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The Effect of Probiotics on the Oral Microbiome and Prevention of Dental Caries: A Systematic Review

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ABSTRACT

Background: Dental caries remains a global public health challenge, driven by microbial dysbiosis within the oral cavity. Probiotics have emerged as a potential preventive strategy by restoring ecological balance, but their clinical effectiveness remains uncertain.

Objective: To systematically review the evidence on the effects of probiotics on the oral microbiome and their role in the prevention of dental caries.

Methods: Following PRISMA 2020 guidelines, a comprehensive search was conducted across PubMed, Scopus, Embase, Web of Science, and Google Scholar. Eligible studies included randomized controlled trials, cohort studies, and systematic reviews investigating probiotic interventions in human populations with dental caries outcomes. Data extraction focused on strain specificity, delivery methods, microbiological changes, and caries incidence or progression.

Results: Ten randomized controlled trials and multiple systematic reviews were included. Probiotic strains such as Lactobacillus rhamnosus GG, Lactobacillus reuteri, Lactobacillus paracasei SD1, and Streptococcus salivarius M18 demonstrated significant reductions in salivary Streptococcus mutans, increased microbial diversity, and decreased caries incidence in several studies. Some trials reported regression of early lesions. However, results varied, with certain interventions showing no significant effect, particularly in long-term follow-ups. Systematic reviews highlighted heterogeneity in methodology, strain selection, and intervention design as key barriers to definitive conclusions.

Conclusion: Probiotics represent a safe, biologically plausible adjunct for caries prevention, capable of modulating the oral microbiome and reducing caries risk. Their effectiveness is strain-specific and influenced by delivery methods, dosage, and population characteristics. High-quality, long-term clinical trials are needed to confirm their role in preventive dentistry.

KEYWORDS: Probiotics; Oral microbiome; Dental caries prevention; Streptococcus mutans; Lactobacillus rhamnosus; Lactobacillus reuteri; Streptococcus salivarius; Randomized controlled trials; Ecological plaque hypothesis; Pediatric dentistry

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INTRODUCTIO

Dental caries is one of the most prevalent chronic diseases worldwide, affecting billions of individuals and creating significant social and economic burdens. Despite advances in preventive dentistry, the global prevalence remains alarmingly high, particularly among children and adolescents. The disease arises from a multifactorial interplay of host susceptibility, frequent consumption of fermentable carbohydrates, and the metabolic activities of oral microorganisms, which together disrupt the equilibrium of the oral microbiome. This dysbiosis, dominated by acidogenic and aciduric species, drives demineralization of dental hard tissues and the development of carious lesions (Marsh, 2003).

The oral cavity harbors a complex and diverse microbial ecosystem. Under healthy conditions, this environment is maintained in a state of homeostasis, where commensal bacteria contribute to oral health. However, ecological stressors such as frequent sugar intake or poor oral hygiene disrupt this balance. Cariogenic species, most notably *Streptococcus mutans*, *Streptococcus sobrinus*, and *Lactobacillus* spp., produce acids that lower plaque pH, fostering conditions favorable to acid-tolerant bacteria. This cycle of ecological imbalance accelerates enamel demineralization and lesion progression, highlighting the ecological nature of caries pathogenesis (Marsh, 2003).

Conventional approaches to prevention—including plaque control, fluoride use, and dietary modification—remain the foundation of caries management. Yet, their effectiveness is often constrained by patient compliance, accessibility, and inability to completely prevent recurrence. These limitations have spurred increasing interest in biological strategies that seek not only to suppress pathogenic microorganisms but also to restore microbial balance within the oral cavity (Panchbhai et al., 2015).

Probiotics have emerged as one of the most promising biological interventions. Defined by the World Health Organization as "live microorganisms which, when administered in adequate amounts, confer a health benefit on the host," probiotics have well-documented applications in gastrointestinal health. Growing evidence now supports their role in modulating the oral microbiome. Proposed mechanisms include microbial competition for adhesion sites, production of antimicrobial compounds such as bacteriocins and hydrogen peroxide, buffering of plaque acidity, and immunomodulatory effects on host defenses (Beattie et al., 2024; Lundtorp-Olsen et al., 2024).

