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Lubricating properties of the dental pellicle: A scoping review

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ABSTRACT

Objectives: This scoping review aimed to evaluate the pellicles' protective potential against mechanical tooth wear and to explore the underlying mechanisms.
Methods: A systematic search was conducted in Medline, Scopus, and Web of Science up to May 2025. Studies examining pellicles formed on enamel, dentin, or hydroxyapatite, using human saliva or salivary proteins, and subjected to mechanical challenges were included. Studies combining erosion or involving diseased subjects or non-dental substrates were excluded. Only original research articles published in English or German were considered. No supplementary approaches to identify studies were performed.
Results: Out of 893 records, 26 studies met the inclusion criteria. The majority focused on pellicles formed on enamel or hydroxyapatite. Outcome measures included wear, abrasion resistance, friction coefficient, and viscoelastic properties. While most studies found that the pellicle reduced friction and wear, its abrasion resistance to high mechanical stress was weak. Since the majority of studies were conducted *in vitro*, the extent to which these findings apply to the dynamic oral environment is uncertain.
Conclusions: The pellicle may offer limited protection against mechanical wear, primarily through a boundary lubrication regime, while evidence regarding its structural integrity and resistance under mechanical stress remains inconclusive, highlighting the need for further research to validate relevant parameters and clarify underlying mechanisms.

1. Introduction

Teeth are exposed to considerable mechanical stress throughout life, resulting in progressive tooth wear. This wear is typically categorized into two types: attrition, caused by direct tooth-to-tooth contact, and abrasion, resulting from interaction with external agents (Grippo et al., 2004). Mechanically induced tooth wear has been present since early human evolution. The craniofacial system is adapted to accommodate such wear through continuous tooth migration and bone remodelling, and is generally considered a physiological process. This is supported by studies on great apes, our closest living relatives, which show consistent patterns of attrition and abrasion on nearly all occlusal and incisal surfaces due to mastication. In modern industrialized societies, however, dietary changes have introduced caries and erosion, a bacterial and chemical demineralization, respectively, as major contributing factors to loss of dental hard tissue (Albrecht et al., 2024; Kaidonis, 2008; Kaifu et al., 2003). However, mechanical tooth wear remains relevant in individuals with parafunctions such as bruxism or improper oral hygiene practices, including aggressive tooth brushing (Grippo et al., 2004). Furthermore, increasing life expectancy demands that teeth maintain functionality over longer periods, raising questions about the long-term effects of extensive mechanical wear on oral health (McKenna et al., 2020; Reeh et al., 1996).

Mechanical wear arises from friction between sliding surfaces or from the action of abrasive particles (Kato, 2000). Within the oral cavity, however, all dental surfaces are coated by a thin, protein-rich film known as the pellicle, which may contribute to reducing mechanical wear (Hannig & Joiner, 2006). The pellicle forms through the adsorption of salivary proteins onto dental hard tissues, which are composed primarily of calcium- and phosphate-containing hydroxyapatite. These surfaces are initially covered by a thin aqueous layer, whose thickness is enhanced by the strong hydration capacity of calcium ions (Tang et al., 2025). Owing to the greater solubility of calcium relative to phosphate, a positively charged surface develops, promoting the selective adsorption of negatively charged salivary proteins. This process begins with low-molecular-weight proteins and progresses to the adsorption of larger proteins and aggregates, ultimately resulting in the formation of the characteristic bilayered pellicle (Hannig & Joiner, 2006). The

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heterogenous pellicle is composed of hundreds of selectively adsorbed proteins, including both universally present and individually variable components (Trautmann et al., 2019, 2020). It also contains monosaccharides, likely originating from dietary or microbial polysaccharides or glycoproteins (Hannig & Joiner, 2006; Schulz et al., 2020), along with lipids such as triacylglycerols and phospholipids, which show a consistent fatty acid profile (Reich et al., 2022, 2013). Additionally, small metabolites including amino acids, fatty acids, and organic acids are present (Schulz et al., 2020).

The pellicle is considered an evolutionary adaptation in mammals comparable to lubrication systems found in other biological interfaces, reducing friction and wear under physiologically demanding conditions (Qin et al., 2025). Beyond lubrication, coating surfaces that are regularly exposed to the environment with a protective mucus layer has provided an evolutionary advantage during metazoan evolution. Mucus first evolved in the gastrointestinal tract and later extended to respiratory surfaces during the transition from water to land (Bakshani et al., 2018). In humans, it is now also present in the eyes, ears, and reproductive system (Qin et al., 2025).

