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Natural Film-Forming Polymers for Antibacterial Mucoadhesive Oral Films Against *Streptococcus mutans* Biofilms in Dental Caries Prevention: A Narrative Review

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Abstract
Dental caries remains a persistent oral health problem because cariogenic biofilms, particularly those involving *Streptococcus mutans*, can adhere to dental surfaces, produce extracellular polysaccharides, generate acids, and promote enamel demineralization. Conventional preventive approaches often face limitations in the oral cavity due to salivary flow, swallowing, short contact time, and reduced local retention of antibacterial agents. This narrative review evaluates natural film-forming polymers as antibacterial mucoadhesive oral films for controlling *Streptococcus mutans* biofilms and proposes a function-based framework to guide polymer selection for dental caries prevention. The review focuses on chitosan, alginate, pectin, pullulan, gelatin, starch, and natural gums by analyzing their film-forming capacity, mucoadhesive behavior, mechanical properties, controlled-release performance, and antibacterial relevance. Chitosan shows the strongest functional potential because it combines film formation, mucosal adhesion, and intrinsic antibacterial and antibiofilm activity. Alginate and pectin mainly support swelling, gel formation, and sustained release, while pullulan improves film transparency, flexibility, disintegration behavior, and patient acceptability. Gelatin, starch, and natural gums provide additional structural and adhesive benefits, although they often require plasticizers, blending, or modification to improve stability and mechanical strength. Current evidence suggests that rational polymer blending, especially chitosan-based composite systems, offers the most feasible strategy for developing effective antibacterial oral films. However, most available studies remain limited to in vitro formulation and antibiofilm evaluations. Future research should prioritize standardized comparative testing, multispecies biofilm models, clinical validation, residence-time assessment, sensory acceptability, and long-term caries-preventive outcomes.

Keywords: Natural Polymers; Mucoadhesive Oral Films; *Streptococcus Mutans*; Antibiofilm Activity; Dental Caries Prevention

1. Introduction

Dental caries remains a major global oral health problem affecting both children and adults. It is a chronic, biofilm-mediated, and diet-related disease that causes progressive demineralization of dental hard tissues. The global burden remains high, with untreated caries affecting billions of permanent teeth and hundreds of millions of primary teeth cases worldwide. Beyond tooth destruction, dental caries can cause pain, infection, eating difficulties, impaired growth, reduced learning performance, and lower quality of life. These consequences show that dental caries prevention remains an urgent public health priority (Astasov-Frauenhoffer & Kulik, 2021).

Streptococcus mutans plays a central role in dental caries development because of its ability to adhere to tooth surfaces, form biofilms, produce acids, and promote enamel demineralization. This bacterium produces glucosyltransferases and extracellular polysaccharides that strengthen biofilm structure and support bacterial persistence on dental surfaces. Its acidogenic and aciduric properties allow it to metabolize fermentable carbohydrates into organic acids and survive in low-pH environments. These mechanisms create favorable conditions for enamel mineral loss and caries progression (Chen et al., 2024).

The elimination of *Streptococcus mutans* biofilms remains difficult because bacterial cells are protected by the extracellular polymeric substance matrix. This matrix limits antimicrobial penetration, strengthens bacterial adhesion, and increases resistance to environmental stress. Biofilm-embedded bacteria can show much higher resistance to antibacterial agents than planktonic cells. Studies have also shown that disrupting the extracellular matrix can restore bacterial sensitivity, confirming that the matrix is a key barrier to antibacterial treatment. Therefore, effective caries prevention should not only target bacterial killing, but also address biofilm persistence and local retention of antibacterial agents (Wang et al., 2025; Zhang et al., 2022).

Current caries prevention strategies, including toothbrushing, fluoride application, mouthwash, gels, and oral hygiene education, remain useful but have practical limitations. In the oral cavity, saliva flow, swallowing, tongue movement, and biofilm structure can reduce the residence time and local availability of active compounds. Mouthwash and conventional gels may produce short antibacterial exposure because active agents can be diluted or removed before reaching sustained activity against biofilms. This limitation supports the need for local delivery

systems that can maintain antibacterial agents near the target site for longer periods and improve their therapeutic effectiveness (Gao et al., 2024; Jiang et al., 2024).

Mucoadhesive oral films offer a promising local delivery platform for antibacterial agents in the oral cavity. These thin and flexible films can adhere to oral mucosa or dental-adjacent surfaces, improve residence time, and support controlled release of active compounds. Controlled release is important because *Streptococcus mutans* biofilms require sustained antibacterial exposure rather than brief contact. Several studies have reported that oral films can deliver antibacterial agents, probiotics, or bioactive compounds against oral bacteria, including *Streptococcus mutans*. Thus, mucoadhesive oral films provide a rational platform for improving local antibacterial delivery in dental caries prevention (Nair et al., 2021).