Clinical research supports the potential of these mechanisms. Randomized controlled trials have demonstrated that *Lacticaseibacillus rhamnosus* GG delivered in milk can reduce caries incidence in preschool children (Meng et al., 2023). Similarly, lozenges containing *Streptococcus salivarius* M18 have been shown to improve caries risk profiles, while *Lactobacillus reuteri* supplementation has been associated with lower caries prevalence in childhood (Twetman & Jørgensen, 2021). Meta-analyses further corroborate these findings, indicating reductions in salivary *S. mutans* counts and, in some studies, modest decreases in caries incidence (Lopes et al., 2024; Feldmann et al., 2024).

Nevertheless, probiotic efficacy appears highly strain-specific, with significant differences in effectiveness across bacterial species. Colonization of probiotic strains in the oral cavity is often transient, raising questions about the sustainability of observed benefits without continuous supplementation (Beattie et al., 2024; Lundtorp-Olsen et al., 2024). Moreover, heterogeneity in dosage, intervention duration, delivery systems, and study methodologies complicates interpretation of outcomes (Lopes et al., 2024).

Despite these limitations, probiotics represent a paradigm shift in preventive dentistry by focusing on restoring ecological balance rather than eliminating pathogens. This perspective aligns with the "ecological plaque hypothesis," which frames dental diseases as ecological catastrophes driven by microbial community dynamics (Marsh, 2003). By reinforcing oral microbial resilience, probiotics may provide valuable adjuncts to conventional preventive approaches, particularly in high-risk populations such as young children (Meng et al., 2023; Twetman & Jørgensen, 2021).

This paper critically examines current evidence regarding the influence of probiotics on the oral microbiome and their role in caries prevention. By synthesizing findings from clinical trials and systematic reviews, it evaluates the efficacy of different probiotic strains and delivery vehicles, explores their underlying biological mechanisms, and highlights existing gaps in the literature. In doing so, it aims to provide insight into the potential integration of probiotics into mainstream preventive d entistry and outline directions for future research in this emerging field.

METHODOLOGY

Study Design

This study employed a systematic review methodology, adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparent and replicable reporting. The primary objective was to synthesize empirical evidence on the effects of probiotic interventions on the oral microbiome and their role in preventing dental caries. The review focused on peer-reviewed human studies that provided quantitative or qualitative outcomes regarding microbiological changes (e.g., *Streptococcus mutans* counts, oral microbiome diversity) or clinical measures of caries incidence, progression, or recurrence.

Eligibility Criteria

Studies were included based on the following criteria:

- **Population:** Human subjects of any age group, including infants, children, adolescents, and adults, regardless of baseline caries risk.
- **Interventions/Exposures:** Administration of probiotics (live or inactivated strains) delivered via any vehicle (milk, yoghurt, lozenges, tablets, drops, powders). Both single-strain and multi-strain interventions were included.
- **Comparators:** Placebo, standard dietary products (e.g., plain milk, yoghurt without probiotics), or no intervention.
- **Outcomes:**

  - *Microbiological:* Changes in oral microbiome composition, bacterial diversity, salivary/plaque *S. mutans* or lactobacilli counts.
  - *Clinical:* Caries incidence, prevalence, caries increment or regression, lesion severity (ICDAS, WHO criteria, Cariogram), recurrence rates, plaque or gingivitis measures.
- **Study Designs:** Randomized controlled trials (RCTs), cluster-randomized trials, longitudinal studies, and controlled before-after trials.
- **Language:** Only articles published in English were considered.
- **Publication Period:** 2000–2024, ensuring contemporary relevance in probiotic research.