While the role of the pellicle in biofilm formation and erosion protection is well documented (Hannig & Hannig, 2025; Hannig & Joiner, 2006), its mechanism in preventing mechanically induced tooth wear lacks clarity. From an anthropological perspective, we postulate that the primary function of the pellicle may have been to protect teeth against mechanical wear. This is supported by the fact that, prior to the Industrial Revolution, diets were largely composed of unprocessed, and thus more abrasive, foods (Alt et al., 2022). In contrast, citrus fruits and related products, major contributors to dental erosion, only became widely consumed in recent centuries (Liu et al., 2012; Lussi, 2006). Therefore, the aim of this scoping review was to systematically examine the literature in this topic to better characterize the protective properties of the pellicle. Specifically, the review aimed to address the following research questions: (1) Does the pellicle provide protection against solely mechanical tooth wear, and (2) what are the underlying mechanisms by which the pellicle provides this protection?

2. Material and methods

2.1. Protocol and registration

This scoping review followed the PRISMA-ScR guideline (Tricco et al., 2018). The protocol was pre-registered on the Open Science Framework (https://doi.org/10.17605/OSF.IO/MK534) on March 27, 2025, and was updated after the initial screening phase.

2.2. Eligibility criteria

In order to evaluate how the pellicle protects against mechanical tooth wear, specific eligibility criteria were defined. Studies were included if they investigated relevant substrates such as enamel, dentin, or hydroxyapatite. Soft tissues and non-dental materials were excluded due to their regenerative capacity and adaptability, which differ from dental hard tissues. Eligible interventions involved pellicles formed either *in vivo* or *in situ* using healthy human subjects, or *in vitro* using human saliva or salivary proteins, and subjected to mechanical challenges such as abrasion or attrition. Studies involving subjects or saliva from individuals with oral or systemic diseases were excluded to avoid confounding factors affecting pellicle formation. Studies focusing solely on erosion, or combining erosion with mechanical wear, were excluded, as erosion was addressed in previous reviews and its complex interaction with mechanical factors complicates clear interpretation. Comparisons could involve different pellicle formation methods, pellicles modified by substances, or protein-free surfaces. Outcomes of interest included wear, lubrication, friction coefficients, viscoelasticity, and other pellicle characterizations; however, studies examining only the mechanical properties of saliva without reference to dental surfaces or the pellicle were excluded. All experimental study designs were considered, while review articles were excluded. No restrictions were applied regarding the year of publication, but only articles published in English or German were included. Manual searching of journals and reference list checking were not conducted to ensure reproducibility.

2.3. Information sources and search

The databases Medline, Scopus, and Web of Science were searched up to May 19, 2025. The full electronic search strategy for Medline via PubMed was as follows: “(wear OR abrasion OR attrition OR lubrication OR friction OR viscoelastic) AND (pellicle OR "salivary film" OR "salivary protein" OR "salivary proteins" OR "saliva substitute" OR "saliva substitutes") NOT review”. No filters were applied. Search strategies were adapted to each database (Supplementary Table 1).

2.4. Selection

All articles retrieved were imported into Rayyan (Rayyan Systems, Cambridge, USA). Duplicates were automatically removed using the auto-resolve function with text normalization and exact title matching; remaining duplicates were resolved manually. Title, abstract, and full-text screening were performed independently and in duplicate by reviewers A.S. and C.M.-P. using Rayyan’s blind mode. Conflicts were resolved by consensus.

2.5. Data charting

A data charting table was created by reviewer A.S., who charted the following data: substrate, pellicle-forming substance, comparison, pellicle formation setting, challenge, outcome measures, results, and conclusions.

2.6. Synthesis of results

Given the high number of included studies, the data were synthesized in narrative form to allow for clearer contextualization and comparison across studies. The studies were grouped according to their primary outcome measures, specifically wear, abrasion resistance, friction coefficient, and viscoelasticity. The detailed data charting table including all study characteristics was provided as a supplement.

3. Results

3.1. Selection

Of the initial 893 records, 26 studies were included for data charting after duplicate removal and screening of titles, abstracts, and full texts (Fig. 1).

3.2. Summary of charting results

A total of 26 studies investigated the role of the pellicle in protecting against abrasion and attrition (Table 1; Supplementary Table 2). The most frequently used substrate was human enamel ($n = 19$), followed by hydroxyapatite ($n = 9$), bovine enamel ($n = 3$), and dentin ($n = 2$); several studies utilized multiple substrates. Pellicle formation was achieved using unstimulated saliva ($n = 10$), stimulated saliva ($n = 5$), whole saliva ($n = 10$), as well as parotid saliva ($n = 2$), submandibular/sublingual saliva ($n = 3$), salivary fractions ($n = 2$), and purified salivary proteins ($n = 5$). In some studies, the type of saliva was not further specified ($n = 4$). The pellicle was primarily formed *in vitro* under standardized laboratory conditions ($n = 22$). In a few cases, the native pellicle on extracted teeth was analysed *ex vivo* ($n = 3$), or formed *in situ* under oral cavity conditions using intraorally worn splints with fixed samples ($n = 1$). Modifications were performed in five studies,

