR, and JGSS made the critical review of article content and writing. All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

Data Availability Data sources are PubMed (MEDLINE), Scopus, Web of Science, EMBASE, Google Scholar, and the System for Information on Grey Literature in Europe (SIGLE) through the OpenGrey.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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