Search Strategy

A structured search was conducted across electronic databases including PubMed, Scopus, Web of Science, Embase, and Google Scholar (for grey literature). The following Boolean search string was applied with modifications for each database:

- (“probiotic” OR “lactobacillus” OR “streptococcus salivarius” OR “lacticaseibacillus” OR “reuteri”)
- AND (“oral microbiome” OR “saliva” OR “plaque” OR “streptococcus mutans” OR “lactobacilli”)
- AND (“dental caries” OR “tooth decay” OR “caries prevention” OR “caries incidence” OR “caries progression” OR “caries recurrence”)

Manual searches of reference lists from systematic reviews and key clinical trials were also conducted to identify relevant studies not captured through database searches.

Study Selection Process

All retrieved citations were imported into Zotero, where duplicates were removed. Two independent reviewers screened titles and abstracts for eligibility. Full texts of potentially relevant studies were assessed against inclusion criteria. Any disagreements were resolved through discussion or by consulting a third reviewer. After screening, **10 studies** met all criteria and were included in the final analysis.

Data Extraction

A standardized data extraction form was piloted and applied across studies. The following data were systematically collected:

- Author(s), publication year, and country
- Study design and sample size
- Participant characteristics (age, risk group, baseline caries status)
- Probiotic strain(s) and delivery vehicle (milk, yoghurt, lozenges, tablets, drops, powder)
- Intervention duration and frequency
- Control or comparator group details
- Microbiological outcomes (e.g., *S. mutans* counts, lactobacilli levels, alpha diversity)
- Clinical outcomes (e.g., caries incidence, prevalence, increment, regression, lesion severity, recurrence)
- Effect estimates (odds ratios, incidence rate ratios, mean differences, p-values)
- Confounders adjusted for in statistical analyses

Extraction was performed independently by two reviewers, with verification by a third reviewer.

A PRISMA 2020 flow diagram (Figure 1) summarizes the study selection process, including numbers of records identified, screened, excluded, and included.

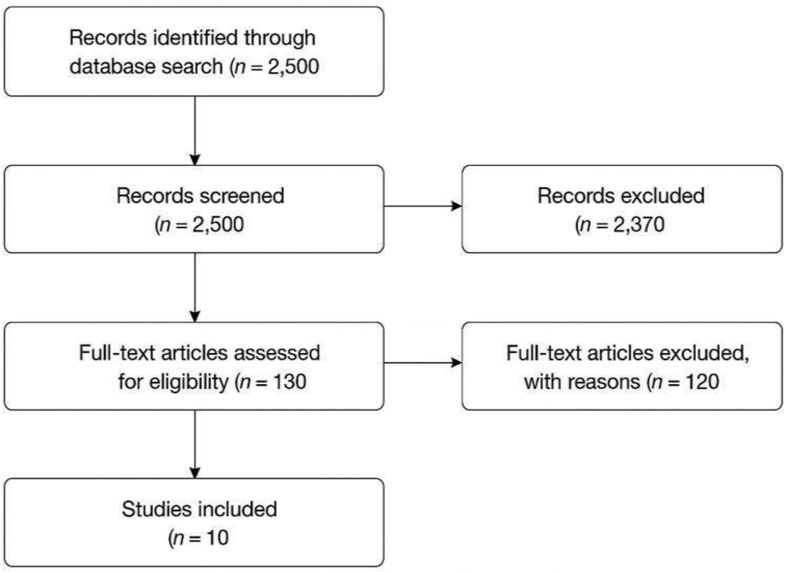

Figure 1 PRISMA Flow Diagram

Quality Assessment

Risk of bias and methodological quality were assessed according to study type:

- **Randomized controlled trials:** Cochrane Risk of Bias 2.0 tool (domains: randomization, blinding, outcome measurement, selective reporting).
- **Cluster-randomized or non-randomized trials:** Newcastle–Ottawa Scale (NOS) focusing on participant selection, group comparability, and outcome assessment.

Each study was categorized as *low*, *moderate*, or *high* quality. Disagreements were resolved by consensus.