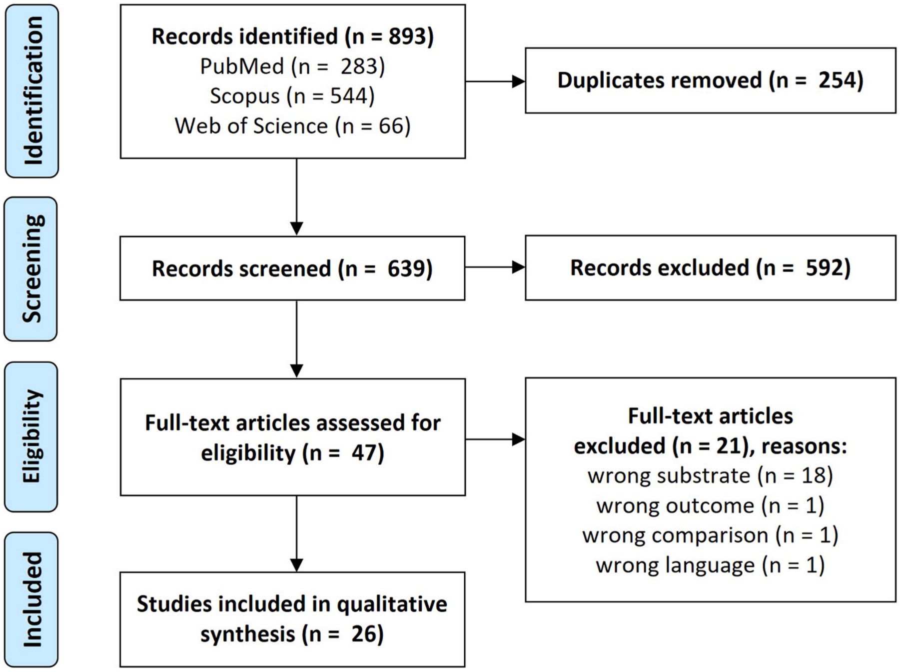

Fig. 1. Flow chart of study selection process.

incorporating astringents, fluorides, calcium, or alcohol. Outcome measures were categorized as follows: wear (n = 3), pellicle thickness or integrity (n = 4), friction coefficient (n = 14), and viscoelasticity (n = 8), with several studies evaluating more than one parameter. Most studies reported that pellicle formation contributed to a reduction in friction and wear. In abrasion resistance studies, the pellicle exhibited partial resistance, although its thickness and structural integrity declined under high mechanical stress.

4. Discussion

4.1. *Methodological approaches*

To investigate the protective properties of the pellicle, a variety of substrates have been used. While human enamel and dentin are most common, some studies have utilised bovine enamel or synthetic hydroxyapatite as alternatives. Despite structural differences, such as crystal size in enamel and tubule characteristics in dentin, bovine and human teeth share similar chemical composition and mechanical behaviour (Yassen et al., 2011). Comparable abrasion loss observed in both materials supports the use of bovine teeth as a reliable model (Attin et al., 2007; Imfeld, 2001; Wegehaupt et al., 2008). Their larger size and consistent availability, along with standardised conditions like slaughter age and diet, further strengthen their suitability (Yassen et al., 2011). Synthetic hydroxyapatite, widely used due to its compositional similarity to enamel, offers even greater availability and standardisation. However, it lacks the complex hierarchical structure of natural enamel, which contributes to enamel's resistance to fracture and wear (Rujiraprasert et al., 2023; Zheng et al., 2013). Although pellicle ultrastructure and composition appear independent of the underlying substrate (Hannig, 1997; Trautmann et al., 2022), intra- and interindividual factors play a more significant role (Trautmann et al., 2020). Whether substrate differences influence the pellicles' protective function against mechanical wear, however, is still under investigation.

Pellicle formation has been achieved using a range of protocols, including *in vitro* application of isolated salivary proteins or whole saliva, *in situ* formation on intraorally worn samples, and *ex vivo* investigation on extracted teeth. *In situ* and *ex vivo* methods offer physiological conditions, whereas *in vitro* approaches vary widely in saliva collection and handling. These differences include the use of stimulated versus unstimulated saliva, centrifugation for cell removal, dilution, addition of protease inhibitors, storage conditions, lyophilisation and resuspension, and frequency of saliva replacement during extended incubation. The impact of these methodological variations on the pellicles' protection against mechanical wear is not yet fully understood due to limited comparative data. However, differences were reported in pellicle composition and erosion-protective properties depending on the formation method and saliva processing, respectively (Baumann et al., 2023; Pelá et al., 2020). While intraoral models better reflect clinical reality, *in vitro* systems remain practical and reproducible, requiring only initial saliva donation without further subject participation (Pelá et al., 2020).

To characterise pellicle properties and their protective effects, various analytical techniques were employed. Friction and viscoelasticity measurements, along with transmission electron microscopy, were used to analyse structural and mechanical pellicle characteristics, while profilometry was applied to assess protection against mechanical wear. Both stylus-based (Sajewicz, 2009), and optical profilometry were applied (Aljulayfi et al., 2022; Joiner et al., 2008). In contrast to erosion, where demineralisation increases susceptibility to contact-profilometry (Attin & Wegehaupt, 2014), abrasion-only wear may reduce the relevance of method choice. Nevertheless, stylus profilometry carries a risk of surface damage and may miss fine surface features due to stylus size, while optical methods can be influenced by non-geometric surface properties (Passos et al., 2013). While pre- and post-characterization of surfaces is commonly used to investigate lubrication, in-situ characterization remains challenging. Further research is needed to determine how factors such as sample moisture and pellicle presence affect abrasion-only wear during in-situ characterization (Zhang & Meng, 2015).

4.2. *Wear protection*

Several studies included in this review investigated whether saliva and the pellicle can protect dental hard tissues from wear. In the study by Aljulayfi et al. (2022), profilometric analyses showed that enamel-to-enamel attrition was only slightly reduced by saliva compared to water. Since the study did not include a control group with

Table 1
Overview of major findings in included studies.

Outcome measure	Study designs	Substrates	Major findings	References
Wear	in-vitro, in-situ	human enamel and dentin	High-viscosity saliva can reduce wear under low-load attrition; pellicle can reduce wear by abrasion.	(Aljulayfi et al., 2022; Joiner et al., 2008; Sajewicz, 2009)
Pellicle thickness or integrity	ex-vivo, in-vitro	human enamel, hydroxyapatite	Pellicle is reduced by abrasion.	(Hannig & Bössmann, 1987, 1988a, 1988b; Veeregowda et al., 2011)
Friction coefficient	in-vitro	human tooth (unspecified), human and bovine enamel, hydroxyapatite	Pellicle, saliva, and especially amphiphilic proteins can reduce friction.	(Aguirre et al., 1989; Douglas et al., 1991; Hatton et al., 1987; Hatton et al., 1985; Lei et al., 2022; Reeh et al., 1995, 1996; Smart & Bryant, 2023; Tang et al., 2025; Wang et al., 2024; Zeng, Ma, et al., 2019; Zeng, Zheng, et al., 2019; Zeng et al., 2017; Zhang et al., 2013)
Viscoelasticity	in-vitro	human enamel, hydroxyapatite	Pellicle is viscoelastic, potentially influenced by its mucin content.	(Ash et al., 2014; Barrantes et al., 2014; Smart & Bryant, 2023; Veeregowda et al., 2011; Wang et al., 2024; Zeng, Zheng, et al., 2019; Zeng et al., 2017; Zimmermann et al., 2019)

bare enamel, the specific role of the lubricant could not be fully assessed (Aljulayfi et al., 2022). Nevertheless, the methods used suggest that hydrodynamic lubrication likely occurred. In this lubrication regime, the sliding surfaces are fully separated by a fluid film, which typically forms under low loads and is primarily influenced by the viscosity of the lubricant (Pajic-Lijakovic et al., 2024). Two observations support the likelihood of hydrodynamic lubrication in the study by Aljulayfi et al. (2022): first, the use of low-load conditions; and second, evidence from another study included in this review, which found that saliva with higher viscosity provided greater protection against wear under similar conditions (Sajewicz, 2009). At higher loads, such as those generated during chewing, clenching, or grinding, the fluid film may be displaced, shifting the lubrication regime to boundary lubrication. Boundary lubrication describes a condition where two solid surfaces move relative to each other with only a very thin lubricant film between them. This thin layer helps reduce friction and wear, even though it does not entirely prevent contact between surface roughness features.

When the surfaces are smooth or the contact forces are minimal, the film can sustain the load on its own. However, on rougher interfaces, part of the load is also supported by the protruding surface features that interact through the lubricant layer. The effectiveness of this lubrication mode depends on multiple factors, including film thickness and composition. Generally, thicker or more structurally robust films offer better protection against wear. Since pressure is unevenly distributed across the contact area, regions of high stress may cause the lubricant to be squeezed out. Additionally, sliding motion can lead to complex behaviours such as intermittent sticking and slipping, heat buildup, and material migration, all of which influence how well the system performs under boundary lubrication conditions (Zhang & Meng, 2015). In the oral cavity, the pellicle provides boundary lubrication (Reeh et al., 1996), which contribute to wear reduction; however, the extent of its protective effect remains unclear, as this has not yet been systematically investigated.

While attrition refers to wear resulting from direct contact and friction between two surfaces, abrasion involves the presence of abrasive particles, constituting a three-body wear mechanism. These particles may originate from external sources or be produced during the wear process itself (Hannig & Hannig, 2010; Kato, 2000). If the particle size exceeds the thickness of the lubricating film, the particles can penetrate the film, leading to increased wear (Mahesh, 2024). Furthermore, abrasive particles may become embedded in the softer surface, thereby increasing the risk of wear to the opposing, harder substrate (Dwyer-Joyce et al., 1994). Although the presence of a lubricant typically reduces wear under three-body conditions when compared to dry wear scenarios (Mahesh, 2024), the complex interactions between the solid surface, the pellicle, the liquid film, and abrasive particles remain insufficiently understood. Abrasive particles can disrupt lubrication by penetrating or damaging the pellicle, compromising its protective function. In addition, lubricating films may degrade over time, losing their effectiveness (Chen & Horng, 2024; Pascovici & Khonsari, 2000). However, under oral conditions, this degradation may be negligible due to the continuous replenishment of salivary proteins through saliva flow, which supports ongoing pellicle formation and contributes to the maintenance of a protective layer (Hannig & Joiner, 2006).

In the only study included in this review that investigated abrasion-related wear, the presence of the pellicle significantly reduced enamel and dentin wear caused by toothbrushes and toothpaste, compared to water (Joiner et al., 2008). Due to differences in composition and morphology, dentin exhibited greater material loss than enamel, reflecting its higher susceptibility to mechanical wear. However, it remains unclear whether the protective properties of the pellicle differ depending on whether it forms on enamel or dentin (Rasputnis et al., 2021).

A few studies also investigated wear as a secondary outcome of friction analyses using nano-scratch tests (Zeng, Ma, et al., 2019; Zeng, Zheng, et al., 2019; Zhang et al., 2013). However, these findings are not discussed further here, as the experimental conditions, applying a single unidirectional load of only 5 mN with a conical diamond tip, did not represent clinically relevant scenarios within the oral cavity.

While the pellicle may contribute to wear reduction by providing boundary lubrication (Reeh et al., 1996), this protective effect is lost once the pellicle is removed. In its absence, wear is primarily determined by friction, which depends on the morphological and physical properties of the sliding surfaces (Kato, 2000). Therefore, this review also considered studies that examined the abrasion resistance of the pellicle itself.

4.3. Abrasion resistance

The resistance of the pellicle to mechanical removal has been investigated in several studies of Hannig's group. In earlier work, the abrasion resistance of natural pellicles formed on extracted human teeth was assessed by evaluating pellicle thickness and integrity using transmission electron microscopy. Several factors were found to influence pellicle removal during tooth cleaning procedures. Specifically, pellicle removal increased with the use of rotary nylon brushes (compared to polishing cups), pumice (compared to chalk), higher dentifrice abrasivity, and lower dilution levels. In contrast, brushing with artificial saliva was non-abrasive, and increased brushing time had no additional effect under *in vitro* conditions (Hannig & Bössmann, 1987, 1988b). However, under clinical conditions, brushing duration may still influence pellicle removal due to the progressive dilution of dentifrice by saliva.

A more recent study examined pellicles formed periodically *in situ* and subsequently subjected to *in vitro* abrasion. The results demonstrated that pellicle thickness decreased with increasing dentifrice abrasivity, irrespective of the underlying substrate. Although the pellicle offers protection against mechanical wear, it is gradually abraded during brushing, leading to a transient loss of its protective properties. Notably, the pellicle appeared to regenerate between brushing sessions, thereby restoring its protective properties over time (Joiner et al., 2008). Although not yet investigated for the pellicle, findings from other tribological systems suggest that thicker film layers, unlike thinner ones, can provide lubrication for longer periods, as they take more time to wear down during repeated sliding (Zhang & Meng, 2015). This highlights the potential importance of pellicle thickness and its regeneration dynamics in maintaining protection under oral cavity conditions.

While Hannig's studies focused on external factors influencing pellicle removal, the mechanical features of the pellicle may also play a role in its abrasion resistance and protective function. In the included studies, these aspects were primarily evaluated through measurements of frictional behaviour and viscoelastic characteristics.

4.4. Friction and lubrication

The friction coefficient is defined as the resistance to sliding between two surfaces (Blau, 2001), but it also provides insight into the durability of surface coatings under mechanical load (Kato, 2000). In the included studies, the frictional coefficients were evaluated through different methods, including rotating glass plate tests (Aguirre et al., 1989; Hatton et al., 1987, 1985), flat-on-flat contact tests involving enamel or ceramic surfaces (Douglas et al., 1991; Reeh et al., 1995, 1996; Sajewicz, 2009; Smart & Bryant, 2023), and nano-scratch tests using diamond tips (Lei et al., 2022; Tang et al., 2025; Wang et al., 2024; Zeng, Ma, et al., 2019; Zeng, Zheng, et al., 2019; Zeng et al., 2017; Zhang et al., 2013). However, in earlier studies using glass plate and flat-on-flat contact tests, the pellicle was not pre-formed prior to the measurements. Instead, the experiments were conducted directly in saliva or salivary protein solutions, allowing for additional hydrodynamic lubrication and making it difficult to assess the specific contribution of the pellicle to friction reduction (Aguirre et al., 1989; Douglas et al., 1991; Hatton et al., 1987; Hatton et al., 1985; Reeh et al., 1995, 1996; Sajewicz, 2009). In contrast, more recent studies that allowed pellicle formation prior to measurement reported consistently lower friction coefficients compared to water or bare enamel. The applied loads in these studies were low to preserve the integrity of the pellicle and to prevent direct substrate contact (Lei et al., 2022; Smart & Bryant, 2023; Tang et al., 2025; Wang et al., 2024; Zeng, Ma, et al., 2019; Zeng, Zheng, et al., 2019; Zeng et al., 2017; Zhang et al., 2013). The following summarizes and discusses the friction coefficients of various experimental pellicles, which may offer preliminary insights into their abrasion resistance. However, interpreting these coefficients as indicators of abrasion resistance remains speculative and requires further experimental validation, such as investigating friction coefficients under varying loads in combination with corresponding ultrastructural analyses of pellicle integrity.

