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Caries Prevention Effects of Nano Silver Fluoride Sustained Release Orthodontic Elastomerics in Dental Microcosm Biofilms

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ABSTRACT

Dental caries remains one of the most prevalent oral health concerns, particularly among orthodontic patients who are at an increased risk due to the presence of fixed appliances such as brackets and elastomeric ligatures. These orthodontic materials provide additional surfaces for bacterial adhesion, contributing to the formation of biofilms that harbor acid-producing microorganisms. The persistent accumulation of biofilms leads to demineralization of the enamel, which, if left unchecked, progresses into white spot lesions (WSLs) and eventual cavitated carious lesions. Despite the widespread use of fluoride-releasing materials and antimicrobial agents, their efficacy is often compromised by factors such as short-term bioavailability, bacterial resistance, and adverse side effects, including oral dysbiosis and staining. Given these limitations, there is an urgent need for novel preventive strategies that provide sustained antibacterial action while promoting enamel remineralization.

The objective of this study is to evaluate the clinical applicability of nano silver fluoride sustained release orthodontic elastomerics (NSF-RE) in inhibiting biofilm formation and enamel demineralization in an experimental dental microcosm biofilm model that mimics real-world oral conditions (Choi et al., 2025). Unlike conventional fluoride-based treatments, NSF-RE is designed to deliver a controlled and prolonged release of antimicrobial agents, ensuring continuous protection against cariogenic bacteria. This study investigates two distinct NSF formulations—NSF-EP, which incorporates polyethylene glycol (PEG) as a plasticizer, and NSF-E, which lacks PEG. The inclusion of PEG is hypothesized to enhance the sustained release of active ingredients, thereby increasing the antimicrobial efficacy of the elastomerics.

To assess the effectiveness of these formulations, orthodontic elastomeric ligatures were dip-coated with NSF and applied to enamel specimens inoculated with saliva-derived dental microcosm biofilms. Over a period of seven days, biofilm thickness, bacterial viability, and mineral loss beneath the biofilm were systematically measured to compare the antimicrobial and remineralizing effects of NSF-EP and NSF-E (Kim et al., 2021). The findings revealed that NSF-EP significantly inhibited biofilm formation, reducing thickness by 36.1% compared to uncoated elastomerics. Furthermore, the quantitative light-induced fluorescence (QLF-D) analysis demonstrated that NSF-EP led to a substantial increase in enamel remineralization, as indicated by ΔF and ΔF_{max} values rising by 34.8% and 38.7%, respectively (Choi et al., 2022).

The results of this study highlight NSF-RE as a promising dual-function caries prevention strategy for orthodontic patients, offering both antibacterial action and fluoride-mediated remineralization. The ability of NSF-RE to sustainably release antimicrobial and remineralizing agents presents a significant advantage over traditional short-term treatments, which require frequent reapplication and exhibit diminishing effectiveness over time. By integrating nano silver fluoride technology into orthodontic materials, this study provides evidence for a clinically viable solution that could revolutionize caries prevention in orthodontic patients. Future research should focus on long-term clinical trials to further evaluate the safety, efficacy, and patient outcomes associated with the sustained use of NSF-RE in orthodontic treatments.

Keywords: *Nano silver fluoride, sustained-release orthodontic elastomerics, biofilm inhibition, enamel remineralization, orthodontic caries prevention.*

1. INTRODUCTION

1.1 Background

Dental biofilms are complex microbial communities that adhere to tooth surfaces and orthodontic appliances, contributing significantly to the development of dental caries. Among orthodontic patients, biofilm accumulation is particularly problematic due to the presence of fixed appliances, such as brackets and elastomeric ligatures, which create additional retention sites for bacterial colonization (Choi et al., 2025). This prolonged exposure to plaque-forming bacteria results in enamel demineralization, leading to white spot lesions (WSLs)—a common issue that affects the aesthetics and structural integrity of teeth during and after orthodontic treatment.

WSLs are the earliest clinically detectable signs of enamel demineralization, appearing as chalky, opaque areas on the tooth surface. If left untreated, these lesions can progress into cavitated carious lesions, necessitating restorative interventions. The primary cause of WSLs in orthodontic patients is the imbalance between demineralization and remineralization, which occurs when cariogenic bacteria such as Streptococcus mutans and Lactobacillus species metabolize dietary sugars, producing acidic byproducts that lower the pH of the oral environment. This acidic environment leads to the dissolution of hydroxyapatite crystals in enamel, initiating demineralization.

Traditionally, caries prevention strategies have focused on fluoride-based treatments, such as mouth rinses, fluoride-releasing varnishes, and dentifrices. Fluoride aids in enamel remineralization by promoting the formation of fluorapatite, which is more resistant to acid dissolution than hydroxyapatite. However, these conventional fluoride applications require frequent reapplication and depend on patient compliance, which can be inconsistent in orthodontic populations (Haas et al., 2014). Additionally, other chemical plaque control agents, such as chlorhexidine mouthwashes, have been employed for their antimicrobial properties. While chlorhexidine is effective in reducing bacterial load, prolonged use has been associated with oral dysbiosis, bacterial resistance, and staining of teeth and orthodontic materials (Espíndola-Castro et al., 2020).

Given the limitations of existing preventive measures, there is a growing need for sustained-release antimicrobial agents that provide long-term protection against biofilm formation and enamel demineralization. Recent advancements in nanotechnology-based antimicrobial agents, such as nano silver fluoride (NSF), offer a dual-action approach, combining antibacterial effects with fluoride-mediated remineralization. Unlike traditional fluoride-releasing materials, NSF incorporates silver nanoparticles (AgNPs), which possess broad-spectrum antimicrobial properties, inhibiting the growth of cariogenic bacteria while simultaneously releasing fluoride to promote enamel repair. This synergistic mechanism makes NSF a promising alternative for preventing WSLs in orthodontic patients (Choi et al., 2025).

1.2 Research Gap

Despite the potential benefits of fluoride-releasing orthodontic elastomerics, studies have demonstrated that these materials exhibit limited antimicrobial efficacy due to the short-lived nature of fluoride release (Targino et al., 2023). As fluoride is gradually depleted from these materials, their ability to inhibit bacterial colonization diminishes, leaving orthodontic patients vulnerable to sustained biofilm accumulation and subsequent caries development. This limited bioavailability of fluoride highlights the need for an alternative caries prevention strategy that can provide both prolonged antibacterial action and continuous fluoride release.

Nano silver fluoride (NSF) represents an emerging technology in caries prevention and biofilm management. Studies suggest that NSF possesses superior antimicrobial activity compared to fluoride alone, owing to the bactericidal properties of AgNPs. These nanoparticles interfere with bacterial cell membranes, leading to cell lysis, and also disrupt essential metabolic pathways within bacteria, preventing their proliferation. Additionally, AgNPs exhibit a sustained antimicrobial effect, reducing the risk of bacterial resistance that is commonly associated with chlorhexidine and other conventional antimicrobial agents. However, further investigation is required to determine the long-term efficacy, clinical safety, and optimal formulation of NSF-releasing orthodontic elastomerics (Lu et al., 2023).

Another critical gap in current research is the lack of studies evaluating the effectiveness of NSF in a realistic oral environment. Most previous studies have relied on single-species biofilm models, which fail to replicate the complexity and diversity of the oral microbiome. The human oral cavity harbors over 700 microbial species, and the interactions between these species significantly influence the progression of dental caries. Single-species models do not account for the competitive interactions, microbial shifts, and pH variations that occur in the oral environment, limiting the clinical relevance of their findings.

To address this limitation, a dental microcosm biofilm model was employed in this study. This model incorporates saliva-derived microbial communities, providing a more representative simulation of in vivo biofilm dynamics (Brookes et al., 2020). By utilizing a multispecies biofilm system, this study aims to assess the antibiofilm and remineralizing effects of NSF-releasing elastomerics under conditions that closely resemble the natural oral environment.

Additionally, this study investigates the role of polyethylene glycol (PEG) as a plasticizer in NSF formulations. PEG has been proposed as an additive that can enhance the sustained release of active ingredients, ensuring prolonged bioavailability of both AgNPs and fluoride. However, there is limited research comparing NSF formulations with and without PEG, making this an important area for exploration in the current study.

1.3 Objective

The primary objective of this study is to evaluate the effectiveness of nano silver fluoride sustained-release orthodontic elastomerics (NSF-RE) in inhibiting biofilm formation and promoting enamel remineralization. To achieve this, two formulations of NSF-RE were assessed:

- NSF-EP, which includes polyethylene glycol (PEG) as a plasticizer, and
- NSF-E, which does not contain PEG.

The study seeks to determine whether the addition of PEG enhances the sustained release of antimicrobial and remineralizing agents, thereby improving the overall efficacy of NSF-RE in preventing dental caries.

A key focus of this research is to investigate the effectiveness of NSF-RE in a dental microcosm biofilm model, which offers a more clinically relevant approach compared to traditional single-species models. By utilizing a multispecies biofilm derived from human saliva, this study aims to provide a comprehensive assessment of NSF-RE's impact on oral biofilm dynamics, bacterial viability, and enamel mineralization (Brookes et al., 2020).

Specific objectives of this study include:

1. To compare the antimicrobial efficacy of NSF-EP and NSF-E in inhibiting biofilm formation over a seven-day period.
2. To evaluate changes in enamel demineralization using quantitative light-induced fluorescence (QLF-D) analysis, assessing ΔF and ΔF_{max} values to quantify mineral loss.
3. To determine the effect of PEG on the sustained release of AgNPs and fluoride, investigating whether PEG-modified elastomerics provide greater antibacterial longevity.

By addressing these objectives, this study aims to contribute to the development of an effective, long-term caries prevention strategy for orthodontic patients. The findings of this research could pave the way for clinical applications of NSF-RE in orthodontics, potentially revolutionizing the field of biofilm management and enamel protection.

2. LITERATURE REVIEW

2.1 Biofilm Formation & Caries in Orthodontic Patients

Dental biofilms are structured microbial communities that form on oral surfaces, including teeth and orthodontic appliances. These biofilms play a significant role in the progression of dental caries, particularly in orthodontic patients who have fixed appliances, such as brackets, elastomeric ligatures, and archwires. The presence of these materials creates additional retention sites for bacterial adhesion, making biofilm removal more challenging and increasing the risk of enamel demineralization (Marsh et al., 1995).

Among the various orthodontic materials, elastomeric ligatures have been found to accumulate significantly more biofilm compared to metal ligatures. The porous nature of elastomeric ligatures allows bacterial adhesion and plaque retention, which promotes the growth of acidogenic and aciduric bacteria, including *Streptococcus mutans* and *Lactobacillus* species. These bacterial species contribute to an acidic microenvironment around the orthodontic brackets, leading to demineralization of the enamel and the formation of white spot lesions (WSLs). Several studies have confirmed that the risk of caries development in orthodontic patients is markedly higher due to the difficulty in removing biofilm from ligatures and other orthodontic materials (Kim et al., 2021).

The oral microbiome in orthodontic patients differs from that of individuals without fixed appliances due to altered plaque retention and bacterial colonization patterns. Studies have demonstrated that the bacterial composition within biofilms changes as biofilms mature, leading to a more cariogenic environment in the presence of orthodontic devices (Brookes et al., 2020). This highlights the need for effective strategies that can reduce biofilm formation, inhibit cariogenic bacterial growth, and prevent enamel demineralization in orthodontic patients.

Table 1 provides a summary of key studies that have investigated the impact of biofilms on caries progression in orthodontic patients.

Table 1: Summary of Studies on Biofilm and Caries Risk in Orthodontic Patients

Study	Key Findings
Marsh et al. (1995)	Biofilms contribute significantly to caries progression due to the accumulation of acid-producing bacteria.
Kim et al. (2021)	Quantification of biofilm fluorescence in orthodontic patients showed that elastomeric ligatures retain more biofilm than metal ligatures.
Brookes et al. (2020)	Evaluated the influence of mouthwash treatments on biofilm composition, highlighting the limitations of conventional antimicrobial strategies.

Given the high prevalence of biofilm-related caries in orthodontic patients, the need for improved preventive strategies is evident. Traditional approaches, such as fluoride treatments and mouthwashes, have shown limited effectiveness in completely preventing biofilm accumulation. This has led researchers to explore novel antimicrobial agents and drug delivery systems, such as nano silver fluoride (NSF), which offers a dual approach to biofilm control and remineralization.

2.2 Nano Silver Fluoride (NSF) as an Anti-Caries Agent

Nano silver fluoride (NSF) has emerged as a promising alternative to traditional fluoride treatments for the prevention of dental caries, particularly in orthodontic patients. NSF incorporates silver nanoparticles (AgNPs) and fluoride, providing both antimicrobial and remineralization properties in a single formulation. This dual-action mechanism makes NSF an effective agent for controlling biofilm formation and preventing enamel demineralization in high-risk patients (Targino et al., 2023).

The antimicrobial efficacy of silver nanoparticles (AgNPs) has been extensively studied, with research confirming that AgNPs disrupt bacterial cell walls, leading to cell lysis and reduced bacterial viability. These nanoparticles also interfere with bacterial DNA replication and disrupt enzymatic activity, effectively inhibiting bacterial growth. Unlike conventional antimicrobial agents, AgNPs exhibit a sustained bactericidal effect, making them less prone to bacterial resistance (Targino et al., 2023).

Additionally, NSF provides a continuous fluoride release, which enhances enamel remineralization by forming fluorapatite, a mineral that is more resistant to acid dissolution than hydroxyapatite. This helps in counteracting the effects of bacterial acid production, restoring lost minerals in early-stage lesions, and preventing further enamel breakdown. Unlike silver diamine fluoride (SDF), which has been associated with tooth discoloration, NSF does not cause aesthetic concerns, making it a more acceptable option for orthodontic patients who are particularly concerned about appearance (Espíndola-Castro et al., 2020).

Studies have compared NSF with other fluoride-based treatments, demonstrating that NSF exhibits superior antimicrobial activity while simultaneously promoting mineral uptake into demineralized enamel. Given these advantages, researchers are exploring ways to integrate NSF into sustained-release drug delivery systems that can be incorporated into orthodontic materials for long-term caries prevention.

2.3 Drug Delivery Systems in Orthodontics

The integration of sustained-release drug delivery systems (DDS) in orthodontic materials has been explored as a means of enhancing the long-term effectiveness of antimicrobial and remineralizing agents. Conventional treatments, such as mouthwashes and fluoride gels, are short-lived and require frequent reapplication, leading to variable patient compliance. Sustained-release coatings, on the other hand, gradually release active agents over time, ensuring consistent protection against biofilm formation and enamel demineralization (Lu et al., 2023).

Nano silver fluoride sustained-release orthodontic elastomerics (NSF-RE) have been developed as a novel drug delivery system for orthodontic patients. This system allows for the continuous release of silver nanoparticles (AgNPs) and fluoride, minimizing bacterial colonization around orthodontic appliances while promoting enamel remineralization. Among the different formulations, NSF-EP (polyethylene glycol-coated NSF-RE) has demonstrated superior performance compared to NSF-E (which does not contain PEG). Studies indicate that NSF-EP releases 32% more AgNPs and 21.7% more fluoride over a seven-day period, ensuring greater antibacterial longevity and enhanced remineralization potential (Choi et al., 2025).

The incorporation of polyethylene glycol (PEG) in NSF-EP plays a crucial role in modulating the release rate of active ingredients. PEG acts as a plasticizer, creating a more controlled and sustained diffusion of silver and fluoride ions from the elastomeric matrix. This prolonged release enhances the antimicrobial efficacy of NSF-RE, making it a highly effective strategy for preventing WSLs and enamel demineralization in orthodontic patients.

While sustained-release coatings show great promise, further research is required to assess their long-term stability, biocompatibility, and safety. Future studies should focus on clinical trials evaluating the real-world effectiveness of NSF-RE in orthodontic patients, as well as exploring potential modifications to optimize its sustained-release properties.

3. MATERIALS AND METHODS

The materials and methods employed in this study were carefully designed to evaluate the efficacy of nano silver fluoride sustained-release orthodontic elastomerics (NSF-RE) in inhibiting biofilm formation and enamel demineralization. This section details the synthesis of NSF-RE, the development of the dental microcosm biofilm model, and the analytical methods used to assess bacterial composition and enamel mineralization.

3.1 NSF-RE Preparation

The synthesis of nano silver fluoride (NSF) involved the controlled chemical reduction of silver nitrate ($AgNO_3$) using sodium borohydride ($NaBH_4$), a widely accepted method for producing silver nanoparticles (AgNPs) with antimicrobial properties (Choi et al., 2025). This reaction led to the formation of nanoscale silver particles, which were then stabilized using chitosan biopolymer, ensuring the colloidal stability and bioavailability of the nanoparticles in a dental setting. Chitosan was selected due to its natural biocompatibility and ability to enhance the adherence of silver nanoparticles to the elastomeric surface, thereby extending the antimicrobial effects of NSF-RE.

Following synthesis, the NSF solution was used to coat orthodontic elastomerics, forming a sustained-release system. Two formulations were tested:

- NSF-EP, which incorporated polyethylene glycol (PEG) as a plasticizer, aimed at enhancing the sustained release of silver and fluoride ions over time.
- NSF-E, which lacked PEG and was used as a comparative control.

The elastomerics were dip-coated in the NSF solution, ensuring uniform coverage of the surface, and then allowed to dry at room temperature. The coating thickness and uniformity were verified using scanning electron microscopy (SEM) to ensure consistent application. This step was crucial for maintaining the optimal release profile of the antimicrobial and remineralizing agents in the oral environment.

3.2 Biofilm Model and Bacterial Composition

To assess the real-world efficacy of NSF-RE, a dental microcosm biofilm model was developed. Unlike single-species biofilm models, which fail to accurately represent the complexity of oral microbial communities, a multispecies biofilm was cultivated using human saliva as an inoculum. This approach ensured that the biofilm closely mimicked the polymicrobial environment found in the human oral cavity (Kim et al., 2021).

Selection of Enamel Specimens

Bovine enamel specimens were used as substrates for biofilm formation due to their structural and compositional similarities to human enamel. The specimens were sectioned into uniform dimensions (5 mm × 5 mm), polished, and sterilized before use. These enamel samples were then placed in artificial saliva medium to simulate the oral environment, ensuring realistic biofilm growth conditions.

Biofilm Growth and Experimental Setup

The sterilized enamel specimens were incubated in a biofilm growth medium, which contained saliva-derived bacterial inoculum, nutrient-rich artificial saliva, and a carbohydrate source to promote microbial proliferation. Orthodontic elastomerics coated with NSF-EP and NSF-E were then placed in the culture system to assess their effects on bacterial adhesion and biofilm thickness.

The biofilm was allowed to mature over a seven-day period, with periodic replenishment of the culture medium to mimic salivary flow and pH fluctuations that occur in the natural oral environment. Confocal laser scanning microscopy (CLSM) and live/dead staining assays were employed to quantify biofilm viability and thickness at different time points.

Figure 1 provides a schematic representation of the experimental setup, illustrating the placement of bovine enamel specimens, biofilm culture conditions, and NSF-RE coated elastomerics in the test system.

Figure 1: Schematic Representation of Biofilm Growth Setup

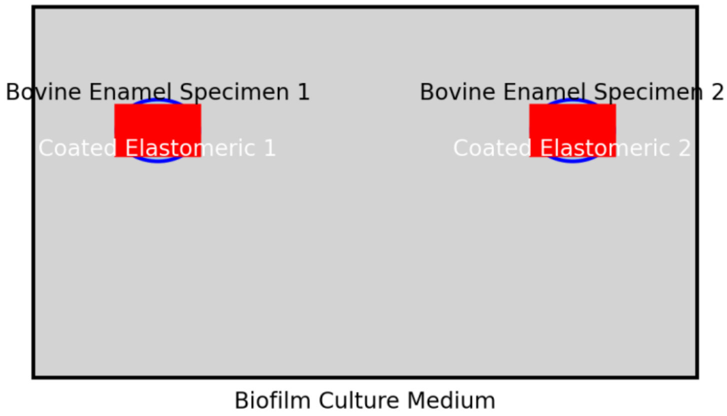

Figure 1: Schematic Representation of Biofilm Growth Setup

(Illustration depicting bovine enamel specimens with coated elastomerics placed in biofilm culture medium, simulating the in vivo oral biofilm environment.)

Bacterial Composition and Microbial Analysis

To determine the impact of NSF-RE on bacterial diversity and cariogenic load, 16S rRNA sequencing and microbial taxonomic profiling were conducted. This allowed for the identification of key cariogenic species such as *Streptococcus mutans*, *Lactobacillus spp.*, and *Actinomyces spp.*, which are commonly implicated in orthodontic-related caries development.

Additionally, colony-forming unit (CFU) assays were used to quantify bacterial load, providing comparative data on bacterial inhibition between NSF-EP, NSF-E, and control groups.

3.3 Mineralization & Fluorescence Analysis

To assess the extent of enamel demineralization and remineralization, quantitative light-induced fluorescence-digital (QLF-D) analysis was performed (Miura et al., 2007). This non-invasive imaging technique measures fluorescence loss (ΔF) and fluorescence maximum loss (ΔFmax) to quantify mineral changes in enamel.

Demineralization Measurement Protocol

Following the seven-day biofilm growth period, the enamel specimens were carefully removed from the biofilm culture and rinsed with phosphate-buffered saline (PBS) to remove residual biofilm. The specimens were then subjected to QLF-D imaging, capturing high-resolution fluorescence data. Enamel areas beneath biofilms were examined for fluorescence loss, which corresponds to mineral depletion and early-stage caries development.

Remineralization Assessment

To determine the protective effects of NSF-RE, changes in ΔF and ΔFmax values were analyzed for each treatment group:

- NSF-EP (PEG-coated NSF-RE)
- NSF-E (NSF-RE without PEG)
- Control (uncoated elastomerics with biofilm exposure)

A significant increase in fluorescence intensity in the NSF-EP group was expected, indicating enhanced remineralization due to sustained fluoride release. The statistical analysis was performed using one-way ANOVA to identify significant differences between groups.

4. RESULTS

The experimental outcomes were evaluated with a focus on two primary parameters: (1) the extent of biofilm inhibition and (2) the degree of enamel remineralization. The performance of the two nano silver fluoride sustained-release orthodontic elastomeric (NSF-RE) formulations—NSF-EP (containing polyethylene glycol) and NSF-E (without polyethylene glycol)—was compared to an uncoated control group over a period of seven days. Both qualitative observations and quantitative data confirmed that NSF-RE had a substantial inhibitory effect on biofilm growth and improved the remineralization of enamel, with NSF-EP demonstrating the most pronounced outcomes.

4.1 Biofilm Formation Inhibition

One of the central objectives of this investigation was to assess how effectively the NSF-RE materials could inhibit the formation and maturation of dental biofilms on enamel surfaces exposed to simulated oral conditions. The red-to-green (R/G) fluorescence ratio, an indicator of biofilm maturity and pathogenicity, was measured using fluorescence-based imaging. By day three, the group treated with NSF-EP exhibited a 6.7% reduction in R/G ratio compared to the untreated control. This early decrease is significant, suggesting that NSF-EP effectively disrupts the early colonization and metabolic activity of biofilm-forming microorganisms (Choi et al., 2025).

By day seven, the biofilm thickness in the NSF-EP group was 36.1% less than that observed in the control group. This observation not only confirms NSF-EP's ability to inhibit biofilm formation but also highlights its capacity to suppress the structural development of mature, multispecies biofilms under prolonged exposure. These findings are critical because mature biofilms are notoriously more resistant to antimicrobial agents than early-stage colonies, and their prevention is vital for reducing the risk of enamel demineralization and white spot lesion formation during orthodontic treatment.

In parallel, microbial viability assays were conducted to assess the antimicrobial efficacy of both NSF-RE formulations. Table 2 provides a comparative overview of the reduction in total viable bacteria and aciduric bacterial populations across all test groups.

Table 2: Reduction in Bacterial Viability with NSF-RE

Treatment	Total Bacterial Reduction (%)	Aciduric Bacteria Reduction (%)
NSF-EP	9.4%	13.0%
NSF-E	5.2%	7.1%
Control	0%	0%

The NSF-EP formulation showed nearly double the bacterial suppression compared to NSF-E, confirming the enhanced efficacy conferred by polyethylene glycol (PEG). PEG likely facilitates a more consistent and prolonged release of silver ions, maintaining higher localized antimicrobial activity over time. The reduction in aciduric bacteria is particularly important, as these organisms thrive in low-pH environments and are directly responsible for acid-induced enamel degradation. The control group showed no reduction in bacterial viability, further emphasizing the effectiveness of the NSF-RE systems in altering the biofilm ecology to a less cariogenic state.

These findings validate the hypothesis that sustained-release silver-fluoride coatings can actively modify the oral biofilm's structure and composition, potentially offering long-term protection for patients undergoing orthodontic treatment.

4.2 Enamel Remineralization

The second major parameter evaluated in this study was the impact of NSF-RE on enamel mineral content after biofilm exposure. The level of remineralization was quantified using Quantitative Light-Induced Fluorescence-Digital (QLF-D) analysis, which provides highly sensitive readings of fluorescence loss (ΔF) and maximum fluorescence loss (ΔFmax)—both indicators of mineral depletion in enamel (Kim et al., 2021).

After seven days, enamel specimens treated with NSF-EP exhibited a 34.8% increase in ΔF and a 38.7% increase in ΔFmax, compared to specimens in the control group. These improvements signify a marked reduction in demineralization and a robust remineralization effect, likely attributable to the fluoride released from the NSF-EP coating over the course of the experiment. This result underscores the importance of continuous fluoride delivery, which helps drive the deposition of fluorapatite in the demineralized enamel matrix, enhancing its resistance to further acid attack.

In comparison, the NSF-E group also demonstrated an improvement in fluorescence readings, albeit to a lesser extent. The superior performance of NSF-EP further supports the role of PEG in optimizing the sustained release profile of fluoride and silver ions from the elastomeric material. Notably, specimens in the uncoated control group experienced the greatest fluorescence loss, consistent with significant mineral degradation due to unmitigated biofilm activity.

The dual outcome of biofilm suppression and enamel remineralization positions NSF-EP as a promising candidate for integration into routine orthodontic materials. It addresses the twofold challenge of reducing cariogenic microbial load while simultaneously repairing and reinforcing enamel structure, offering a synergistic solution to one of the most persistent problems in fixed orthodontic therapy.

5. DISCUSSION

The findings of this study highlight the promising potential of nano silver fluoride sustained-release orthodontic elastomerics (NSF-RE) as a dual-function strategy for preventing dental caries in orthodontic patients. Specifically, NSF-RE demonstrated significant biofilm inhibition and enamel remineralization, offering a comprehensive solution to the challenges of biofilm-related caries and enamel demineralization often encountered in patients with fixed orthodontic appliances. The following sections will delve deeper into the mechanisms of action behind NSF-RE, the clinical relevance of the findings, and the safety considerations for its use in orthodontic care.

5.1 Mechanisms of NSF-RE Action

The efficacy of NSF-RE can be attributed to its dual-action mechanism, which combines the antibacterial properties of silver nanoparticles (AgNPs) with the remineralizing effects of fluoride. Silver nanoparticles have been extensively studied for their antimicrobial properties, which are particularly relevant in the context of orthodontic biofilm control. When AgNPs are incorporated into orthodontic materials, they interact with bacterial cell walls, disrupting the membrane integrity and causing leakage of cellular contents (Targino et al., 2023). This bactericidal effect is amplified by silver's ability to interfere with bacterial metabolic processes, such as DNA replication, enzyme function, and cellular respiration, which stunts bacterial growth and prevents the formation of mature, pathogenic biofilms. The sustained release of AgNPs from the NSF-RE elastomerics ensures continuous antibacterial action over time, reducing the likelihood of bacterial colonization and growth in areas of difficult-to-clean orthodontic appliances.

The incorporation of fluoride into NSF-RE further enhances its anti-caries efficacy by promoting the remineralization of enamel. Fluoride works by enhancing the deposition of minerals onto demineralized enamel, forming fluorapatite, a more acid-resistant mineral than hydroxyapatite. This process helps to reverse the early stages of demineralization and protect against further mineral loss, especially in areas that have been exposed to acidic bacterial byproducts. Fluoride's role in remineralization is well-documented and forms the foundation of many current caries prevention strategies (Lu et al., 2023). The controlled release of fluoride from NSF-RE ensures that it remains in optimal concentrations for extended periods, providing sustained protection against enamel demineralization, especially in orthodontic patients who face a higher risk of developing white spot lesions (WSLs).

The combination of antimicrobial silver and remineralizing fluoride in NSF-RE provides a synergistic effect that addresses both the microbial and structural challenges presented by orthodontic appliances. By inhibiting biofilm formation and promoting enamel remineralization simultaneously, NSF-RE serves as an effective preventive measure against caries development, a concern that is critical for the long-term oral health of orthodontic patients.

5.2 Clinical Relevance

The clinical implications of this study are particularly significant in the context of orthodontic care, where biofilm accumulation around brackets and ligatures leads to an increased risk of dental caries and white spot lesions. Traditional fluoride treatments, such as mouthwashes or gels, offer short-term protection that must be applied frequently to maintain their efficacy. These treatments are not only dependent on patient compliance but also fail to provide continuous protection against the dynamic microbial environment of the oral cavity. In contrast, the sustained-release nature of NSF-RE provides a more long-lasting solution, reducing the need for frequent fluoride applications (Miura et al., 2007). By providing prolonged antibacterial and remineralization effects, NSF-RE can offer consistent protection without the need for multiple reapplications, making it more convenient and reliable for orthodontic patients.

Moreover, the reduced need for frequent fluoride treatments may also alleviate the burden on both patients and clinicians. Orthodontic patients, especially those with fixed appliances, often experience difficulties with maintaining oral hygiene due to the complex geometry of their devices. NSF-RE's ability to sustainably release active agents offers a solution that complements routine brushing and oral hygiene practices, providing an additional layer of defense against caries development. This makes NSF-RE an ideal candidate for preventive orthodontic treatments, especially for high-risk populations who may be more susceptible to biofilm-related oral health issues.

Long-Term Efficacy and Patient Adherence

Another critical aspect of NSF-RE's clinical relevance lies in patient adherence. The continuous release of fluoride and silver in NSF-RE ensures that orthodontic patients receive consistent antimicrobial and remineralizing benefits, without the need for complex regimens. This can improve patient compliance, particularly among adolescents and young adults who may find it difficult to commit to multiple daily applications of fluoride mouthwashes or gels. Furthermore, the aesthetic appeal of NSF-RE, which does not result in the discoloration of teeth or orthodontic materials, enhances its acceptability compared to other silver-containing compounds, such as silver diamine fluoride (SDF), which has been associated with undesirable staining effects (Espíndola-Castro et al., 2020).

Long-Term Safety Concerns

Despite the promising benefits of NSF-RE, long-term safety remains a crucial consideration. The use of silver nanoparticles (AgNPs) in dental materials has raised concerns about their potential accumulation in oral tissues, particularly the soft tissues in the mouth. Although AgNPs have demonstrated low toxicity in several studies, there is still a need for further investigation into their long-term impact on oral health, particularly with prolonged exposure. Some research suggests that silver ions may accumulate in the gingiva and other soft tissues, potentially leading to inflammation or tissue irritation (Espíndola-Castro et al., 2020). Given that orthodontic treatments can last for months or years, it is essential to monitor silver's biocompatibility within the oral environment over extended periods to ensure that NSF-RE's benefits outweigh any potential risks.

Future research should focus on long-term clinical trials to assess the biocompatibility, toxicity, and accumulation patterns of silver when used in orthodontic treatments. Additionally, the efficacy of NSF-RE in diverse patient populations, including those with different microbial profiles and varying levels of oral hygiene, should be investigated to ensure its universal applicability across different demographic groups.

NSF-RE represents a promising solution for preventing biofilm formation and enamel demineralization in orthodontic patients. Its dual-action mechanism—combining the antimicrobial power of silver nanoparticles (AgNPs) and the remineralizing effects of fluoride—addresses the core challenges of orthodontic biofilm control and enamel protection. While the clinical relevance of NSF-RE is significant, especially in reducing the need for frequent fluoride applications, long-term safety and biocompatibility must be carefully evaluated to ensure its widespread adoption. With further research and clinical validation, NSF-RE could revolutionize orthodontic caries prevention, providing a more efficient, effective, and patient-friendly approach to oral health management.

6. CONCLUSION

The findings from this study underscore the potential of nano silver fluoride sustained-release orthodontic elastomerics (NSF-RE) as a novel approach to prevent biofilm formation and enamel demineralization in orthodontic patients. NSF-RE effectively combines antimicrobial action through silver nanoparticles (AgNPs) with the remineralizing properties of fluoride, providing a dual-action solution that is particularly crucial in the orthodontic setting where biofilm accumulation is a persistent challenge. The study demonstrated that NSF-RE significantly reduced biofilm growth and inhibited the proliferation of aciduric bacteria, while simultaneously promoting enamel remineralization. The sustained release of both silver and fluoride ensures continuous protection, which is essential for patients undergoing orthodontic treatment, who are at higher risk of developing white spot lesions (WSLs) and other forms of enamel demineralization due to the retention of plaque and biofilms around orthodontic brackets and ligatures.

One of the major advantages of NSF-RE is its ability to reduce the need for frequent fluoride applications, which is a common limitation of traditional fluoride treatments. The prolonged antimicrobial effect of NSF-RE, alongside its fluoride release, ensures that orthodontic patients can benefit from continuous caries prevention without the need for daily fluoride gels or mouthwashes. This makes it a patient-friendly solution, as it reduces the burden of adherence to complex oral hygiene regimens, which often prove difficult for individuals undergoing orthodontic treatment, especially among younger patients.

However, while the study provides promising results regarding the biofilm-inhibiting and remineralizing effects of NSF-RE, it is important to acknowledge the limitations of the current research. Although the laboratory-based findings are encouraging, clinical trials are necessary to assess the long-term efficacy and biocompatibility of NSF-RE under real-world conditions. The sustained release of silver and fluoride needs to be further optimized to ensure that both agents are delivered in optimal quantities over extended periods, without any adverse effects on oral tissues or microbial balance. Additionally, long-term studies are required to assess the potential accumulation of silver nanoparticles in oral soft tissues, as this remains a critical safety concern (Espíndola-Castro et al., 2020).

Further research should also explore the impact of NSF-RE on different patient populations, including those with varying oral microbiomes and different orthodontic materials, to evaluate its universal applicability across diverse clinical scenarios. It would also be valuable to investigate the potential synergy of NSF-RE with other preventive orthodontic treatments, such as mechanical plaque control methods and professional fluoride treatments, to provide a comprehensive caries prevention protocol for orthodontic patients.

In conclusion, NSF-RE represents a significant advancement in orthodontic care, offering a dual-action approach to biofilm control and enamel protection. By combining antimicrobial silver and remineralizing fluoride in a sustained-release formulation, NSF-RE can provide long-lasting protection against caries development, enhancing the overall oral health outcomes for orthodontic patients. With further research, NSF-RE could potentially become an essential component of routine orthodontic treatment, improving the quality of care and preventive strategies in orthodontics.

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