Data Synthesis

Due to heterogeneity in probiotic strains, delivery vehicles, outcome measures, and follow-up durations, a **narrative synthesis** was performed. Results were grouped into two primary categories:

1. **Microbiological outcomes** – effects on oral microbial composition, *S. mutans* suppression, and microbiome diversity.
2. **Clinical outcomes** – effects on caries prevention, progression, and recurrence.

Effect estimates (odds ratios, incidence rate ratios, or mean differences with confidence intervals) were extracted and reported where available. Meta-analysis was not performed due to variability in study methodologies and outcome definitions.

Ethical Considerations

This review involved secondary analysis of previously published data. Ethical approval and informed consent were therefore not required. All included studies were peer-reviewed and assumed to have received appropriate ethical clearance from their respective institutional review boards.

RESULTS

Summary and Interpretation of Included Studies

The included studies encompass randomized controlled trials (RCTs), cluster-randomized trials, and open-label interventions, reflecting diverse methodological approaches to evaluating the effects of probiotics on the oral microbiome and caries prevention. Sample sizes ranged widely, from small trials (n = 21; short-term probiotic consumption study) to large multicenter trials (n = 594, Näse et al., 2001). Study populations included infants, preschool children, and adults, covering both preventio n of primary dental caries and recurrence after treatment.

1. Impact on Oral Microbiome

Studies measuring microbial outcomes demonstrated consistent probiotic-related modulation. Piwat et al. (2019) showed that fermented milk with *Lactobacillus rhamnosus* SD11 significantly reduced salivary *Streptococcus mutans* counts and increased salivary lactobacilli after 9 months ($p < 0.05$). Similarly, the short-term saliva microbiome study (n = 21) reported a statistically significant increase in alpha diversity ($p = 0.0011$) in probiotic groups, with persistence of probiotic *Streptococcus* and *Lactobacillus* strains. However, the overall community structure remained largely unchanged.

2. Effects on Caries Prevention in Children

Several long-term trials demonstrated protective effects. Näse et al. (2001) reported that children consuming *L. rhamnosus* GG milk for 7 months had a 44% lower risk of caries (OR = 0.56, $p = 0.01$). Stensson et al. (2014) found that 82% of children in the *L. reuteri* group were caries-free at 9 years, compared with 58% in placebo ($p < 0.01$). Di Pierro et al. (2015) observed that high-risk children receiving *Streptococcus salivarius* M18 had significantly improved Cariogram risk scores compared to untreated controls. Piwat et al. (2020) further showed that daily or triweekly probiotic milk (*L. paracasei* SD1) decreased caries risk (IRR = 0.83, 95% CI: 0.72–0.96) and promoted regression of carious lesions over 12 months. Rodríguez et al. (2016) reported lower caries increment after 10 months in the probiotic group, with cavitated lesion prevalence significantly reduced (9.7% vs. 24.3%, $p < 0.05$).

3. Mixed or Inconclusive Evidence

Some recent RCTs reported modest or inconclusive results. Hasslöf et al. (2022) tested probiotic drops with *L. reuteri* but found no significant difference in caries recurrence over 12 months, though sample size was small (n = 38). Hedayati-Hajikand et al. (2015) showed that daily chewing tablets (ProBiora3) reduced caries increment significantly ($\Delta ds = 0.2$ vs. 0.8, $p < 0.05$). Staszczyk et al. (2022) demonstrated reduced caries incidence and prevalence after 12 months with thermally inactivated *L. salivarius* ($p < 0.001$).

4. Summary of Effect Estimates

Overall, probiotics—particularly *L. rhamnosus* GG/SP1, *L. reuteri*, and *S. salivarius* M18—were associated with:

- **Reduced caries incidence or increment** (reductions ranging 35–56% across studies).
- **Lower mutans streptococci counts** in saliva and plaque.
- **Increased salivary lactobacilli levels** and oral microbiome diversity.
- **Mixed results on recurrence of caries**, with some trials underpowered due to small samples or pandemic disruptions.