Differences in pellicle composition may contribute to its frictional properties. Smart and Bryant (2023) compared pellicles formed from crude versus purified mucin and found that those created from crude mucin exhibited slightly lower friction. This effect was attributed to the formation of a multilayered pellicle containing larger aggregates and residual impurities, such as proteins, DNA, and ions. Crude mucin might have promoted the formation of an inner layer composed of smaller proteins and an outer layer of larger aggregates, which were stabilized through intermolecular interactions involving the impurities. Furthermore, the pellicle formed from crude mucin exhibited an enhanced water binding capacity, allowing the development of a thicker outer hydration layer that contributed to further friction reduction (Smart & Bryant, 2023). In addition to composition, the time allowed for pellicle formation and the rate of salivary flow appear to affect its lubricating behaviour. Zhang et al. (2013) demonstrated that a thin, smooth, and highly adhesive pellicle forms within seconds. As formation time increased, loosely bound protein aggregates accumulated, raising surface roughness and friction (Zhang et al., 2013). The friction coefficient depends on multiple factors, including surface roughness, lubrication regime, chemical composition of the lubricant, and electrostatic interactions, which may explain the variation in lubricating properties between initial and mature pellicles (Blau, 2001). These findings suggest that nature has developed an efficient mechanism to minimize friction. When salivary glands are functioning properly, lubrication of dental surfaces, even if temporarily lost under high mechanical loads, can be rapidly restored within seconds through pellicle reformation (Zhang et al., 2013). In cases of impaired salivary gland function, salivary flow is reduced. Zeng, Ma et al. (2019) showed that under these conditions, forming a stable multilayer pellicle takes longer. Simultaneously, there is increased adsorption of loosely bound protein aggregates. While these may be more easily removed under mechanical load, they likely contribute to a thicker outer layer that enhances lubrication during periods of low salivary flow and minimal load, such as between teeth and the oral mucosa during sleep (Zeng, Ma, et al., 2019).

The characteristics of enamel itself can further influence pellicle-mediated lubrication. Wang et al. (2024) investigated pellicle formation on deproteinised enamel and their findings showed that the resulting pellicle had a higher friction coefficient, which was attributed to reduced protein adsorption due to enamel crystallite aggregation and decreased surface area. These results highlight the importance of the substrate in modulating pellicle formation and suggest that changes to the dental surface may impair the pellicles' lubricating properties (Wang et al., 2024).

Environmental and behavioural factors may also play a role. Zeng et al. (2017) examined the effects of alcohol rinsing on pellicle formation, prompted by clinical reports of increased tooth wear in individuals with high alcohol consumption. Although alcohol stimulated saliva secretion and increased protein content, it led to pellicles with higher friction coefficient and a disorganized structure, likely due to protein denaturation and impaired multilayer formation. Compared to the control, this pellicle exhibited a heterogeneous structure lacking the typical multilayer organization and containing more agglomerates, likely due to alcohol-induced protein denaturation. This structural instability may contribute to the increased wear observed in alcoholics, as the pellicle appears more susceptible to mechanical removal (Zeng et al., 2017). Similarly, Lei et al. (2022) investigated the influence of dietary polyphenols, which are known to interact with salivary proteins and induce aggregation (Lei et al., 2022). While such modifications may enhance resistance to erosion and bacterial adhesion (Câmara et al., 2025), they were also associated with increased friction, possibly reflecting reduced mechanical stability under load. This interpretation finds support in investigations of great apes, where polyphenol-rich diets are linked to pronounced tooth discoloration, whereas a human-like diet consisting of softer foods and lower polyphenol intake is associated with reduced abrasion (Albrecht et al., 2024). In contrast, Zeng, Zheng et al. (2019) found that elevated salivary calcium concentrations reduced friction, likely by promoting protein–protein interactions of the predominantly negatively charged proteins within the pellicle. However, this effect was accompanied by weakened protein–enamel binding, highlighting the limitation of considering frictional data alone (Zeng, Zheng, et al., 2019).

Taken together, the friction coefficient may offer a useful, albeit indirect, indication of pellicle behaviour under mechanical stress. Lower values are generally observed in smooth, dense, initial pellicles or when salivary flow is high. In contrast, as the pellicle matures, outer layers composed of loosely bound larger protein aggregates tend to increase surface roughness and friction, a pattern also observed following exposure to alcohol, polyphenols, or under reduced salivary flow. While these associations are suggestive, no pellicle studies to date have demonstrated a direct correlation between friction coefficients and abrasion resistance.

4.5. Pellicle viscoelasticity

Viscoelasticity describes a material's viscous and elastic responses to deformation, reflecting its ability to store and dissipate energy over time. The viscoelastic properties of the pellicle were included as an outcome measure in this review because they may be associated with its protective properties and resistance to mechanical removal (Fukada et al., 2015; Zhang & Meng, 2015). In the included studies, viscoelasticity was assessed using quartz crystal microbalance with dissipation monitoring (QCM-D), but only measurements obtained using hydroxyapatite-coated sensors were considered. These coatings provide a more realistic substrate for pellicle formation compared to uncoated quartz surfaces.

Consistent with findings from friction measurements, pellicles formed under conditions that favour the accumulation of larger protein aggregates, such as those derived from crude rather than purified mucin (Smart & Bryant, 2023), whole human saliva versus parotid saliva (Ash et al., 2014), unfiltered compared to filtered saliva (Barrantes et al., 2014), and under low salivary flow (Zeng, Ma, et al., 2019), exhibited higher viscoelasticity. This increase is attributed to the formation of a heterogeneous and loosely organized pellicle structure, enriched with high-molecular-weight mucins. Conversely, pellicle viscoelasticity can be modulated by stannous fluoride, which interacts with proteins via divalent stannous ions, resulting in a more rigid and condensed layer (Veeregowda et al., 2011).

Despite these trends, studies that evaluated both viscoelasticity and friction coefficients have reported inconsistent relationships. Some found a negative correlation (Smart & Bryant, 2023; Wang et al., 2024; Zeng, Zheng, et al., 2019), while others reported a positive correlation (Zeng, Ma, et al., 2019). Although the limited number of investigations precludes definitive conclusions regarding the relationship between viscoelasticity, friction, and abrasion resistance, the pellicle, as a viscoelastic film, may reduce friction and wear through energy dissipation. Unlike water, the pellicle is compressible and may distribute applied energy via deformation (Hu et al., 2013; Zhang & Meng, 2015) (Fig. 2).

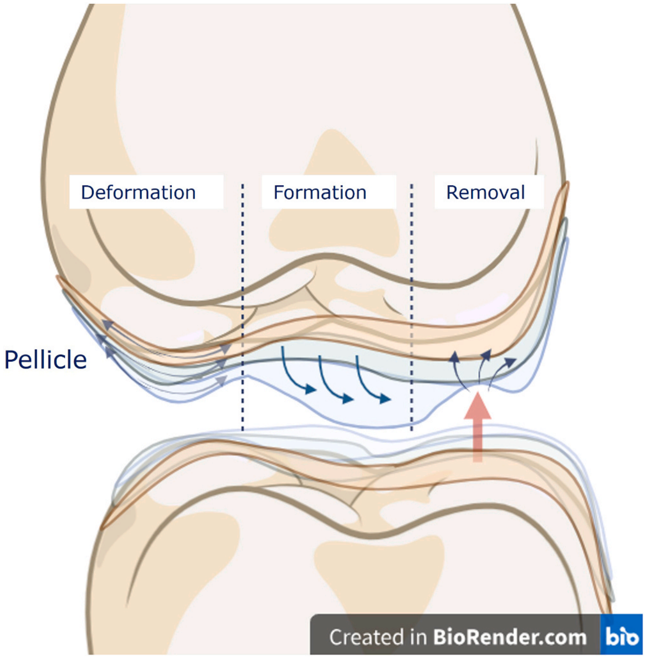

Fig. 2. Schematic illustration of the viscoelastic salivary pellicle formed on opposing dental surfaces under load. The pellicle may contribute to boundary lubrication and undergo deformation, enabling energy dissipation. Although it is gradually removed during repeated sliding, it rapidly reforms through the adsorption of salivary proteins.

5. Limitations

This review focused on dental and hydroxyapatite surfaces, excluding other substrates such as dental restorative materials. While the structure and composition of the pellicle appear to be largely substrate-independent and could (Hannig, 1997; Trautmann et al., 2022), in principle, extend to other substrates or dental restorative materials, the relevance of its protective properties on materials with modifiable abrasion resistance remains uncertain. To ensure better comparability, only healthy individuals were included in the in-situ experiments and as saliva donors, which helped to clarify the physiological functions of the pellicle. However, it is still unclear whether individuals with reduced salivary flow may form pellicles with altered protective characteristics, especially since reduced saliva has been associated with increased multifactorial tooth wear (Young, 1998). Although 26 studies were included, the literature search was limited to three databases and restricted to publications in English or German, meaning that relevant studies published in other languages or found in grey literature may have been overlooked. For reasons of reproducibility, no supplementary approaches to identify studies were performed, and review articles were not included, which may have led to the omission of additional relevant sources not captured by the selected databases. Moreover, the studies primarily focused on the enamel pellicle or used hydroxyapatite as a substitute, while the dentine pellicle remains a largely neglected area of research, as also noted in a recent review (Rasputnis et al., 2021). When the type of saliva was specified, it was typically unstimulated, even though saliva is naturally stimulated during wear-related activities such as chewing and differs from unstimulated saliva in both flow rate and composition (Proctor, 2016). The influence of stimulated saliva on the pellicles' protective functions against mechanical wear remains unclear. Finally, only a few studies investigated actual wear, and the majority were conducted *in vitro*. Therefore, the findings of this review should be interpreted with caution, as they do not allow for a fully comprehensive evaluation of the pellicles' roles in protecting dental hard tissues against mechanical stress. Under clinical conditions, tooth wear is influenced by multiple dynamic and heterogeneous factors that cannot be fully replicated *in vitro* or *in situ* and is further modulated by chemical processes that reduce the mechanical load required for tissue loss (Shellis & Addy, 2025). Although the pellicle is involved in all interfacial processes, including both chemical and mechanical, this review focused on the mechanical perspective to better clarify its contribution to the complex wear process.

5.1. Outlook

The pellicle may protect against mechanical wear through various mechanisms. While the studies reviewed suggest boundary lubrication as the main contributor, many aspects of this process remain unclear. Other factors known from tribology, such as surface energy, adhesion and cohesion, hydration layers, and energy dissipation, could also influence its protective function (Hu et al., 2013; Zhang & Meng, 2015). Investigating these factors could not only advance our understanding of the pellicles' physiological functions but also support the development of effective saliva substitutes for individuals with impaired salivary gland function or elevated mechanical stress. Existing saliva substitutes primarily aim to reduce friction between teeth and mucosa, often using mucins due to their ability to form a lubricating hydration layer that lowers friction at low loads (Aguirre et al., 1989; Reeh et al., 1995, 1996; Smart & Bryant, 2023). However, under higher loads, the intrinsic abrasion resistance of the pellicle itself may become increasingly relevant. Future research should therefore examine the abrasion resistance of the pellicle under both physiological and pathological conditions, considering variables such as pellicle morphology, composition, and mechanical properties. It remains uncertain whether the parameters addressed in this review, specifically the coefficient of friction and viscoelasticity, are reliable predictors of abrasion resistance. In addition to mucins, statherin deserves further attention, as it has demonstrated promising lubricating properties in a limited number of studies (Douglas et al., 1991; Reeh et al., 1995). Given its strong affinity for hydroxyapatite, which may relate to abrasion resistance, as well as its known protective role against erosion, statherin could be a key factor in preventing multifactorial tooth wear and represents a promising candidate for inclusion in saliva substitutes (Câmara et al., 2025). Finally, whether mechanical wear should be considered problematic is a matter of debate, given that human dentition is adapted to respond to it (Albrecht et al., 2024; Kaidonis, 2008; Kaifu et al., 2003). A lack of wear may even interfere with natural dental development and contribute to malocclusion (Kaifu et al., 2003). Wear may become problematic when it leads to premature tooth loss or pulp exposure, although such cases are rarely observed in anthropological studies (Albrecht et al., 2024; Kaidonis, 2008). The long-term implications of reduced wear on dental morphology and function remain insufficiently understood and warrant further investigation, particularly in contexts where pellicle formation may be impaired by hyposalivation or disrupted by chemical agents (Faruque et al., 2022; Schestakow et al., 2022, 2024), conditions that may be less relevant in other mammals (Albrecht et al., 2024).

6. Conclusions

Regarding both research questions of this scoping review, (1) the available evidence indicates that the pellicle may offer limited protection against mechanical wear, and (2) this effect is likely attributable to a boundary lubrication regime. Although numerous studies report reductions in friction and wear associated with the presence of a pellicle, data concerning its structural integrity and resistance under mechanical stress remain sparse and inconclusive. Further research is required to understand the underlying mechanisms and to validate different parameters in clinically relevant settings.

CRediT authorship contribution statement

Anton Schestakow: Writing – original draft, Methodology, Investigation. **Clara Theres Meyer-Probst:** Writing – review & editing, Visualization, Methodology, Investigation. **Matthias Hannig:** Writing – review & editing, Funding acquisition, Conceptualization. **Christian Hannig:** Writing – review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Matthias Hannig reports financial support was provided by German Research Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.archoralbio.2026.106551.

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