Natural film-forming polymers have gained attention for oral film development because they are generally biocompatible, biodegradable, safe for oral use, and capable of forming functional films. Polymers such as chitosan, alginate, pectin, pullulan, gelatin, starch, and natural gums can provide film-forming ability, mucoadhesion, mechanical strength, swelling behavior, and controlled release properties. Chitosan is especially relevant because it may also show antibacterial activity against *Streptococcus mutans* and inhibit adhesion or biofilm formation. However, previous studies have often discussed natural polymers, oral films, and antibacterial activity as separate topics. Limited reviews have integrated these aspects into a function-based comparison that considers film formation, mucoadhesion, controlled release, mechanical performance, antibiofilm activity, and translational feasibility for dental caries prevention. Therefore, this review provides a function-based comparative framework for selecting natural film-forming polymers in antibacterial mucoadhesive oral films against *Streptococcus mutans* biofilms. This framework is expected to clarify the specific formulation roles of chitosan, alginate, pectin, pullulan, gelatin, starch, and natural gums in designing oral films for caries-preventive applications (Cazorla-Luna et al., 2021; Chaves Magalhães et al., 2021).

2. Methods

This article used a narrative literature review approach to examine the potential of natural film-forming polymers in antibacterial mucoadhesive oral films against *Streptococcus mutans* biofilms for dental caries prevention. This approach was chosen because previous studies vary in polymer type, formulation design, antibacterial agent, and biofilm evaluation method. Literature was collected from Scopus, PubMed, Web of Science, ScienceDirect, and Google Scholar using keywords such as “natural polymer,” “mucoadhesive oral film,” “oral thin film,” “chitosan,” “alginate,” “pectin,” “pullulan,” “*Streptococcus mutans*,” “dental caries,” “antibacterial,” and “biofilm.” The references used were mainly published between 2016 and 2026, while older sources were included only when they provided basic theories related to dental caries, biofilm formation, mucoadhesion, or polymer-based drug delivery. The selected literature was reviewed descriptively by focusing on three main aspects, namely the role of *Streptococcus mutans* biofilm in dental caries, the use of mucoadhesive oral films as local antibacterial delivery systems, and the potential of natural polymers such as chitosan, alginate, pectin, pullulan, gelatin, starch, and natural gums. The findings were synthesized to identify the strengths, limitations, and future research directions of natural polymer-based oral films for dental caries prevention.

3. Discussion

3.1. Role of *Streptococcus mutans* biofilm in dental caries

Streptococcus mutans plays a major role in dental caries because it can adhere to tooth surfaces and initiate dental plaque biofilm formation. This early attachment allows the bacterium to colonize dental hard tissues and persist under dynamic oral conditions. Adhesion represents a critical stage in caries development because it provides the biological foundation for biofilm maturation and cariogenic plaque accumulation. Previous studies have identified *Streptococcus mutans* as a major cariogenic bacterium involved in plaque formation and caries progression through surface adhesion and biofilm development (Ikäläinen et al., 2024). Thus, early bacterial attachment is a relevant target for caries-preventive strategies.

After adhesion, *Streptococcus mutans* strengthens biofilm architecture through extracellular polysaccharide production. These polysaccharides form a matrix that promotes bacterial attachment, cohesion, and structural stability. The matrix also creates a protective microenvironment that helps embedded bacteria tolerate stress and resist salivary clearance. Li et al. (2021) described extracellular polysaccharides as a key framework of dental plaque because they support adhesion, cohesion, and resistance to environmental stress. Similar evidence shows that *Streptococcus mutans* biofilms contain an exopolysaccharide-rich matrix, while sucrose-mediated polysaccharide formation increases bacterial adhesion strength to substrates (Waldman et al., 2023). The matrix also protects bacteria from salivary flushing and buffering effects, which helps explain why mature biofilms are more difficult to eliminate than planktonic bacterial cells (Ikäläinen et al., 2024).

The cariogenic potential of *Streptococcus mutans* also depends on its acidogenic activity. When fermentable carbohydrates are available, *Streptococcus mutans* metabolizes sugars and produces organic acids, particularly lactic acid. This process lowers plaque pH and shifts the local environment toward acidification. Experimental

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evidence shows that *Streptococcus mutans* can reduce pH after exposure to glucose, sucrose, and lactose, with sucrose showing strong cariogenic relevance (Jurakova et al., 2023). Other studies also confirm that carbohydrate metabolism by *Streptococcus mutans* increases oral acidity and links bacterial activity to clinical caries progression (Spatafora et al., 2024). When plaque pH remains below the critical threshold for enamel stability, mineral loss occurs from hydroxyapatite crystals. Low-pH biofilms have been associated with enamel demineralization, reduced mineral density, and increased cariogenic virulence (Harper et al., 2021). Acidic microenvironments may also favor acidogenic and aciduric bacterial proliferation, which can accelerate disease development (Hu et al., 2026).

The interaction between adhesion, extracellular matrix formation, acid production, and enamel demineralization makes *Streptococcus mutans* biofilm a complex therapeutic target. Antibacterial strategies that only reduce planktonic bacterial cells may be insufficient because mature biofilms protect embedded bacteria and maintain localized acidic conditions. Effective caries-preventive systems should therefore interfere with several biofilm-related mechanisms, including bacterial adhesion, extracellular polysaccharide synthesis, biofilm accumulation, and acidogenic activity. Gao et al. (2024) described these processes as interconnected mechanisms in *Streptococcus mutans*-mediated caries, while Kashi et al. (2025) showed that natural compounds can affect acid production, adhesion-related gene expression, and biofilm formation. Intervention studies further support this direction. Probiotic strains have been reported to inhibit *Streptococcus mutans* biofilm formation and downregulate biofilm-associated genes, while combined antibacterial strategies can reduce lactic acid production in biofilms (Luan et al., 2022). In vivo evidence also shows that Lactiplantibacillus plantarum K41 reduced caries incidence, supporting the relevance of antibiofilm approaches in caries prevention (Sravanthi et al., 2025).

