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Tribological aspects of enamel wear caused by zirconia and lithium disilicate: A meta-narrative review

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ABSTRACT

The contact between enamel and an antagonist surface is the primary factor in tooth wear. Loss of tooth structure can cause changes in occlusion, chewing functionality, dental sensitivity, and appearance. However, enamel wear caused by opposing restorations is multifactorial and there is a lack of consensus regarding its behavior. This meta-narrative review assesses the multiple factors that affect enamel wear when using two common indirect restorative materials, lithium disilicate and zirconia. PubMed, Google Scholar, MEDLINE, and CINAHL databases were searched using keywords “zirconia,” “lithium disilicate,” “antagonistic tooth wear,” and “enamel wear” to identify studies related to enamel wear caused by zirconia and lithium disilicate restorations. The Realist and Meta-narrative Evidence Syntheses: Evolving Standards (RAMESES) publication standard was used to report this meta-narrative literature review. Four broad categories of influencing factors were identified and reviewed: (1) mechanical and physical properties, (2) wear behavior and microstructural characteristics, (3) surface state, and (4) environmental factors. We conclude that well-polished zirconia is a more favorable indirect restorative material than lithium disilicate in terms of tribology because of its microstructure and surface integrity during wear. This review will enable clinicians to better comprehend the intricate nature of tooth wear caused by dental restorations.

1. Introduction

Within dentistry, four distinct terms are used to describe the wear mechanisms of teeth and dental materials: attrition, abrasion, abfraction, and erosion. This nomenclature differs from that used in conventional tribology; in certain instances, it may be misleading [1,2]. Wear is not a property of a material but rather a response of a system [3]. In the oral cavity, contact wear occurs between tooth and tooth or between tooth and restorative material. Notably, contact wear can be accelerated when the properties of the restorative material differ from those of hard dental tissue. This is particularly the case for materials with higher toughness, increased fracture resistance, altered surface roughness, increased frictional resistance, or increased hardness compared to teeth [4,5]. Occlusal antagonist contact is a fundamental factor in contact wear [6]. Hence, the restorative materials used as antagonists can significantly alter tooth wear [1].

Computer-aided design and manufacturing (CAD-CAM) methodologies have facilitated the fabrication of monolithic restorations from zirconia or glass-ceramics. These ceramic restorations have gained popularity owing to their enhanced aesthetic outcomes. In addition, surface treatments such as polishing and glazing are often used to achieve a smooth surface [7]. However, ceramic restorations tend to cause significant abrasion of the opposing enamel surface [1]. Considering recent advancements in dental technology and materials, a better understanding of the extent of wear of natural teeth caused by ceramic antagonists is important. Few *in vivo* studies have justified the clinical use of some ceramic restorations from the perspective of enamel wear. For instance, zirconia has been widely studied owing to its high hardness. However, few studies have explored lithium disilicate glass-ceramics because their compositions vary significantly [5].

Loss of tooth structure can cause changes in occlusion and has implications for chewing functionality, dental sensitivity, and appearance

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[8,9]. The issue of tooth wear is becoming increasingly significant because aging populations mean teeth are required to last longer. Understanding the mechanisms underlying tooth wear can contribute to the advancement of superior restorative materials [5]. Therefore, it is important to comprehensively assess the tribological performance of restorative materials [9].

Various types of zirconia are used in dental restorations. The earliest zirconia restorations comprised 3 mol% yttria-stabilized zirconia (3YSZ), which has exceptional strength and toughness. Subsequently, highly translucent 3YSZ was introduced, which has a lower alumina content. This was followed by 4 and 5 mol% yttria-stabilized zirconia (4YSZ and 5YSZ, respectively), which offer even greater translucency. Ultra-translucent zirconia exhibits remarkable translucency and flexural strength; its translucency is similar to that of lithium disilicate, while its flexural strength is comparable to that of 5YSZ [10]. Recently, two novel types of zirconia have been introduced: shade-gradient zirconia with a uniform yttria content, and strength-gradient zirconia with a varying yttria content in a single disk [11]. Lithium disilicate glass-ceramic is another common dental material. Its composition varies widely depending on the content of oxides such as silica, lithium oxide, and potassium oxide [12]. Recently, zirconia-reinforced lithium disilicate glass-ceramics have also been introduced commercially. These materials have mechanical properties similar to those of zirconia and aesthetic qualities similar to those of lithium disilicate [13].

Numerous *in vitro* and *in vivo* investigations have been conducted to assess factors influencing the wear of enamel antagonists. Nevertheless, there is a lack of consensus regarding enamel wear behavior against commonly used dental ceramics. Thus, the effects of different restorative materials on enamel wear and the factors influencing the wear mechanisms need to be comprehensively analyzed. Consequently, in this meta-narrative review, we aimed to assess the multiple factors affecting enamel wear against two common indirect restorative dental materials, namely, zirconia and lithium disilicate glass-ceramics. A literature search revealed 98 studies that aligned with the stated objectives, published between 2001 and 2023. A total of 12 factors influencing the wear behavior of zirconia and lithium disilicate glass-ceramics were identified and classified into four broad categories: (1) mechanical and physical properties, (2) wear behavior and microstructural characteristics, (3) surface state, and (4) environmental factors. This review advances our understanding of tribology in dentistry and will stimulate further research in this area.