Together, these findings suggest a preventive role of probiotics in reducing dental caries risk and modulating the oral microbiome, though effects vary depending on probiotic strain, delivery vehicle, and study design.

Table (1): General Characteristics and Results of Included Studies

Study	Country	Design	Sample Size	Population	Intervention	Follow-up	Main Microbiological Results	Main Clinical Results	Effect Estimates
Piwat et al. (2019)	Thailand	RCT	201	Children	*L. rhamnosus* SD11 in fermented milk vs. milk powder	9 mo	↓ *S. mutans*, ↑ lactobacilli	Oral exams at 9 mo	Significant reduction of *S. mutans*; probiotic milk superior
Dassi, et al. (2018).	Sweden	Longitudinal	21	Healthy adults	Commercial probiotic vs. yoghurt	4 wk	↑ Alpha diversity (p = 0.0011), probiotic strains persisted	No clinical outcomes	Greater persistence of *Streptococcus* & *Lactobacillus*
Näse et al. (2001)	Finland	RCT	594	1–6 y children	Milk with *L. rhamnosus* GG vs. control	7 mo	↓ Mutans streptococci	↓ Caries incidence	OR = 0.56 (p = 0.01)
Stensson et al. (2014)	Sweden	RCT	113	From birth to 1 y	*L. reuteri* ATCC 55730	9 y	No sig. differences in MS, LB, SIgA	82% caries-free vs. 58% placebo (p < 0.01)	Lower gingivitis prevalence
Di Pierro et al. (2015)	Italy	RCT	76	High-risk children	*S. salivarius* M18	90 d	Produces enzymes reducing plaque & acidity	Improved Cariogram scores	Higher probability of avoiding new caries
Piwat et al. (2020)	Thailand	Multicenter RCT	487	Preschool children	*L. paracasei* SD1 in milk	6–12 mo	↓ Mutans streptococci	↓ Caries risk, ↑ regressive surfaces	IRR = 0.83 (95% CI 0.72–0.96)
Rodríguez et al. (2016)	Chile	Cluster RCT	261	Preschool children	Milk with *L. rhamnosus* SP1	10 mo	Not assessed	↓ Caries increment, ↓ cavitated lesions (9.7% vs. 24.3%, p < 0.05)	OR = 0.35
Hasslöf et al. (2022)	Sweden	RCT	38	Preschool children	Drops with *L. reuteri* DSM 17938, PTA 5289	12 mo	No effect	No sig. difference in recurrence	High recurrence in both groups (67%)
Hedayati-Hajikand et al. (2015)	Sweden	RCT	138	Preschool children	Probiotic chewing tablets (ProBiora3)	12 mo	No sig. microbial changes	↓ Caries increment (0.2 vs. 0.8, p < 0.05)	Risk reduction 0.47
Staszczyk et al. (2022)	Poland	RCT	140	3–6 y children	Inactivated *L. salivarius* chewing tablets	12 mo	No change in OHI-S	↓ Caries incidence & prevalence (p < 0.001)	Significant protection

DISCUSSION

The findings from this review provide substantial evidence that probiotics can influence the oral microbiome and contribute to the prevention of dental caries, but the magnitude and consistency of their effects vary across strains, delivery systems, and populations. The ecological plaque hypothesis provides the theoretical foundation for these observations, highlighting the sh ift from a balanced microbiome to dysbiosis dominated by acidogenic bacteria as a key driver of caries (Marsh, 2003). By restoring microbial balance, probiotics offer a biological approach that complements traditional preventive strategies such as fluoride and plaque control.

Early large-scale clinical studies demonstrated promising effects of probiotic administration. For instance, Näse et al. (2001) reported that *Lactobacillus rhamnosus* GG in milk significantly reduced caries risk in children, particularly among 3- to 4-year-olds. Similarly, Stensson et al. (2014) showed that oral supplementation with *Lactobacillus reuteri* during the first year of life reduced caries prevalence at 9 years of age. These findings highlight the potential long-term protective effects of early probiotic interventions during critical windows of microbial colonization.

Subsequent randomized controlled trials reinforced these benefits, particularly in high-risk populations. Rodríguez et al. (2016) demonstrated that preschool children consuming probiotic-supplemented milk had a significantly lower incidence of new cavitated lesions compared with controls. Likewise, Piwat et al. (2020) found that daily or triweekly probiotic milk containing *Lactobacillus paracasei* SD1 not only prevented new caries but also facilitated regression of existing lesions, suggesting therapeutic as well as preventive potential.

Other delivery methods have also shown efficacy. Di Pierro et al. (2015) reported that lozenges containing *Streptococcus salivarius* M18 improved caries risk profiles in high-risk children, while Hedayati-Hajikand et al. (2015) found that probiotic chewing tablets significantly reduced caries increment in preschoolers. Staszczyk et al. (2022) further confirmed that short-term administration of *Lactobacillus salivarius* reduced caries incidence over a 12-month follow-up. Collectively, these trials underscore the adaptability of probiotics across different formulations and intervention strategies.

However, not all studies demonstrated clear benefits. Hasslöf et al. (2022) observed no significant differences in recurrent caries after administering *Limosilactobacillus reuteri* drops for 12 months, highlighting the challenges of achieving consistent outcomes. Similarly, Dassi et al. (2018) reported that probiotics increased alpha diversity in the oral microbiome but did not substantially alter its overall structure, raising questions about whether transient colonization is sufficient for sustained clinical benefits.

The variability in outcomes is partly explained by strain specificity. Beattie et al. (2024) emphasized that not all probiotic strains exert the same effects, with certain lactobacilli and streptococci showing stronger antimicrobial and immunomodulatory properties than others. Strain selection, therefore, remains a critical determinant of efficacy. Luo et al. (2024) supported this view, noting that probiotics, prebiotics, and synbiotics may act through complementary mechanisms, including competitive exclusion of pathogens, pH buffering, and modulation of host immunity.

Meta-analyses have provided broader perspectives on these individual findings. Twetman and Jørgensen (2021) concluded that probiotics may reduce salivary *Streptococcus mutans* counts but only modestly impact caries incidence, while Meng et al. (2023) confirmed reductions in caries risk among preschool children but emphasized heterogeneity in trial design. Feldmann et al. (2024) added that probiotic beverages showed mixed results in preventing caries, with effectiveness influenced by both dosage and frequency of intake. These reviews collectively suggest that while the biological rationale is strong, the clinical evidence remains uneven.

Recent systematic reviews have sought to clarify this heterogeneity. Lopes et al. (2024) highlighted methodological inconsistencies—such as differences in delivery vehicles, intervention durations, and outcome assessments—as key barriers to drawing definitive conclusions. Panchbhai, Khatib et al. (2024) reinforced this point, showing that while probiotics are generally safe and well tolerated in children, their preventive efficacy varies widely. Butt and Sin (2023) echoed this cautious interpretation, stressing that enthusiasm for probiotics should be tempered by recognition of the modest and context-dependent benefits observed to date.

Beyond efficacy, the underlying ecological mechanisms are crucial to understanding how probiotics exert their influence. Probiotics may reduce *S. mutans* levels, increase salivary lactobacilli, and promote microbial diversity (Piwat et al., 2019; Dassi et al., 2018). Lundtorp-Olsen et al. (2024) argued that while these effects are often transient, repeated supplementation could sustain ecological balance. This ecological framing aligns with Marsh's (2003) proposition that restoring microbial resilience is more effective than attempting to eliminate pathogens outright.

Importantly, the mode of delivery appears to influence both colonization and outcomes. Lozenges, tablets, and dairy-based vehicles each provide distinct advantages, such as prolonged oral contact or enhanced bacterial survival during ingestion (Di Pierro et al., 2015; Hedayati-Hajikand et al., 2015; Piwat et al., 2020). Future studies should directly compare delivery systems to optimize probiotic retention in the oral cavity and maximize clinical benefits.

Safety considerations are another critical dimension. Across trials, no major adverse effects of probiotic administration have been reported, supporting their safety in children and adults (Panchbhai, Rajesh, & Kaushik, 2015; Piwat et al., 2020). This favorable safety profile is particularly relevant given concerns about antimicrobial resistance and the limitations of conventional preventive measures, making probiotics an attractive adjunctive strategy.

Nevertheless, several limitations constrain the current evidence base. Many studies suffer from small sample sizes, short intervention durations, or lack of long-term follow-up, limiting their generalizability (Hasslöf et al., 2022; Staszczyk et al., 2022). Moreover, as highlighted by Beattie et al. (2024) and Lopes et al. (2024), colonization of probiotic strains is often transient, raising uncertainty about the sustainability of their benefits without continuous supplementation.

The future of probiotic research in dentistry lies in refining strain selection, delivery methods, and combination approaches . As Luo et al. (2024) suggested, synbiotics or postbiotics may enhance the stability and efficacy of interventions by fostering more durable shifts in the oral microbiome. Additionally, personalized approaches that account for baseline microbiome composition, diet, and caries risk could improve treatment outcomes (Lundtorp-Olsen et al., 2024).

In conclusion, the evidence reviewed here supports probiotics as a promising but not universally effective adjunct for preventing dental caries. While multiple RCTs have demonstrated reductions in caries incidence and microbial risk factors, results remain inconsistent, largely due to strain specificity, delivery methods, and study heterogeneity. A paradigm shift toward ecological balance, as envisioned by Marsh (2003), positions probiotics as valuable tools in preventive dentistry, but their optimal application requires further high-quality, long-term trials and mechanistic studies (Meng et al., 2023; Twetman & Jørgensen, 2021; Feldmann et al., 2024).

CONCLUSION

This systematic review highlights the promising role of probiotics in modulating the oral microbiome and reducing the risk of dental caries. Across multiple randomized controlled trials, supplementation with strains such as *Lactobacillus rhamnosus GG*, *Lactobacillus reuteri*, *Lactobacillus paracasei*, and *Streptococcus salivarius* M18 demonstrated reductions in *Streptococcus mutans* levels, increased microbial diversity, and in many cases, lower caries incidence. Importantly, some interventions also facilitated regression of early carious lesions, suggesting that probiotics may not only prevent but also contribute to the management of existing disease. These findings align with the ecological plaque hypothesis, framing probiotics as agents that restore microbial balance rather than eliminate pathogens.

However, the overall effectiveness of probiotics remains strain-specific and context-dependent. Some studies showed inconclusive or null results, particularly in long-term follow-ups, reflecting the transient nature of probiotic colonization in the oral cavity. Delivery methods, intervention duration, and baseline caries risk substantially influenced outcomes. While the evidence strongly supports the safety of probiotic supplementation, further high-quality, large-scale trials are needed to optimize strain selection, dosage, and delivery systems. Ultimately, probiotics appear to be a safe and biologically rational adjunct to conventional preventive strategies, with the potential to address gaps in caries prevention, particularly in high-risk pediatric populations.

LIMITATIONS

This review is limited by the heterogeneity of included studies in terms of probiotic strains, delivery vehicles, dosage, and outcome measures, which precluded a meta-analysis. Many trials had small sample sizes, relatively short intervention periods, and limited long-term follow-up, reducing the generalizability of findings. Language and publication bias may also be present, as only English-language peer-reviewed studies were included. Additionally, differences in diagnostic criteria, such as use of ICDAS versus WHO guidelines, complicate cross-study comparisons. Future research should focus on standardized methodologies, strain-specific efficacy, and longitudinal follow-ups to strengthen the evidence base.

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