3.2. Mucoadhesive Oral Films as Antibacterial Delivery Systems

Mucoadhesive oral films represent a promising localized drug delivery platform for the prevention and management of oral diseases, particularly dental caries associated with *Streptococcus mutans* biofilms. These systems are designed as thin polymeric matrices that adhere to the oral mucosa through physicochemical interactions with the mucus layer, allowing active compounds to remain in close contact with the target site for an extended period. This characteristic is clinically relevant because conventional antimicrobial preparations often experience rapid clearance due to salivary flow, swallowing, and mechanical disturbance in the oral cavity. By improving mucosal residence time, mucoadhesive oral films can enhance local drug availability, reduce systemic exposure, and support more efficient antibacterial action (Sravanthi et al., 2025). Evidence that oral thin films may improve drug absorption and bioavailability further supports their use for localized antibacterial therapy in the oral cavity (Haney et al., 2021)

The effectiveness of mucoadhesive oral films depends on their ability to combine adequate adhesion, mechanical integrity, and controlled release behavior. Maslii et al. (2025) reported that plant-based mucoadhesive films showed strong adhesive strength and sustained release, with approximately 90% of active compounds released within 360 to 420 minutes. Similar findings have been reported in antibiotic-loaded films. Gellan gum-based bilayer films containing moxifloxacin hydrochloride maintained controlled drug release for up to 48 hours, while doxycycline hyclate films demonstrated prolonged topical release profiles (Dinte et al., 2023). These findings indicate that mucoadhesive films can sustain antibacterial exposure at the infection site, which is critical for suppressing persistent biofilm communities. Mechanical properties also determine clinical usability. Oral thin films require sufficient folding endurance, tensile strength, and resistance to breakage to maintain integrity during handling and application (Alaei et al., 2021). These parameters are central to clinical performance because films that adhere well but fracture easily, or release drugs too rapidly, may fail under real oral conditions.

Mucoadhesive oral films also offer a strategic advantage for delivering antibacterial agents directly to cariogenic microorganisms. Localized administration allows higher concentrations of active substances to reach the biofilm environment while minimizing unnecessary systemic exposure. This approach is especially relevant for *Streptococcus mutans*, which plays a central role in dental plaque formation, acid production, enamel demineralization, and caries progression. Dodoo et al. (2020) showed that probiotic-containing oral films incorporating Streptococcus salivarius reduced *Streptococcus mutans* populations by approximately 3-log CFU/mL, indicating substantial antibacterial potential. Other studies also support the use of biopolymer-based films for antimicrobial delivery. Oral films containing probiotic cell-free supernatants inhibited *Streptococcus mutans* growth, while plant-based mucoadhesive films demonstrated sustained release and antimicrobial activity against oral microorganisms (Tunçer Çağlayan, 2025). These findings position natural polymer-based oral films as functional systems for localized biofilm control. However, current evidence remains dominated by formulation and preclinical studies, so further clinical validation is needed to confirm long-term safety, efficacy, and patient outcomes (Zhang et al., 2022).

Patient acceptability further strengthens the potential of mucoadhesive oral films in dental caries prevention. Their thin, flexible, and easy-to-administer form may improve comfort and adherence, especially among pediatric, geriatric, dysphagic, and bedridden patients who often struggle with conventional tablets or rinses (Waghmare, 2024). Regular and comfortable application is important because caries prevention requires repeated and sustained

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intervention. Despite these advantages, several formulation barriers remain unresolved. Stability, taste masking, drug loading, disintegration control, and manufacturing scalability continue to limit broader commercialization and clinical translation (Chogale et al., 2025; Dhankar et al., 2025). The dynamic oral environment also complicates formulation performance because salivary turnover may dilute active compounds and reduce residence time (Jacob et al., 2021). These limitations indicate that the clinical value of antibacterial mucoadhesive oral films depends on formulation performance as much as antibacterial efficacy.

3.3. Natural Film-Forming Polymers for Oral Films

Natural polymers have become important materials in mucoadhesive oral films because they offer biocompatibility, biodegradability, low toxicity, and diverse functional properties. In antibacterial oral film design, polymer selection determines film integrity, mucoadhesion, swelling behavior, drug release, and antimicrobial performance. Chitosan is one of the most widely studied natural polymers because it combines film-forming, mucoadhesive, and antibacterial properties. As a polysaccharide obtained from chitin deacetylation, chitosan can form homogeneous and flexible films suitable for biomedical and pharmaceutical applications (Picos-Corrales et al., 2023). Its amino and hydroxyl groups support hydrogen bonding and electrostatic interaction with negatively charged mucin, which increases mucosal residence time (Edo et al., 2024). Chitosan also shows broad antimicrobial activity through membrane disruption, permeability alteration, and inhibition of microbial growth and biofilm formation, making it particularly relevant for suppressing *Streptococcus mutans* colonization (Confederat et al., 2021).