2. Materials and methods

When faced with extensive volumes of information, such as literature on dental ceramics, a careful and detailed approach is essential to analyze a given topic. Herein, the Realist and Meta-narrative Evidence Syntheses: Evolving Standards (RAMESES) publication standard was adopted to conduct a meta-narrative literature review [14]. This methodology is useful for exploring the intricate mechanisms underlying various complex and interacting phenomena. We chose a realistic approach because it provides a rationale and tools for understanding complex wear phenomena, which are characterized by multiple influencing factors and inter-study variation in the test methods. The meta-narrative approach aims to extract and examine the complete spectrum of philosophical viewpoints in the primary literature. The methods and techniques, as indicated in Refs. [14–16], were tailored to align with the specific objectives of this review. This meta-narrative review was conducted in three steps: study design, literature search, and analysis.

2.1. Study design

This review aimed to identify factors influencing enamel wear against zirconia and lithium disilicate glass-ceramic antagonists. Each factor was evaluated using a meta-narrative approach.

2.2. Literature search

The literature search was iterative and was continued continuously throughout the review process. The PubMed, Google Scholar, MEDLINE, and CINAHL databases were searched using keywords "zirconia," "lithium disilicate," "antagonist tooth wear," and "enamel wear." In total, 1139 manuscripts were identified during the initial search: 234 from PubMed, 750 from Google Scholar, 123 from MEDLINE, and 32 from CINAHL. In the first screening, titles were reviewed for duplication. After removing duplicates ($n = 970$), titles and abstracts were reviewed to determine the relevance of the articles to this narrative review. The shortlisted articles ($n = 169$) underwent a full-text review in the context of the current objectives. Additionally, a "snowballing" method was employed, wherein the references of each article were surveyed to discover additional articles for evaluation ($n = 6$). The final articles ($n = 98$) were categorized depending on the study type: *in vitro* study ($n = 67$), *in vivo* study ($n = 16$), in vivo and *in vitro* study ($n = 1$), systematic review ($n = 9$), or literature review ($n = 5$) (see Fig. 1). The final articles were all published between 2001 and 2023.

2.3. Analysis

A macro analysis of the selected manuscripts was conducted. To assess the wear behavior of enamel antagonists by zirconia and lithium disilicate dental ceramics, we broadly classified the influencing factors into four categories (Fig. 2): (1) mechanical and physical properties, (2) wear behavior and microstructural characteristics, (3) surface state, and (4) environmental factors.

This meta-narrative review evaluated two commonly used dental ceramics, zirconia and lithium disilicate glass-ceramics, as antagonists of human enamel ($n = 57$) or bovine enamel ($n = 3$). The types of zirconia included 3YSZ ($n = 42$), 4YSZ ($n = 3$), 5YSZ ($n = 13$), 6YSZ (n = 3), and strength-gradient zirconia ($n = 1$), while the types of lithium disilicate glass-ceramics included lithium disilicate (various compositions; $n = 30$) and zirconia-reinforced lithium disilicate ($n = 3$). Most of the restorations were monolithic ceramic restorations; however, one of the reviewed studies included lithium disilicate bonded to a zirconia framework, which we grouped with the monolithic lithium disilicate restorations.

We assessed the impact of these materials, along with a range of parameters, on the overall wear behavior of enamel. Therefore, we reviewed parameters that influence wear characteristics within the oral environment and contribute to the occurrence of failure, whether they exhibit a direct or indirect correlation.

3. Results and discussion

A total of 12 parameters were identified, and 169 studies that aligned with the stated objectives were selected. After full-text review, we selected 92 manuscripts, along with six additional manuscripts from snowballing, from which to analyze the multiple factors influencing the wear behavior of zirconia and lithium disilicate glass-ceramics. The types of zirconia and lithium disilicate used and the enamel antagonists are summarized in Table 1.

3.1. Mechanical and physical properties

Dental wear is a multifaceted phenomenon characterized by the removal of a material upon direct contact with its antagonist. The bio-tribological and microstructural properties of dental materials must be very similar to those of natural enamel. The physical, chemical, surface, and microstructural characteristics of dental ceramics all contribute to the wear behavior of natural enamel [17].

3.1.1. Hardness

Hardness is defined as resistance to plastic deformation. Because the

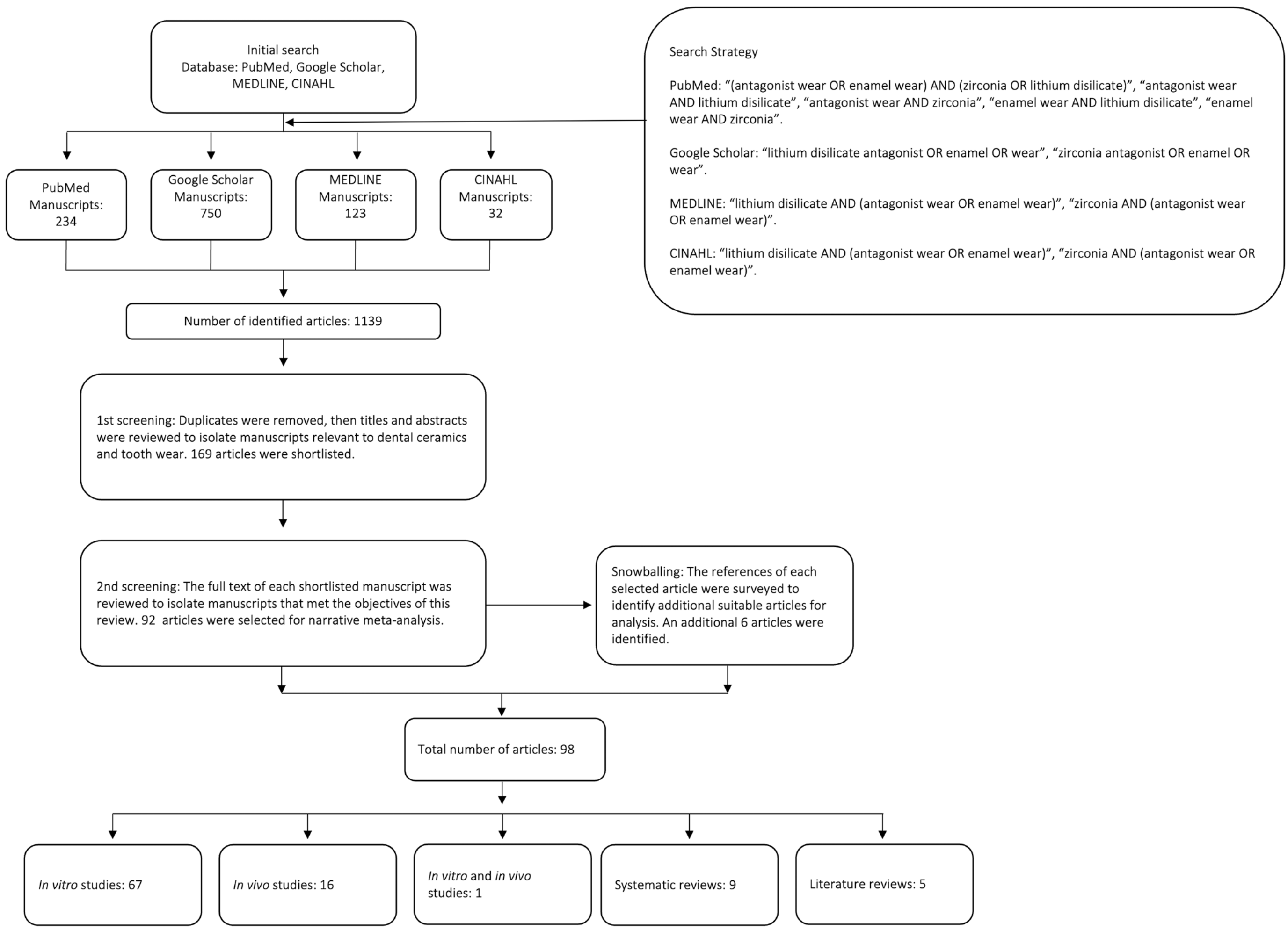

Fig. 1. Flow chart for selection of relevant manuscripts.

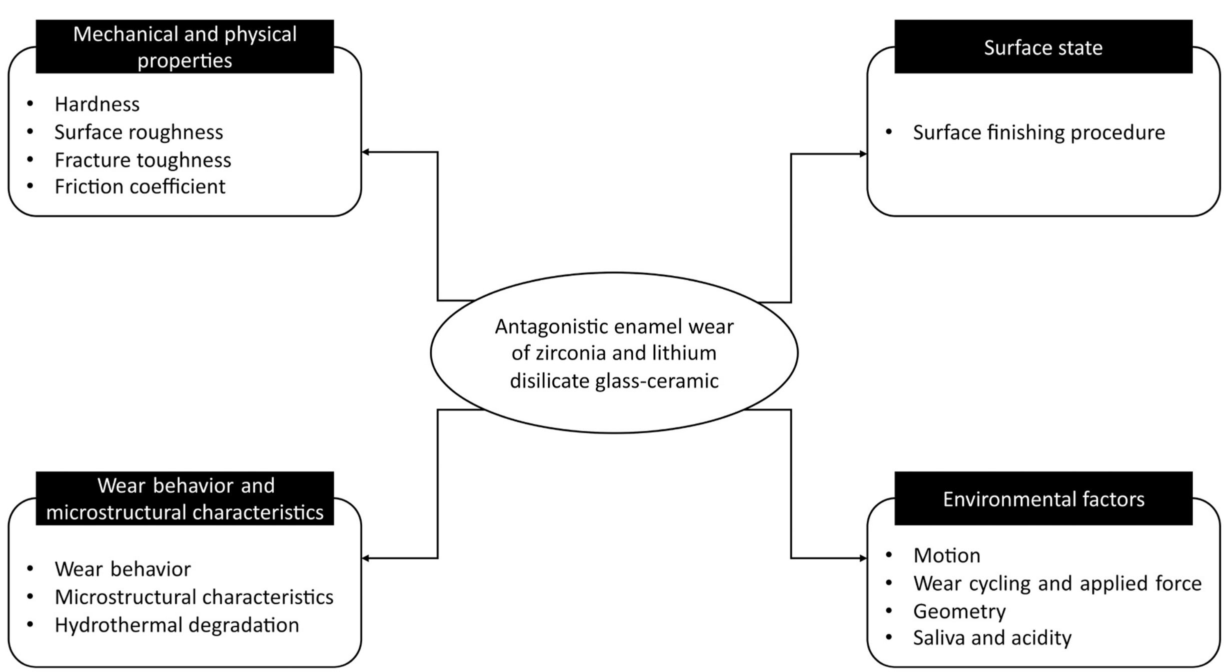

Fig. 2. Categorization of factors influencing antagonist enamel wear caused by zirconia and lithium disilicate glass-ceramics.

Table 1
Summary of restoration material, antagonist enamel, and study types used in the selected articles.

Material tested	Type	Studies
Zirconia	3YSZ	*In vitro*: $n = 32$[4,7,8,12,19,28,32–34,36–38,42,43,45–47,49,55–58,65,67–70,76,77,79,97,105] *In vivo*: $n = 10$[46,51,70,84–88,91,106]
	4YSZ	*In vitro*: $n = 3$[40,60,62]
	5YSZ	*In vitro*: $n = 13$[9,22,23,30,35,37,41,53,54,56,61,99,100]
	6YSZ	*In vitro*: $n = 3$[30,35,40]
	Strength-gradient zirconia	*In vitro*: $n = 1$[61]
Glass-ceramic	Lithium disilicate	*In vitro*: $n = 26$[8,12,28,29,31,34–36,40,42,43,49,52–56,61,63,65,67,72,78,98,100,104] *In vivo*: $n = 4$[6,51,80,94]
	Zirconia-reinforced lithium disilicate	*In vitro*: $n = 3$[28,35,47]
Enamel antagonist	Bovine enamel	$n = 3$[12,68,99]
	Permanent molar	$n = 28$[4,7,13,15,17–20,23,24,26,28,36,38,39,42,43,53–55,58,64,70–75]
	Permanent premolar	$n = 24$[8,19,29,30,32,35,37–39,41,48,53,54,57,58,65,67,70,73,75,76,78,95,104]
	Permanent incisor	$n = 3$[25,26,69]
	Primary canine	$n = 1$[22]
	Primary second molar	$n = 1$[49]

Abbreviations: 3YSZ = 3 mol% yttria-stabilized zirconia, 4YSZ = 4 mol% yttria-stabilized zirconia, 5YSZ = 5 mol% yttria-stabilized zirconia, 6YSZ = 6 mol% yttria-stabilized zirconia. Note: The numbers of studies in the table do not total the number of articles reviewed, because many articles included multiple materials, types of teeth, or study types, and several articles did not report this information.

dulling of sharp edges in fractured ceramics is hindered by their limited susceptibility to plastic deformation [18], the rough asperities of ceramics may cause significant wear to enamel antagonists as wear continues. Conventionally, hardness is used to estimate the wear caused by restorative dental materials [19]. More wear is thought to occur when the antagonist has high surface hardness [20], and the role of hardness in wear has been reported [17,18]. However, no relationship between ceramic hardness and the rate of enamel wear in humans has been established [9,17,21].

Zirconia ceramics have high hardness. Therefore, researchers were initially concerned about enamel wear when using zirconia restorations, particularly monolithic restorations [20,21]. However, Hatanaka *et al.* [12] reported that the wear of bovine tooth enamel is lower when paired with a dental material with higher hardness than one with lower hardness. Therefore, despite having lower hardness than zirconia, lithium disilicate glass-ceramics can induce more significant enamel wear [22]. In fact, there is no correlation between surface hardness and antagonist enamel wear when comparing zirconia with the relatively soft feldspathic porcelain [23].

In the context of ceramic materials, when a ceramic surface contacts another ceramic or enamel surface, the wear mechanism differs from that observed for metals. Unlike metals, ceramics primarily experience wear through fracture rather than plastic deformation [18]. This implies that enamel wear may be determined not only by the hardness of the material [1,18,24], but also by other mechanical properties and microstructural features.

3.1.2. Surface roughness

Smooth ceramic surfaces are crucial for minimizing antagonist enamel wear. Surface roughness also plays a significant role in ensuring the structural integrity of the material. This is because surface roughness can weaken the ceramic, increasing the likelihood of chipping [25]. Moreover, these chips may act as third-body abrasive particles, causing more wear on the opposing tooth. Therefore, the degree of enamel wear appears to be well-predicted by the surface roughness of the antagonist [26]. Consequently, achieving optimally smooth surfaces is necessary for the long-term success of ceramic restorations.

Polished monolithic zirconia typically has lower surface roughness than glazed [7,26,27] and ground zirconia [7]. However, Çakmak *et al.* [28] reported lower surface roughness for glazed zirconia than polished zirconia, and Cherian *et al.* [29] concluded that polishing could be a favorable alternative to glazing for reducing wear on antagonist teeth. These inconsistent findings can be attributed to the different compositions and fabrication methods of glazing materials. Therefore, well-designed studies are needed to evaluate the effects of different glazing materials and fabrication methods on the surface roughness of dental restorations.

Enamel wear is exacerbated when the antagonist has increased surface roughness [30]. For example, enamel wear is greatly increased when the antagonist surface roughness (R_a) exceeds 1.5 µm [31]. This value is significant because the burs used for clinical adjustments produce this extent of surface roughness on dental restorations [31]. The findings of Mehzabeen *et al.* [32] and Rodríguez-Rojas *et al.* [33] support this result. Specifically, they indicate that the polishing degree has a statistically significant effect on the surface roughness (R_a) of zirconia. However, their experiments did not yield any statistically significant differences in the amount of wear induced on the opposing enamel [33]. Furthermore, roughening of polished zirconia does not cause significant antagonist enamel wear [32] as long as the surface roughness remains well below than the $R_a = 1.5$ µm threshold [32,33]. Therefore, maintaining a smooth ceramic surface is important. It is recommended that roughened occlusal contact areas are regularly repolished [34]. Table 2 lists the surface roughness of various zirconia and lithium disilicate ceramics with different surface finishes.

3.1.3. Fracture toughness

Restorative ceramic materials that lack fracture toughness may undergo brittle chipping during abrasive wear. Brittle chipping can resharpen particle edges, resulting in an increased wear rate [18]. The fracture resistance of zirconia is significantly higher than that of lithium disilicate glass-ceramics, and its crystalline structure hinders microcrack propagation, making it less prone to the formation of microfractures along the surface [35,36]. The glazing on zirconia has low fracture toughness; therefore, the glazing layer is prone to brittle chipping, producing sharp particles that act as abrasive media [26,30]. Furthermore, materials with lower toughness are associated with high cusp wear. The detachment of large angular particles can cause surface damage to the cusps, resulting in increased antagonist wear [9].

Sripetchdanond and Leevailoj [36] reported that microfracture is the predominant ceramic wear mechanism and that fracture toughness is key to preventing microfractures. However, 5YSZ exhibits less wear than lithium disilicate glass-ceramics, despite having similar fracture toughness [35]. Furthermore, among zirconia, 3YSZ induces the highest wear of antagonist enamel, followed by highly translucent 3YSZ; 5YSZ induces the least wear [37]. Therefore, fracture toughness alone is not a good predictor of antagonist enamel wear.

3.1.4. Friction coefficient

In tribology, the friction coefficient is a crucial parameter that reflects the intrinsic interaction between two surfaces. For optimal masticatory function and minimal wear of natural teeth, the friction coefficient of dental restorations should be appropriately matched with that of natural teeth [38]. The friction coefficient is influenced by several factors, including geometric parameters such as the surface roughness, shape, and area of the contact materials. Patients with a broader range of movements or parafunctional habits, along with increased masticatory load and/or sliding velocity, are more likely to produce an increased friction coefficient, leading to increased wear

Table 2
Surface conditions and surface roughness of zirconia and lithium disilicate before and after wear tests.

Table 2 (*continued*)

Year	Author (s)	Study type	Material and surface finish	Initial surface roughness	Surface roughness after wear test (mean value)
2016	Nakashima *et al.* [8]	*In vitro*	Polished zirconia Polished lithium disilicate	$R_a = 0.5$ µm $R_a = 0.4$ µm	N/A
2018	Santos *et al.* [9]	*In vitro*	Polished zirconia	$S_a = 21$ nm	N/A
2013	Janyavula *et al.* [26]	*In vitro*	Polished zirconia Glazed zirconia Polished and reglazed zirconia	$R_a = 0.17$ µm $R_a = 0.76$ µm $R_a = 0.69$ µm	N/A
2012	Mitov *et al.* [7]	*In vitro*	Polished zirconia Ground (30 µm diamond bur) Ground (100 µm diamond bur) Glazed zirconia Polished glass ceramic	$R_a = 0.006$ µm Presented in a figure Presented in a figure Presented in a figure Presented in a figure	N/A
2022	Shaik *et al.* [27]	*In vitro*	Polished zirconia Glazed zirconia	$R_a = 0.19$ µm $R_a = 0.30$ µm	$R_a = 0.26$ µm $R_a = 0.50$ µm
2014	Lawson *et al.* [31]	*In vitro*	Adjusted lithium disilicate Adjusted and polished lithium disilicate Adjusted and glazed lithium disilicate Adjusted zirconia Adjusted and polished zirconia Adjusted and glazed zirconia	$R_a = 1.68$ µm $R_a = 0.56$ µm $R_a = 0.91$ µm $R_a = 2.73$ µm $R_a = 1.11$ µm $R_a = 0.82$ µm	N/A
2022	Fouda *et al.* [35]	*In vitro*	Polished and glazed partially crystalized lithium disilicate Polished fully crystalized lithium disilicate Polished zirconia-reinforced lithium silicate Polished super-translucent monolithic zirconia Polished ultra-translucent monolithic zirconia	$R_a = 0.55$ µm $R_a = 0.69$ µm $R_a = 0.45$ µm $R_a = 0.59$ µm $R_a = 0.54$ µm	$R_a = 1.83$ µm $R_a = 1.06$ µm $R_a = 0.85$ µm $R_a = 0.53$ µm $R_a = 0.51$ µm
2016	Preis *et al.* [34]	*In vitro*	Glazed zirconia Glazed, ground and polished zirconia Glazed, ground and polished lithium disilicate Glazed and ground Cercon ht zirconia and lithium disilicate	$R_a = 4.84$ µm $R_a = 4.59$ µm $R_a = 6.68$ µm $R_a \leq 12.05$ µm	N/A
2020	Emam *et al.* [30]	*In vitro*	Glazed zirconia Polished zirconia	$R_a = 1.479$ µm $R_a = 1.459$ µm	$R_a = 1.903$ µm $R_a = 1.802$ µm
2014	Amer *et al.* [52]	*In vitro*	Rough zirconia Polished zirconia Polished and glazed zirconia Rough lithium disilicate Polished lithium disilicate Polished and glazed lithium disilicate	$R_a = 0.435$ µm $R_a = 0.119$ µm $R_a = 0.317$ µm $R_a = 1.371$ µm $R_a = 0.247$ µm $R_a = 0.357$ µm	N/A
2012	Kim *et al.* [104]	*In vitro*	Ground Prettau zirconia (600 grit silicon carbide paper) Ground Lava zirconia (600 grit silicon carbide paper) Ground Rainbow zirconia (600 grit silicon carbide paper) Ground lithium disilicate (600 grit silicon carbide paper) Ground Prettau zirconia (1200 grit silicon carbide paper) Ground Lava zirconia (1200 grit silicon carbide paper) Ground Rainbow zirconia (1200 grit silicon carbide paper) Ground	$R_a = 0.784$ µm $R_a = 0.785$ µm $R_a = 0.678$ µm $R_a = 0.455$ µm $R_a = 0.284$ µm $R_a = 0.459$ µm $R_a = 0.411$ µm $R_a = 0.249$ µm	N/A

(*continued on next page*)

Table 2 (*continued*)

Year	Author (s)	Study type	Material and surface finish	Initial surface roughness	Surface roughness after wear test (mean value)
			lithium disilicate (1200 grit silicon carbide paper)		
2022	Rodríguez-Rojas *et al.* [33]	*In vitro*	Polished zirconia (15 μm) Polished zirconia (6 μm) Polished zirconia (1 μm)	0.077 μm 0.059 μm 0.024 μm	N/A
2020	Branco *et al.* [45]	*In vitro*	Polished robocasting 3D printed zirconia Polished unidirectional compression 3D printed zirconia	$R_a = 241$ nm $R_a = 62$ nm	N/A
2012	Rosentritt *et al.* [55]	*In vitro*	Polished lithium disilicate Polished Vita In-Ceram YZ zirconia Polished ICE Zircon Prettau zirconia Polished ICE Zircon Translucent zirconia	$R_a = 0.3$ μm; $R_z = 1.9$ μm $R_a = 0.1$ μm; $R_z = 0.9$ μm $R_a = 0.1$ μm; $R_z = 0.8$ μm $R_a = 0.1$ μm; $R_z = 1.0$ μm	N/A
2019	Habib *et al.* [53]	*In vitro*	Glazed zirconia Glazed lithium disilicate	$R_a = 0.67$ μm $R_a = 0.35$ μm	$R_a = 0.96$ μm $R_a = 1.04$ μm
2021	Hajhamid *et al.* [57]	*In vitro* and *in vivo*	Zirconia irradiated with 70 Gy	$R_a = 2.66$ μm $R_a = 6.52$ and 4.63 μm	$R_a = 3.12$ μm $R_a = 7.63$ and 5.06 μm
2018	Hao *et al.* [65]	*In vitro*	Aged zirconia Non-aged zirconia	$R_a = 0.038$ μm $R_a = 0.040$ μm	Presented in a graph
2019	Yang *et al.* [70]	*In vitro* and *in vivo*	Polished Rainbow zirconia Polished Katana zirconia	$R_a = 0.78$ μm $R_a = 1.06$ μm	$R_a = 0.76$ μm $R_a = 1.14$ μm
2020	Mehzabeen *et al.* [32]	*In vitro*	Laboratory polished zirconia Laboratory polished and clinically adjusted zirconia	$R_a = 0.1058$ μm $R_a = 0.7174$ μm	N/A
2011	Preis *et al.* [4]	*In vitro*	Polished zirconia Polished and glazed zirconia Sandblasted and glazed zirconia	N/A	$R_a = 0.1$ μm $R_a = 0.1$ μm $R_a = 0.1$ μm
2020	Ryu *et al.* [73]	*In vitro*	Untreated zirconia	N/A	$R_a = 0.20$ μm

Table 2 (*continued*)

Year	Author (s)	Study type	Material and surface finish	Initial surface roughness	Surface roughness after wear test (mean value)
			Glazed zirconia (IPS e.max Ceram) Glazed zirconia (VITA AKZENT® Plus) Glazed zirconia (glass)		$R_a = 0.25$ μm $R_a = 0.16$ μm $R_a = 0.38$ μm
2022	Rouchdy *et al.* [80]	*In vivo*	Polished Glazed	N/A	R_a (at 2, 4, 6, 8, 10, and 12 months) = 0.0654, 0.0508, 0.057, 0.0525, 0.0565, and 0.0818 μm R_a (at 2, 4, 6, 8, 10, and 12 months) = 0.1117, 0.1503, 0.1671, 0.1664, 0.161, and 0.1731 μm
2013	Figueiredo-Pina *et al.* [105]	*In vitro*	Polished zirconia	$R_a = 1.27$ μm; $R_t = 8.11$ μm; $R_p = 3.76$ μm; $R_z = 6.05$ μm	$R = 1.36$ μm; $R_t = 10.64$ μm; $R_p = 4.50$ μm; $R_z = 8.16$ μm
2023	Çakmak *et al.* [28]	*In vitro*	Glazed zirconia Polished zirconia Glazed lithium disilicate Polished lithium disilicate Glazed zirconia-reinforced lithium disilicate Polished zirconia-reinforced lithium disilicate	$R_a = 0.15$ μm $R_a = 1.12$ μm $R_a = 0.19$ μm $R_a = 0.66$ μm $R_a = 0.33$ μm $R_a = 0.95$ μm	N/A
2021	Tachibana *et al.* [42]	*In vitro*	Polished zirconia (experiments 1, 2, and 3) Ground zirconia (experiments 1, 2, and 3) Polished lithium disilicate (experiments 1, 2, and 3) Ground lithium disilicate (experiments 1, 2, and 3)	$R_a = 0.02$, 0.02, and 0.03 μm $R_a = 3.16$, 3.18, and 3.17 μm $R_a = 0.04$, 0.05, and 0.05 μm $R_a = 2.24$, 2.24, and 2.25 μm	$R_a = 0.03$, 0.03, and 0.03 μm $R_a = 3.30$, 3.19, and 3.23 μm $R_a = 0.23$, 0.12, and 0.42 μm $R_a = 0.34$, 1.32, and 0.35 μm

Abbreviation: R_a = average roughness, R_z = mean roughness depth, R_t = maximum peak to valley height, R_p = maximum profile peak height according to roughness profile, S_a = arithmetical mean height of a line, N/A = not applicable.

[18]. Furthermore, the friction coefficients between enamel and dental materials vary based on the hardness, elastic modulus, and surface finish of the materials. Polished zirconia and veneering ceramics exhibit relatively high average friction coefficients with enamel of approximately 0.55, whereas that between enamel and lithium disilicate glass-ceramics is 0.61. The highest recorded friction coefficient between enamel and rough zirconia is 0.65 [38].

Glass-ceramics are composed of crystalline particles surrounded by a weak glassy matrix [20]. Therefore, in the context of abrasive wear between enamel and lithium disilicate glass-ceramics, the glass matrix wears more quickly than the lithium disilicate crystalline grains. This is attributed to the relatively low strength and hardness of the glass matrix. The resultant increase in surface roughness increases the maximum friction coefficient [38]. However, the surface roughness of rough lithium disilicate glass-ceramics tends to decrease after wear cycling, so the friction coefficient may decrease again after an extended period of wear.

Polished zirconia surfaces maintain their smoothness over long periods of wear cycling [38–43]. Consequently, they exhibit consistent and stable friction coefficients over time [38]. Nevertheless, the surface integrity of zirconia may mean that the higher friction coefficient of a rough zirconia surface is less likely to decrease over time. However, few studies have investigated the friction coefficient between teeth and dental restorations. As novel zirconia materials with various stabilizers and lithium disilicate glass-ceramics with different compositions become commercially available, more studies will be required to better understand the tribology of new dental ceramics.

3.2. Wear behavior and microstructural characteristics

3.2.1. Wear behavior

The extent of enamel wear depends on the properties of the antagonist restorative material [44]. The predominant wear mechanism of zirconia is polishing wear [9]. This is attributed to its high hardness and small grain size [9]. Other possible wear mechanisms between zirconia and enamel include abrasive wear, fatigue wear [38,45,46], and delamination [45]. Abrasive wear typically damages the enamel and is intensified by fatigue wear under high stress conditions [38]. Subsurface fatigue of the enamel induces delamination through the accumulation of plastic deformation. The subsurface region is subjected to cyclic loading during chewing, leading to crack nucleation, followed by parallel propagation of the crack and its inflection toward the surface. Delamination of the enamel occurs when the fracture reaches the tooth surface [45].

The principal wear mechanism of lithium disilicate glass-ceramics is fatigue wear. The glassy matrix fractures as a result of fatigue, leading to the exposure and loss of the embedded crystalline particles. Therefore, variations in the composition of lithium disilicate glass-ceramics result in different abrasive behaviors [20]. For example, zirconia-reinforced lithium disilicate glass-ceramics [13] cause significantly higher antagonist enamel wear than zirconia [47]. Nevertheless, the wear mechanisms are not well understood [35,48]. More studies are needed to evaluate the wear behavior of zirconia-reinforced lithium disilicate glass-ceramics because their composition differs from that of conventional lithium disilicate glass-ceramics.

Most studies report that monolithic zirconia restorations cause less enamel wear than lithium disilicate glass-ceramics [35,36,49]. In fact, zirconia induces a lower enamel wear rate than all other reported dental ceramics and enamel itself [8]. It exhibits limited abrasiveness to human enamel and is less abrasive than other dental ceramics, particularly when its surface is polished rather than glazed [50]. Monolithic translucent zirconia restorations with polished and glazed finishes induce significantly less enamel wear than zirconia restorations layered with lithium disilicate glass-ceramics [51]. When different types of zirconia are compared, 5YSZ exhibits superior wear properties to 3YSZ [40]. Furthermore, despite the reduced strength and fracture toughness of 5YSZ, no surface fracturing or roughening occur during wear cycling. However, a few studies have reported that the enamel wear rate of zirconia is comparable to [6,12] or greater than that of glass-ceramics [52–55].

Zirconia is typically considered to be compatible with enamel [20]. In particular, it offers better wear performance than glass-ceramics, particularly where high wear is expected [35]. It has been identified as the most appropriate restorative material for clinical dentistry because of its tribological properties [9].

3.2.2. Microstructural characteristics

Zirconia and lithium disilicate glass-ceramics have different microstructures. Glass-ceramics are composed of crystalline particles surrounded by a weak glassy matrix [20], whereas zirconia comprises biphasic tetragonal/cubic phases consisting of fine grains and strong grain boundaries [56]. These differences in microstructure are responsible for the variations in their wear behaviors and wear mechanisms [20].

Regarding zirconia, the extent of wear on the antagonist enamel is significantly influenced by factors including the yttria content, zirconia phase composition, and alumina content [37]. Mechanical stress and subsequent crack initiation result in a localized phase transformation from the tetragonal phase to the monoclinic phase. This phase transformation leads to an increase in volume, generating compressive stress at the crack tip that effectively constricts the crack and inhibits its propagation, thereby enhancing the strength of 3YSZ. This is commonly referred to as transformation toughening. Notably, this phenomenon may contribute to the surface integrity and smoothness of zirconia restorations, reducing antagonistic wear [20]. Zirconia experiences both thermal and mechanical stresses during chewing. Comparing different types zirconia, 3YSZ induces the highest wear on natural antagonist teeth, followed by highly translucent 3YSZ; finally, 5YSZ induces the least wear [37].

Care should be taken when interpreting the effects of microstructural changes. For example, ionizing radiation alters the microstructure of zirconia through the tetragonal-to-monoclinic phase transformation, resulting in volumetric expansion of the grains and thus increased compressive stress along the grain boundaries. This provides greater resistance to nanoindentation, which, in turn, affects the reported mechanical properties at the nanoscale [57]. However, radiation therapy does not significantly change the microhardness or surface roughness of zirconia. Furthermore, enamel that has been exposed to radiation and rubbed against irradiated or nonirradiated zirconia does not wear more than nonirradiated enamel-to-enamel controls [58].

The high-speed sintering of zirconia results in a smaller average grain size [59]. Despite this, previous investigations have consistently found that the high-speed sintering of zirconia does not necessarily increase antagonist enamel loss [60–62].

The abrasiveness of individual ceramics is determined by the base mineral type and the quantity, distribution, and configuration of crystals [20]. Novel lithium disilicate glass-ceramics with an increased content of silica, alumina, and potassium oxide crystals induce higher antagonist enamel wear than pressed lithium disilicate glass-ceramics. Leucite crystals within lithium disilicate glass-ceramics can detach during mastication, leading to increased surface roughness [63]. However, these glass crystals can cause microfractures to branch, deflect, or dull, thereby diminishing their propagation and reducing abrasiveness [54]. It is difficult to draw conclusions about the wear behavior of different lithium disilicate glass-ceramics because their compositions differ significantly. Furthermore, it is not possible to draw conclusions from the results of zirconia to represent all dental ceramics.

3.2.3. Hydrothermal degradation

The hydrothermal degradation of zirconia can cause surface and subsurface microcrack formation and surface roughening [64]. Mechanical stresses, temperature fluctuations, and wet environments can exacerbate the development of flaws in zirconia, leading to a reduction in its mechanical strength [65]. Therefore, even low-temperature degradation can trigger the tetragonal-to-monoclinic phase transformation, strength reduction, and surface degradation, which subsequently alters the surface roughness [66].

Zirconia exhibits almost no tetragonal-to-monoclinic phase transformation, even after 10,000 wear cycles in a wet environment. This ensures that there are no harmful alterations to its mechanical properties when utilized in the oral cavity [67]. This minimal alteration of mechanical properties can be explained by the degree of low-temperature degradation. If the tetragonal-to-monoclinic phase transformation is restricted to the surface, the surface roughness of zirconia will not differ following low-temperature degradation. Nevertheless, if microcracks initiate and propagate deep into the material owing to mechanical loading and wear cycling, the surface roughness will increase, particularly when influenced by a low-temperature-degradation-induced phase transformation [57]. Badarneh *et al.* [68] proposed a "latent effect" model to further support this phenomenon. Specifically, they hypothesized that the effects of degradation are latent and only revealed under mechanical loading. The aging-affected superficial layer of zirconia can fracture off instead of being abraded, exposing a rough layer of tetragonal zirconia underneath. This reflects the increased risk of microchipping and fracture in aged zirconia. While glazing may provide protection against the low-temperature degradation of zirconia by functioning as an insulating layer, the glaze layer itself is prone to hydrothermal degradation, which can cause significant microcracking and chipping. Consequently, glazing may result in increased enamel wear [68].

Several studies have reported that hydrothermal degradation increases antagonist enamel wear; however, the increase is not statistically significant [23,68,69]. By contrast, Hao *et al.* [65] reported a considerable reduction in enamel wear in aged zirconia specimens compared with non-aged ones. They ascribed this to a decrease in surface hardness of the zirconia, making it more prone to induce wear. The surface roughness (R_a) values of the aged and non-aged samples did not differ before wear cycling; however, after wear cycling, the R_a values of aged zirconia balls were greater than those of non-aged antagonist balls [57]. Additionally, Madanshetty *et al.* [37] reported that, unlike 3YSZ and 4YSZ, 5YSZ does not undergo hydrothermal degradation. This enables it to maintain its strength and microstructure over extended wear periods. Further studies are required to understand the effects of hydrothermal degradation on the wear of antagonist enamel. Notably, in clinical situations, restorations are usually adjusted in the occlusal contact area, so these areas will have already undergone the tetragonal-to-monoclinic phase transformation [70]. These clinical situations should be considered when developing a methodology for evaluating the effects of low-temperature degradation in clinical situations.

3.3. Surface state

The surface finish [21] and surface treatment [71] of zirconia restorations affect antagonist enamel wear. Glazing and polishing both have benefits and drawbacks. Glazing offers exceptional aesthetic qualities and a glossy finish. However, unlike polishing, which can be performed even after cementation, glazing must be applied before cementation. Another disadvantage of glazing is that the glaze layer gradually wears during practical use, thereby exposing the underlying ceramic surface. This can have detrimental effects on the opposing dentition [27]. Enamel wear differs according to the surface state [24,52,72,73]. In contrast to enamel-to-enamel wear, enamel-to-zirconia wear is generally lower *in vitro*, regardless of surface preparation [25,30,32,73].

Antagonist enamel wear is more prevalent for glazed zirconia restorations than polished ones [24,26,27,30,31,44,52,67,74–77]. Glazing reduces the wear resistance of the antagonist enamel compared with polishing [17]. Furthermore, the glaze layer is damaged during wear cycling [4,7,25,27,30,68,77,78]. Once the glaze is damaged, glazed restorations have greater surface roughness than their unglazed counterparts. The loss of the glaze layer is attributed to inherent flaws within the glaze layer that arise from the entrapment of air during the liquid-mixing process. Stress concentrations during chewing are heavily influenced by the size of preexisting cracks or defects. Consequently, chewing forces cause the glazed ceramic to crack, potentially resulting in surface roughening and increased susceptibility to wear [79]. Moreover, wear particles from the glaze layer can function as third-body abrasives [26]. Glaze layer wear can also occur in glazed lithium disilicate glass-ceramics [80], exposing the underlying rough surface [63]. Nevertheless, glazing can fill and smoothen uneven surfaces [4]. The glaze layers in deep surface grooves are protected from wear by the surrounding hard zirconia and therefore effectively seal superficial defects [34].

Under clinical conditions, glaze layers tend to experience wear after approximately six months, exposing the underlying surface. Therefore, it may be necessary to polish the zirconia surface before glazing to ensure the exposed surface is smooth [4]. This is supported by a study by Stawarczyk *et al.* [77], in which polished zirconia specimens that were glazed by spraying exhibited less enamel wear than zirconia glazed by a layering technique after airborne particle abrasion [77]. Additionally, Chong *et al.* [25] reported comparable wear between polished zirconia and polished and glazed zirconia. