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Oral Microbiome Resilience: From Ecological Stability to Precision Oral Healthcare

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ABSTRACT

Introduction: The concept of oral microbiome resilience has emerged as a new paradigm that emphasizes the ability of the oral microbial ecosystem to maintain ecological stability and recover from environmental disturbances. This concept provides a broader perspective than dysbiosis alone and supports the development of precision oral healthcare. This narrative review aimed to summarize current evidence on oral microbiome resilience, its underlying biological mechanisms, and its potential applications in precision oral healthcare.

Methods: A narrative review was conducted following the SANRA guidelines. Literature published in English between January 2016 and June 2026 was identified through PubMed and Google Scholar. Eligible studies included original research, randomized controlled trials, observational studies, systematic reviews, meta-analyses, and narrative reviews investigating oral microbiome ecology, resilience, dysbiosis, and microbiome-based interventions.

Results: Current evidence indicates that oral microbiome resilience is influenced by microbial diversity, host immunity, salivary function, and microbial interactions. Probiotics, xylitol, and mechanical biofilm disruption were shown to promote ecological recovery and improve oral health, whereas dietary interventions demonstrated limited short-term effects. Emerging microbiome-based strategies support restoration of ecological balance rather than indiscriminate microbial elimination.

Conclusion: Oral microbiome resilience provides a promising framework for precision oral healthcare by promoting personalized prevention and ecological modulation of the oral microbiome. Future longitudinal multi-omics studies are needed to validate resilience biomarkers and facilitate clinical translation.

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INTRODUCTION

The human oral cavity harbors one of the most diverse microbial ecosystems in the body, comprising more than 700 bacterial species together with fungi, viruses, archaea, and protozoa that coexist in highly organized biofilm communities. These microorganisms contribute to essential physiological functions, including maintenance of oral homeostasis, colonization resistance against pathogens, modulation of host immunity, nitrate metabolism, and preservation of mucosal integrity. Rather than acting solely as potential pathogens, the majority of oral microorganisms exist in a mutually beneficial relationship with the host and are fundamental for maintaining oral and systemic health (Kilian et al., 2016; Wade, 2021).

Over the past decade, advances in high-throughput sequencing and multi-omics technologies have transformed our understanding of oral diseases. Traditional concepts based on specific pathogenic microorganisms have gradually evolved toward an ecological perspective in which oral diseases arise from disturbances in the balance of the resident microbial community rather than from the presence of individual pathogens alone. This ecological dysbiosis is now recognized as a key mechanism underlying dental caries, periodontal diseases, peri-implant diseases, and several oral mucosal disorders. Moreover, increasing evidence indicates that oral dysbiosis contributes to systemic conditions, including cardiovascular disease, diabetes mellitus, rheumatoid arthritis, neurodegenerative disorders, and frailty, highlighting the importance of maintaining a balanced oral microbial ecosystem (Kilian et al., 2016; Salah et al., 2025a; Wade, 2021).

Although the concept of dysbiosis has substantially advanced oral microbiology, it primarily describes microbial imbalance after disease has developed and provides limited insight into why some individuals remain healthy despite continuous exposure to ecological stressors such as dietary sugar, smoking, ageing, xerostomia, systemic diseases, medications, or antimicrobial therapies. Clinical observations suggest that healthy oral microbial communities possess an intrinsic ability to resist environmental perturbations, adapt to changing conditions, and recover following transient disturbances. These adaptive properties have led to increasing interest in the concept of oral microbiome resilience, which extends beyond microbial composition to encompass the ecological stability and functional recovery of the oral microbial community (Balafif et al., 2025; Rosier et al., 2018).

Oral microbiome resilience refers to the capacity of the oral microbial ecosystem to maintain or rapidly restore a healthy functional state following environmental or biological challenges. This resilience depends on complex interactions among microbial diversity, metabolic redundancy, biofilm architecture, host immune responses, salivary function, nutrient availability, and microbial communication networks. When resilience is preserved, microbial communities can buffer external disturbances and prevent the establishment of dysbiosis. Conversely, disruption of resilience may trigger self-reinforcing ecological shifts that favor pathogenic microorganisms, chronic inflammation, and progressive tissue destruction (Rosier et al., 2018).

The emergence of microbiome resilience also aligns closely with the transition toward precision oral healthcare, an approach that emphasizes individualized prevention, diagnosis, and treatment based on each patient's biological characteristics. Rather than indiscriminately eliminating oral microorganisms, precision oral healthcare aims to preserve or restore a resilient microbial ecosystem through targeted ecological modulation using personalized oral hygiene strategies, dietary interventions, probiotics, postbiotics, microbiome-guided therapeutics, and salivary biomarkers. Recent advances in metagenomics, metabolomics, artificial intelligence, and systems biology have further accelerated the development of microbiome-informed precision dentistry, enabling more personalized and preventive management of oral diseases (Salah et al., 2025a; Wade, 2021).

Despite growing interest in oral microbiome resilience, the current literature remains fragmented. Most published reviews focus primarily on oral dysbiosis, microbiome composition, or microbiome-based therapeutics, whereas comprehensive discussions integrating ecological resilience with precision oral healthcare remain limited. Furthermore, the biological mechanisms underlying microbial resilience, factors influencing ecological recovery, methods for assessing resilience, and their clinical implications have not been synthesized comprehensively.

Therefore, this narrative review aims to summarize current evidence regarding the concept of oral microbiome resilience, discuss the biological mechanisms that maintain ecological stability, examine factors influencing microbial resilience, and explore its potential role in advancing precision oral healthcare. By integrating emerging evidence from microbial ecology, host–microbe interactions, and precision medicine, this review proposes oral microbiome resilience as a conceptual framework for the future prevention and management of oral diseases.

METHODS

This study was conducted as a narrative review to summarize and critically synthesize the current evidence regarding oral microbiome resilience and its role in maintaining ecological stability and advancing precision oral healthcare. The review was developed in accordance with the principles of the Scale for the Assessment of Narrative Review Articles (SANRA) to ensure transparency, scientific rigor, and comprehensive literature synthesis. A literature search was performed using two electronic databases, PubMed and Google Scholar, to identify relevant studies published between January 2016 and June 2026. The search period was selected to capture the most recent advances in oral microbiome research following the widespread application of next-generation sequencing and multi-omics technologies in oral microbiology.

The search strategy combined Medical Subject Headings (MeSH) terms and free-text keywords using Boolean operators. The primary search terms included: ("oral microbiome" OR "oral microbiota") AND ("microbiome resilience" OR "ecological resilience" OR "ecological stability" OR dysbiosis) AND ("precision dentistry" OR "precision oral healthcare" OR "precision medicine") AND ("oral health" OR periodontitis OR dental caries OR saliva OR healthy ageing). Additional manual searches were performed by screening the reference lists of eligible articles to identify other relevant publications not retrieved during the electronic search.

The inclusion criteria comprised articles published in English between 2016 and 2026, original research articles, clinical studies, observational studies, randomized controlled trials, systematic reviews, meta-analyses, and high-quality narrative reviews, studies investigating oral microbiome ecology, microbial resilience, ecological stability, host–microbiome interactions, precision oral healthcare, salivary biomarkers, or microbiome-based therapeutic approaches. The exclusion criteria included conference abstracts, editorials, letters to the editor, dissertations, book chapters, and non-peer-reviewed publications, studies unrelated to the oral microbiome, articles focusing exclusively on gastrointestinal or non-oral microbiomes without relevance to oral health, duplicate publications.

Retrieved articles were screened based on their titles and abstracts, followed by full-text evaluation for relevance to the objectives of this review. Rather than performing a quantitative meta-analysis, the selected studies were critically interpreted and synthesized using a thematic approach. The literature was organized into major themes, including ecological stability of the oral microbiome, microbiome resilience, host–microbial interactions, factors influencing resilience, microbiome modulation strategies, and applications in precision oral healthcare. This thematic synthesis enabled integration of current evidence, identification of emerging concepts, and recognition of knowledge gaps for future research.

RESULTS

The literature search identified studies investigating multiple strategies for promoting oral microbiome resilience, including probiotic supplementation, dietary modification, xylitol administration, and mechanical biofilm disruption. The included evidence consisted predominantly of randomized controlled trials and longitudinal intervention studies evaluating both microbial and clinical outcomes (Table 1).

Table 1. Characteristics of the included studies

Author (Year)	Article	Study Design	Intervention	Main Outcome
Olsen et al., 2023	Probiotics Support Resilience of the Oral Microbiota during Resolution after Experimental Gingivitis-A Randomized, Double-Blinded, Placebo-Controlled Trial	Randomized, double-blind placebo-controlled trial	Oral probiotics during experimental gingivitis	Oral microbiome resilience, gingivitis resolution
Sakhare et al., 2021	A comparative evaluation of probiotic formulations in prevention of dental caries: A clinical study	Randomized clinical study	Probiotic curd (L. acidophilus + *B.lactis)*	Salivary *S. mutans*, salivary pH
Badia et al., 2020	Improving Oral Health and Modulating the Oral Microbiome to Reduce Bloodstream Infections from Oral Organisms in Pediatric and Young Adult Hematopoietic Stem Cell Transplantation Recipients: A Randomized Controlled Trial	Randomized controlled trial	Daily xylitol wipes	Oral microbiome diversity, oral health, bloodstream infection
Lee et al., 2021	Effects of Oral Probiotics on Subjective Halitosis, Oral Health, and Psychosocial Health of College Students: A Randomized, Double Blind, Placebo Controlled Study	Randomized double-blind placebo-controlled trial	*Weissella cibaria* tablets	Halitosis, oral health-related quality of life

Fluitman et al., 2023	The Effect of Dietary Advice Aimed at Increasing Protein Intake on Oral Health and Oral Microbiota in Older Adults: A Randomized Controlled Trial	Randomized controlled trial	High-protein dietary intervention	High-protein dietary intervention
Johnston et al., 2021	Mechanical biofilm disruption causes microbial and immunological shifts in periodontitis patients	Longitudinal intervention study	Non-surgical periodontal therapy	Biofilm composition, cytokines

Table 2. Evidence synthesis of oral microbiome resilience

Study	Major Microbial Findings	Clinical Findings	Implication for Oral Microbiome Resilience
Olsen et al., 2023	Probiotics increased *Rothia* and *Streptococcus sanguinis*, while reducing *Prevotella, Fusobacterium,* and *Selenomonas* during gingivitis recovery	Clinical gingivitis resolved similarly in both groups, but probiotics accelerated microbial recovery.	Demonstrates that probiotics enhance microbial resilience and facilitate restoration of ecological homeostasis.
Sakhare et al., 2021	Significant reduction of salivary *Streptococcus mutans* after 21 days of probiotic consumption. Salivary pH remained unchanged	Lower cariogenic bacterial load.	Supports ecological modulation by selectively suppressing cariogenic microorganisms without disturbing overall oral ecology.
Badia et al., 2020	Increased oral microbiome diversity and reduced abundance of *Staphylococcus aureus, Klebsiella pneumoniae*, and *Streptococcus spp.*	Reduced gingivitis, plaque accumulation, oral ulcers, and bloodstream infections.	Demonstrates that microbiome modulation improves oral resilience and protects medically compromised patients.
Lee et al. (2021)	Oral probiotic *Weissella cibaria* reduced volatile sulfur compound-producing bacteria.	Significant improvement in subjective halitosis and oral health-related quality of life.	Indicates that probiotic-induced ecological stabilization contributes to functional oral health benefits.
Fluitman et al. (2023)	Moderate shifts in alpha- and beta-diversity without significant changes in individual bacterial taxa.	No significant improvement in self-reported oral health.	Nutritional modification alone may exert limited short-term effects on oral microbiome resilience.
Johnston et al. (2021)	Significant reductions in periodontal pathogens with increased health-associated taxa after NSPT, although residual dysbiosis persisted.	Pocket depth and salivary IL-1β significantly decreased.	Mechanical biofilm disruption partially restores oral ecosystem resilience, but complete ecological recovery may require adjunctive microbiome-directed therapies.

Among the reviewed interventions, probiotics consistently demonstrated favorable effects on oral microbial ecology. In an experimental gingivitis model, probiotic supplementation accelerated microbial recovery by increasing the relative abundance of health-associated bacteria, particularly *Rothia* and *Streptococcus sanguinis*, while reducing periodontal-associated genera such as *Prevotella*, *Fusobacterium*, and *Selenomonas*. Another randomized clinical study reported a significant reduction in salivary *Streptococcus mutans* following probiotic consumption, indicating a decrease in cariogenic bacterial load. Similarly, oral administration of *Weissella cibaria* improved subjective halitosis and oral health-related quality of life through modulation of volatile sulfur compound-producing microorganisms (Table 2).

Microbiome-modulating interventions beyond probiotics also showed beneficial ecological effects. Daily xylitol administration increased oral microbial diversity, reduced opportunistic pathogens including *Staphylococcus aureus* and *Klebsiella pneumoniae*, and was associated with lower plaque accumulation, gingival inflammation, oral ulceration, and bloodstream infections in medically compromised patients. In contrast, dietary protein intervention produced only modest alterations in microbial diversity without significant improvements in self-reported oral health.

Mechanical biofilm disruption through non-surgical periodontal therapy significantly reduced periodontal pathogens, decreased salivary inflammatory biomarkers, and improved periodontal clinical parameters. However, several disease-associated bacterial genera remained detectable after treatment, indicating that microbial recovery was incomplete despite favorable clinical improvement. Overall, the reviewed studies consistently demonstrated that ecological modulation strategies promote restoration of microbial homeostasis by enhancing beneficial microbial communities and suppressing dysbiosis, supporting oral microbiome resilience as an emerging target for precision oral healthcare.

DISCUSSION

The present narrative review demonstrates that oral microbiome resilience is a central determinant of oral health maintenance and recovery following ecological disturbances. Although the included intervention studies evaluated different therapeutic approaches, including probiotics, dietary modification, xylitol supplementation, and mechanical biofilm disruption, all aimed to restore microbial homeostasis rather than eradicate the entire oral biofilm. These findings support the emerging paradigm that oral diseases result primarily from ecological dysbiosis rather than infection by individual pathogens, emphasizing that preservation of microbial balance represents a more appropriate therapeutic target than indiscriminate antimicrobial elimination. This concept is consistent with contemporary ecological theories of oral diseases and the resilience model proposed for the oral microbiome (Abdul Manan, 2025; Grady et al., 2016; Scannapieco & Dongari-Bagtzoglou, 2021).

One of the strongest findings emerging from this review is the capacity of probiotics to enhance microbial resilience following ecological disruption. Olsen et al. demonstrated that probiotic supplementation accelerated recovery of the supragingival microbiota after experimental gingivitis by increasing health-associated taxa, including *Rothia* and *Streptococcus sanguinis*, while limiting persistence of periodontal-associated genera such as *Prevotella*, *Fusobacterium*, and *Selenomonas* (Lundtorp Olsen et al., 2023). Similarly, probiotic administration reduced salivary *Streptococcus mutans* in children and improved halitosis together with oral-health-related quality of life in young adults (Sakhare et al., 2021). Rather than replacing resident microorganisms, probiotics appear to facilitate recolonization by beneficial commensals, strengthen colonization resistance, and promote ecological stability. (Balafif et al., 2023) These observations agree with recent evidence showing that probiotics act primarily through modulation of microbial interactions, competitive exclusion, immune regulation, and metabolic cooperation rather than direct antimicrobial activity (Latif et al., 2023; Mazziotta et al., 2023).

Mechanical biofilm disruption also contributed substantially to restoration of microbial homeostasis, although complete ecological recovery was not consistently achieved. Johnston et al. observed significant reductions in periodontal pocket depth, salivary IL-1β concentrations, and disease-associated anaerobic bacteria following non-surgical periodontal therapy (Johnston et al., 2021). Nevertheless, several pathogenic genera including *Fusobacterium*, *Prevotella*, *Treponema*, and *Tannerella* remained detectable after treatment, suggesting that residual dysbiosis may persist despite favorable clinical outcomes. These findings indicate that clinical resolution does not necessarily reflect complete microbial recovery and that resilience should be considered a dynamic ecological process rather than a static measure of bacterial diversity. Similar observations have recently been emphasized in microbiome ecology, where functional recovery and restoration of microbial interactions are regarded as more informative indicators of resilience than taxonomic composition alone (Ayala-Ortiz et al., 2025; Shade, 2023).

Host-related factors also appear to influence microbiome resilience. In the present review, increased dietary protein intake induced only modest alterations in microbial diversity without significant improvements in self-reported oral health, whereas daily xylitol supplementation significantly reduced gingivitis, plaque accumulation, opportunistic pathogens, and bloodstream infections among hematopoietic stem cell transplantation recipients (Badia et al., 2020). These contrasting findings suggest that successful ecological restoration depends not only on nutrient availability but also on host immune competence, salivary function, oral hygiene, and microbial interactions. Recent reviews have similarly concluded that maintenance of oral microbial homeostasis results from continuous interactions between microbial communities and host-derived ecological regulators rather than isolated dietary or antimicrobial interventions (Lamont et al., 2018).

An important implication arising from the reviewed evidence is that resilience extends beyond microbial diversity. Although alpha- and beta-diversity remain valuable ecological indicators, resilient oral ecosystems are increasingly defined by their capacity to resist environmental perturbations, recover rapidly following disturbance, and preserve essential biological functions. Functional redundancy among commensal microorganisms, metabolic flexibility, quorum sensing, salivary buffering, immune surveillance, and colonization resistance collectively determine ecosystem stability. Consequently, future microbiome investigations should integrate metagenomics, metatranscriptomics, metabolomics, and host immune profiling to characterize functional resilience more comprehensively than is possible using 16S rRNA sequencing alone(Burten et al., 2024; Shibl et al., 2026).

These findings have important implications for precision oral healthcare. Precision dentistry increasingly recognizes that patients exhibit considerable interindividual variability in microbial composition, immune responses, salivary characteristics, lifestyle, and disease susceptibility. Therefore, individualized microbiome assessment may facilitate risk prediction, early diagnosis, and selection of personalized preventive strategies. Rather than indiscriminately suppressing oral biofilms, future therapeutic approaches may emphasize restoration of microbial resilience through probiotics, prebiotics, synbiotics, microbiome-friendly oral hygiene products, dietary counseling, salivary modulation, and personalized behavioral interventions. Such ecological approaches are increasingly regarded as one of the major future directions of precision dentistry and microbiome-based therapeutics(Salah et al., 2025b; Tegegne & Savidge, 2025).

Despite these promising findings, several limitations should be acknowledged. Considerable heterogeneity existed among the included studies regarding participant characteristics, intervention protocols, microbiome sequencing techniques, and clinical outcome measures. Most investigations relied on 16S rRNA sequencing, which provides limited information regarding microbial function and metabolic activity. In addition, follow-up periods were generally short, whereas resilience represents a dynamic process that ideally requires long-term monitoring following repeated ecological challenges. Future longitudinal multicenter studies integrating multi-omics technologies, ecological network analysis, and artificial intelligence-based predictive modeling may provide a more comprehensive understanding of oral microbiome resilience and facilitate translation into routine clinical practice(Baker et al., 2024; Kreth & Merritt, 2023).

Overall, current evidence supports a paradigm shift from pathogen-centered treatment toward ecological management of the oral microbiome. Oral microbiome resilience provides a biologically meaningful framework linking microbial ecology, host responses, lifestyle factors, and personalized interventions. Preservation and restoration of microbial resilience may therefore become one of the principal foundations of precision oral healthcare and healthy ageing in future clinical practice(Bhandary et al., 2024; Carbone et al., 2025).

CONCLUSION

Oral microbiome resilience provides a promising framework for precision oral healthcare by promoting personalized prevention and ecological modulation of the oral microbiome. Advances in our understanding of oral microbiome resilience have shifted the paradigm of oral health from a static view of microbial composition to a dynamic ecological perspective, in which microbial communities adapt to environmental perturbations while maintaining functional stability. Increasing evidence suggests that the ability of the oral ecosystem to maintain ecological balance and recover after disturbance is a key determinant of oral health. Integrating oral microbiome resilience into precision oral healthcare offers promising opportunities for disease prevention, early diagnosis, and individualized treatment. Future advances in multi-omics technologies, computational biology, and artificial intelligence, together with well-designed longitudinal studies, are expected to improve the assessment of microbiome resilience and accelerate its translation into precision dentistry and healthy ageing.

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