Sodium alginate and pectin are also valuable for oral film development because both polymers support hydration, adhesion, and controlled release. Sodium alginate, a brown algae-derived polymer, forms stable hydrogel networks through ionotropic gelation with divalent or polyvalent cations (Jadach et al., 2022; Morozkina et al., 2022). Its high water-holding capacity promotes swelling after contact with saliva, while its pH-dependent swelling behavior may support responsive drug release in the oral environment (Morozkina et al., 2022). Alginate-based systems have also been recognized for their capacity to sustain and regulate drug release over prolonged periods (Colin et al., 2024; Frenț et al., 2022). Pectin offers similar advantages as a plant-derived biopolymer with strong film-forming and adhesive properties. Pectin-based films have shown high adhesiveness, rapid hydration, and strong mucoadhesive behavior under ex vivo and in vivo conditions (Martín-Illana et al., 2022). These characteristics make alginate and pectin suitable for oral films that require prolonged retention and sustained antibacterial exposure against cariogenic biofilms.

Other natural polymers, including pullulan, gelatin, and starch, contribute mainly to film appearance, flexibility, mechanical performance, and patient acceptability. Pullulan produces transparent, smooth, biodegradable, and flexible films, which is useful for oral dosage forms that must be comfortable and acceptable for repeated use (Kaith et al., 2025). Pullulan-based oral films have shown favorable mechanical properties, rapid disintegration, non-irritating behavior on the tongue, and good patient acceptability (Gupta et al., 2023). Gelatin also has strong film-forming potential and good biocompatibility, but native gelatin films often suffer from brittleness and limited mechanical stability (Ahmad et al., 2023; Lou & Chen, 2023). Plasticizers such as glycerol and sorbitol can improve gelatin flexibility by reducing intermolecular forces and increasing polymer chain mobility (Byram et al., 2025; Sancaklı et al., 2021). Starch provides a low-cost and renewable film-forming option, although native starch films also require modification because retrogradation and plasticizer instability can reduce flexibility (Yang et al., 2024). Blending, plasticization, reinforcement, and chemical modification can improve starch-based films and expand their potential as sustainable oral film matrices (Yang et al., 2024).

Natural gums provide additional formulation value because they can improve viscosity, swelling, gelling behavior, and mucoadhesion. Guar gum has demonstrated strong viscosity and mucoadhesive behavior, while other natural gums may enhance mechanical strength and bioadhesive performance when blended with film-forming polymers (Pacheco et al., 2021). Chemical modification may further improve swelling behavior and controlled-release potential in gum-based systems (Tanwar et al., 2024). For antibacterial mucoadhesive oral films against *Streptococcus mutans*, polymer selection should therefore match the intended formulation function. Chitosan is valuable when intrinsic antibacterial activity is required, alginate and pectin are useful for swelling and controlled release, pullulan improves acceptability, gelatin and starch require mechanical optimization, and natural gums can strengthen mucoadhesion and formulation stability. This functional matching is essential because an oral film must deliver antibacterial activity while remaining adhesive, flexible, stable, and acceptable within the oral cavity.

3.4. Film-forming and mucoadhesive properties of natural polymers

The performance of antibacterial mucoadhesive oral films depends strongly on the film-forming and mucoadhesive properties of the selected polymers. Natural polymers must form uniform, flexible, and mechanically stable films while maintaining sufficient adhesion to oral mucosa. These properties influence handling, residence time, drug release, patient comfort, and antibacterial performance against *Streptococcus mutans* biofilms. Film quality is commonly evaluated through thickness, weight uniformity, tensile strength, elongation at break, folding endurance, and surface pH. These parameters reflect whether a film can tolerate handling and administration

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without fracture while remaining compatible with the oral mucosa (Mohammed et al., 2025). Similar evaluation parameters have been applied in edible films, oral films, wound dressings, and ophthalmic systems, although standardization across oral film formulations remains incomplete (Mir et al., 2023).

Mucoadhesive performance is controlled by polymer charge, molecular weight, hydration capacity, swelling behavior, and polymer–mucin interaction. Positively charged polymers generally interact more strongly with negatively charged mucin residues through electrostatic attraction, which can improve adhesion and mucosal retention (Ahmad et al., 2024; Pham et al., 2021). Molecular weight has a less predictable role. Some studies suggest that higher molecular weight may reduce intimate polymer–mucin interaction by limiting chain mobility, while others report no direct relationship between molecular weight and adhesive strength (Watchorn et al., 2022). Hydration and swelling show a more consistent contribution because water uptake allows polymer chains to expand, establish closer contact with the mucus layer, and support adhesion under wet oral conditions (Kulkarni et al., 2023). In practice, strong mucoadhesion requires more than one favorable property. It depends on the balance between electrostatic interaction, chain mobility, hydration, and swelling.

Chitosan remains one of the most relevant natural polymers for mucoadhesive antibacterial oral films because of its cationic character. Its positively charged amino groups interact with negatively charged sialic acid residues in mucin, resulting in prolonged retention on mucosal surfaces (Ahmad et al., 2024). Experimental evidence also supports the strong mucoadhesive capacity of chitosan-based systems, including positively charged nanoparticles and modified nanoparticle formulations with increased mucin binding (Abruzzo et al., 2021). Alginate and pectin support mucoadhesion through different mechanisms. Their hydration, swelling, and ionotropic gelation properties allow the formation of expanded or cross-linked structures that improve contact with mucosal surfaces and support controlled release. Alginate–pectin systems have shown swelling capacity, calcium-mediated gelation, tunable mucoadhesion, and hydrogel-forming behavior suitable for oral delivery applications (Kurl et al., 2025; Manna et al., 2026). Pullulan contributes mainly through transparency, smoothness, and flexibility, which are important for patient acceptability. However, its mechanical and mucoadhesive performance may need improvement through blending with polymers such as hydroxypropyl methylcellulose or other natural biopolymers (Liu et al., 2024; Pacheco et al., 2021).

Plasticizers are also essential for improving the mechanical performance of natural polymer films. Glycerol, propylene glycol, polyethylene glycol, and sorbitol can reduce intermolecular forces between polymer chains, increase chain mobility, and prevent brittleness during handling and application. Glycerol has been shown to markedly increase elongation at break in curdlan films, while other studies report improved ductility in soybean polysaccharide, tamarind seed, and potato flour films after plasticizer incorporation (Chen et al., 2024). The effect of a plasticizer depends on the polymer matrix, so plasticizer selection cannot be treated as a routine additive decision. For antibacterial mucoadhesive oral films, the formulation must maintain mechanical stability, adequate flexibility, mucosal adhesion, and controlled release under wet and mechanically active oral conditions.

3.5. Antibacterial and Antibiofilm Activity Against *Streptococcus mutans*

The antibacterial and antibiofilm activity of natural polymer-based oral films is central to their potential use in dental caries prevention. *Streptococcus mutans* can adhere to tooth surfaces, produce extracellular polymeric substances, and develop structured biofilms that are more resistant to antimicrobial exposure than planktonic cells. Among natural polymers, chitosan shows the strongest intrinsic antibacterial activity against *Streptococcus mutans*. Its cationic structure enables interaction with negatively charged bacterial cell surfaces, leading to membrane disruption, altered permeability, leakage of intracellular components, and reduced metabolic activity. Modified chitosan derivatives have shown high antibacterial efficacy, including inhibition rates above 90% against *Streptococcus mutans*, while chitosan nanoparticles can alter transmembrane potential, induce reactive oxygen species, and damage bacterial membranes (Gao et al., 2024; Wu et al., 2023). Nanochitosan formulations have also demonstrated low MIC values and the ability to disrupt *Streptococcus mutans* biofilm architecture, supporting chitosan as a leading natural polymer for antibacterial mucoadhesive oral films (Magalhães et al., 2021; Valian et al., 2023).

Chitosan also interferes with *Streptococcus mutans* adhesion and biofilm development, although its effect depends on formulation characteristics. Concentration, molecular weight, degree of deacetylation, degree of substitution, exposure time, and pH can influence antibacterial and antibiofilm performance. Evidence from experimental and review studies shows that chitosan can inhibit bacterial adhesion, suppress biofilm formation, and reduce mature biofilm viability under different test conditions (Magalhães et al., 2021; Valian et al., 2023). Modified chitosan derivatives may enhance this activity because structural changes can improve interaction with bacterial cells and biofilm matrices. For example, the degree of acetylation affects the physicochemical and biological properties of chitosan, while selected derivatives have shown stronger antibiofilm effects than unmodified chitosan (Lim et al., 2021). These findings are promising, but the current evidence remains largely laboratory-based. Clinical studies are still needed to determine whether chitosan-based oral films can produce sustained caries-preventive effects in real oral conditions.

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Other natural polymers, including alginate, pectin, pullulan, gelatin, starch, and natural gums, generally function more as structural matrices and delivery vehicles than as direct antibacterial agents. Their value lies in encapsulating, protecting, and controlling the release of antibacterial compounds at the oral application site. Polysaccharide-based systems can improve the stability and delivery of natural antimicrobial substances through encapsulation, entrapment, and conjugation strategies (Kotenkova et al., 2025). Natural gums also show potential as carriers for antimicrobial compounds because of their biocompatibility and favorable physicochemical characteristics (Yu et al., 2023).These polymers can be loaded with bioactive agents such as essential oils, curcumin, and green tea polyphenols to enhance antibacterial effects. Essential oil-loaded films based on chitosan, alginate, cellulose, and proteins have shown improved antibacterial performance, while curcumin-loaded and polyphenol-loaded biopolymer films have demonstrated activity against bacterial pathogens and improved film functionality (Borges et al., 2024; Yu et al., 2023). This positions natural polymer-based oral films as flexible platforms for localized antibiofilm delivery rather than simple polymeric barriers.

Reliable evaluation of antibacterial and antibiofilm activity requires a combination of complementary assays rather than reliance on a single method. Antibacterial assays are needed to determine inhibitory, bactericidal, and time-dependent effects, while antibiofilm assays are required to assess biomass reduction, cell viability, matrix disruption, structural damage, and acidogenic activity. Table 1 presents an evidence-based evaluation framework for assessing antibacterial and antibiofilm activity in *Streptococcus mutans*-targeted mucoadhesive oral films.

Table 1. Evidence-based evaluation framework for antibacterial and antibiofilm activity in *Streptococcus mutans*-targeted mucoadhesive oral films

Evaluation domain	Representative methods	Primary endpoint	Main limitation	Role in evidence package	References
Initial antibacterial screening	Inhibition zone assay	Growth inhibition around the film or active agent	Strongly affected by diffusion, solubility, and film hydration	Preliminary screening only	Song et al. (2020)
Antibacterial potency	MIC and MBC	Inhibitory and bactericidal concentrations against planktonic *Streptococcus mutans*	Does not represent mature biofilm resistance	Establish baseline antibacterial activity	Song et al. (2020)
Bacterial viability	CFU enumeration and time-kill assay	Viable bacterial reduction over time	Sensitive to sampling, detachment, and recovery method	Confirm killing effect and sustained activity	Song et al. (2020)
Biofilm biomass	Crystal violet assay	Total attached biofilm mass	Does not distinguish live and dead cells; staining artifacts may occur	Screen antibiofilm biomass reduction	Haney et al. (2021); Latka & Drulis-Kawa (2020)
Biofilm metabolic activity	XTT, MTT, resazurin, or related assays	Metabolic activity of biofilm-embedded cells	Metabolic signal may not directly equal viable cell number	Complement biomass and CFU data	Haney et al. (2021); Minich et al. (2022)
Matrix disruption	EPS, extracellular protein, or extracellular DNA analysis	Biofilm matrix reduction or disruption	Requires standardized extraction and quantification	Assess matrix-targeting antibiofilm effects	Haney et al. (2021); Minich et al. (2022)
Structural confirmation	CLSM, SEM, FE-SEM, or TEM	Biofilm architecture, surface coverage, and cell damage	Requires specialized equipment and image interpretation	Confirm structural antibiofilm disruption	Ashrafudoulla et al. (2020)
Cariogenic function	pH, acid production, or lactic acid assay	Acidogenic activity and local acidification	Does not directly measure bacterial killing	Link antibiofilm effect to caries-relevant outcomes	Gao et al. (2024); Luan et al. (2022)

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As shown in Table 1, no single assay can fully establish the antibacterial and antibiofilm performance of mucoadhesive oral films. MIC, MBC, CFU enumeration, and time-kill assays are useful for determining antibacterial potency and viable bacterial reduction, but they do not fully represent biofilm-specific resistance. Crystal violet staining, metabolic assays, EPS analysis, and microscopy provide broader information on biofilm biomass, cell viability, matrix disruption, and structural damage (Haney et al., 2021; Minich et al., 2022; Song et al., 2020).

However, crystal violet results should be interpreted cautiously because biomass staining may be affected by assay artifacts and cannot distinguish live from dead cells (Latka & Drulis-Kawa, 2020). For *Streptococcus mutans*-targeted oral films, pH, acid production, or lactic acid assays should also be included because caries prevention depends not only on bacterial reduction, but also on suppression of acidogenic activity (Gao et al., 2024; Luan et al., 2022). Therefore, future studies should combine viability, biomass, EPS, microscopy, and acidogenicity assays to distinguish genuine antibiofilm effects from general antibacterial inhibition.

3.6. Comparative potential of natural polymers

The comparative potential of natural polymers for antibacterial mucoadhesive oral films depends on how each polymer supports film formation, mucoadhesion, mechanical strength, drug release, and antimicrobial function. No single polymer provides optimal performance across all formulation requirements. Chitosan, alginate, pectin, pullulan, gelatin, starch, and natural gums each offer specific advantages, but they also present technical limitations that must be considered during formulation design. Therefore, polymer selection should follow the intended role of the film, whether as an active antibacterial matrix, a controlled-release carrier, a mucoadhesive platform, or a patient-friendly oral dosage form. Table 2 presents a function-based comparison of the reviewed natural polymers to clarify their most relevant roles in antibacterial mucoadhesive oral film design.

Natural polymer	Primary function	Key contribution	Antibiofilm role	Main limitation	Composite-film role
Chitosan	Antibacterial and mucoadhesive core	Cationic interaction with mucin and bacterial membranes	Direct antibacterial and antibiofilm activity	pH-dependent solubility and possible brittleness	Main active polymer
Alginate	Release-control matrix	Swelling and ionotropic gelation	Sustained delivery of antibacterial agents	Requires controlled crosslinking	Release modulator
Pectin	Mucoadhesive carrier	Hydration, swelling, and gel formation	Retention and delivery of active compounds	Moisture sensitivity and weak mechanics	Adhesive support polymer
Pullulan	Film-quality enhancer	Transparency, flexibility, and rapid disintegration	Indirect role through acceptability	Limited intrinsic antibacterial activity	Acceptability enhancer
Gelatin	Structural support polymer	Film formation and mechanical support	Mainly carrier-based	Brittleness and moisture sensitivity	Mechanical support polymer
Starch	Renewable film matrix	Biodegradable and low-cost film formation	Mainly carrier-based	Retrogradation and poor flexibility	Modified or blended matrix
Natural gums	Adhesion and viscosity enhancer	Swelling, viscosity, and chain entanglement	Supports residence time and release control	Excessive viscosity may reduce comfort and release	Mucoadhesive excipient

Table 2. Function-based comparison of natural polymers for antibacterial mucoadhesive oral films targeting *Streptococcus mutans* biofilms

As summarized in Table 2, chitosan has the most complete functional profile because it contributes directly to mucoadhesion and antibiofilm activity. Its cationic structure supports interaction with mucin and bacterial membranes, making it more functionally active than most other natural polymers in antibacterial oral film design (Magalhães et al., 2021; Picos-Corrales et al., 2023; Shah et al., 2025). Alginate and pectin are more relevant as release-control and adhesive carriers, while pullulan mainly improves film quality and patient acceptability. Gelatin, starch, and natural gums mainly serve as supporting polymers that improve structure, flexibility, viscosity,

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or residence time. This comparison supports a composite-film strategy in which chitosan provides the main antibacterial function and other natural polymers are selected to address specific formulation limitations.
Chitosan should be positioned as the core polymer in antibacterial mucoadhesive oral films because it provides the strongest combination of film formation, mucosal adhesion, and intrinsic antibacterial activity. Previous studies have identified chitosan as a suitable polymer for topical, transmucosal, dental, wound-healing, and antimicrobial film applications because of its mucoadhesive and antimicrobial properties (Picos-Corrales et al., 2023; Shah et al., 2025). However, pH-dependent solubility and possible brittleness may limit the performance of chitosan as a single-polymer system. This supports the need for composite films that combine chitosan with polymers that improve release control, flexibility, and patient acceptability.
Alginate and pectin are suitable supporting polymers because they contribute swelling, hydration, gel formation, and controlled-release behavior. These properties can help maintain antibacterial agents near the target site for a longer period and improve local retention in the oral cavity (Leonard et al., 2023). Pullulan has a different function. Its main value lies in improving film clarity, flexibility, disintegration behavior, and patient acceptability rather than providing direct antibacterial activity (Gupta et al., 2023; Kaith et al., 2025; Pacheco et al., 2021). Gelatin, starch, and natural gums can also support oral film formulation, but their use requires careful optimization because brittleness, moisture sensitivity, retrogradation, or excessive viscosity may reduce film performance (Castro et al., 2022; Ray et al., 2021).
Polymer blending therefore offers the most realistic strategy for developing natural polymer-based antibacterial mucoadhesive oral films against *Streptococcus mutans* biofilms. A rational formulation may use chitosan as the active antibacterial and mucoadhesive polymer, alginate or pectin as release-control carriers, pullulan as an acceptability enhancer, and gelatin, starch, or natural gums as structural or adhesive support. Previous studies have shown that polymer blending can improve tensile properties, mucoadhesion, and sustained antimicrobial release, although poor physicochemical compatibility may reduce adhesive strength or formulation performance (Constantin et al., 2022; Maslii et al., 2025). This function-based approach is more suitable than selecting polymers only based on general biocompatibility or film-forming ability.

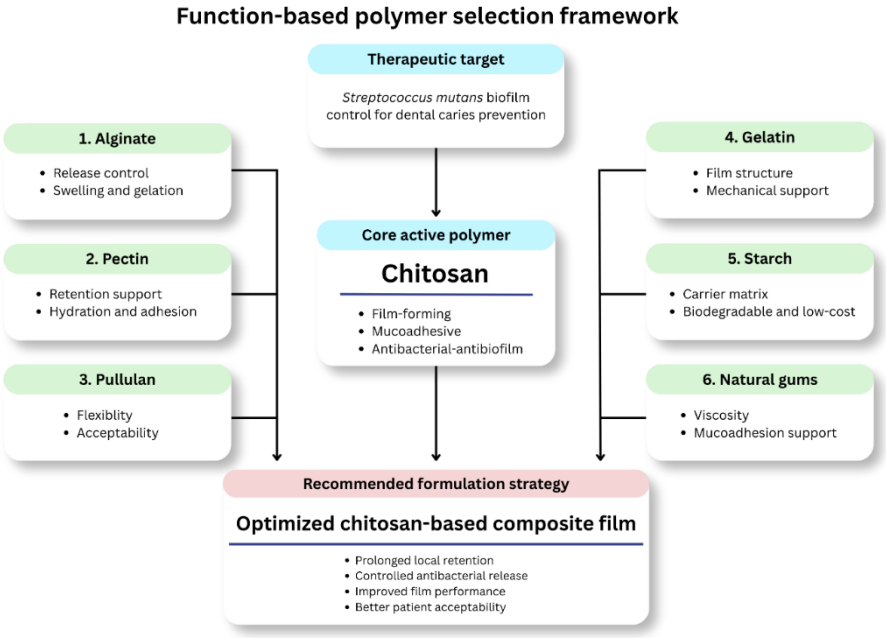

Figure.1. Function-based framework for selecting natural polymers in antibacterial mucoadhesive oral films targeting *Streptococcus mutans* biofilms.

Figure 1 presents the proposed function-based polymer selection framework for antibacterial mucoadhesive oral films targeting *Streptococcus mutans* biofilms. Chitosan is positioned as the core active polymer because it combines film-forming capacity, mucoadhesion, and direct antibacterial-antibiofilm activity. Alginate, pectin, pullulan, gelatin, starch, and natural gums are positioned as complementary polymers that support release control, retention, flexibility, mechanical strength, viscosity, and patient acceptability. This framework supports the development of optimized chitosan-based composite films rather than single-polymer systems.

3.7. Challenges and future research direction

Despite the promising potential of natural polymer-based mucoadhesive oral films, current evidence on their antibacterial activity against *Streptococcus mutans* remains largely dominated by in vitro studies. Most available investigations evaluate bacterial inhibition, biofilm reduction, membrane disruption, or drug release under

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controlled laboratory conditions. These models are useful for early formulation screening, but they do not fully represent the complexity of the oral cavity, where saliva flow, pH fluctuation, enzymatic activity, diet, oral hygiene behavior, and multispecies biofilms can affect film performance. This limitation is particularly important because *Streptococcus mutans* biofilms are structurally protected by extracellular polymeric substances and can maintain localized acidic microenvironments that are difficult to reproduce in simplified assays (Gao et al., 2024; Ikäläinen et al., 2024; Li et al., 2021). Therefore, strong in vitro antibacterial activity should not be interpreted as direct evidence of clinical effectiveness.

Clinical evidence is still needed to confirm whether antibacterial oral films can produce measurable benefits in plaque control, salivary pH regulation, biofilm suppression, and caries prevention. Future studies should evaluate outcomes that are directly relevant to dental practice, including plaque index, *Streptococcus mutans* load in saliva or plaque, salivary pH, enamel demineralization markers, caries incidence, and patient adherence. This is essential because current evidence on chitosan, probiotic films, plant-based films, essential oils, curcumin, and polyphenol-loaded polymer films remains mostly preclinical or formulation-based (Magalhães et al., 2021; Maslii et al., 2025; Yu et al., 2023). Without controlled clinical trials, the preventive value of these films against dental caries remains promising but not yet established.

Formulation stability also remains a major challenge. Natural antibacterial compounds may degrade during processing, storage, or exposure to the oral environment. Their activity can be affected by polymer composition, moisture content, pH, temperature, drug loading, and release kinetics. Stability, taste masking, disintegration control, and manufacturing scalability have already been identified as persistent barriers in oral film development (Dhankar et al., 2025; Kumar et al., 2026). Patient acceptability also requires close attention. Taste, texture, film thickness, flexibility, and residence time can determine whether patients are willing to use the product repeatedly. This is especially relevant in caries prevention because effective use requires regular application rather than one-time treatment. Films that show strong antibacterial activity but feel uncomfortable, dissolve too quickly, adhere too aggressively, or leave an unpleasant taste may fail in practical use despite favorable laboratory results.

Future research should include direct comparisons between natural polymers using the same formulation design, active compound concentration, testing method, and antibiofilm model. At present, comparisons across chitosan, alginate, pectin, pullulan, gelatin, starch, and natural gums remain difficult because studies often use different polymer grades, plasticizers, active agents, microbial strains, exposure times, and outcome measures. Standardized testing should combine antibacterial assays, biofilm biomass analysis, viable cell counting, EPS quantification, metabolic activity assays, and microscopic observation to avoid overreliance on a single method (Haney et al., 2021; Minich et al., 2022). Among the available polymers, chitosan-based blends deserve priority because chitosan has strong mucoadhesive and antibacterial potential, while blending can improve flexibility, controlled release, and patient acceptability (Constantin et al., 2022; Gao et al., 2024; Magalhães et al., 2021). Rational composite systems that combine chitosan with alginate, pectin, pullulan, gelatin, starch, or natural gums may provide the most practical route for developing clinically useful antibacterial mucoadhesive oral films against *Streptococcus mutans* biofilms.

4. Conclusion

Natural film-forming polymers provide a promising platform for antibacterial mucoadhesive oral films for dental caries prevention associated with *Streptococcus mutans* biofilms. This review shows that *Streptococcus mutans* contributes to caries progression through adhesion, extracellular polysaccharide production, biofilm maturation, acid generation, and enamel demineralization. These mechanisms make the biofilm a complex preventive target. Therefore, an effective oral film should prolong local retention, support controlled release, and interfere with both the structural and metabolic activity of the biofilm.

Among the reviewed polymers, chitosan appears to be the most promising candidate because it combines film-forming ability, mucoadhesion, and intrinsic antibacterial and antibiofilm activity. Alginate and pectin are useful as swelling, gel-forming, and controlled-release matrices, while pullulan improves transparency, flexibility, disintegration, and patient acceptability. Gelatin, starch, and natural gums also provide formulation benefits, although they often require plasticizers, blending, or modification to improve mechanical stability and release performance. Based on these properties, chitosan-based composite films offer the strongest formulation strategy, with other natural polymers selected according to the intended functional role.

However, this conclusion remains provisional because current evidence is still dominated by in vitro antibacterial, antibiofilm, mechanical, and release evaluations. Future studies should use standardized comparative methods, multispecies biofilm models, residence-time assessment, sensory acceptability testing, and clinical validation. These steps are needed to determine whether natural polymer-based mucoadhesive oral films can progress from promising formulation systems to clinically reliable tools for dental caries prevention.

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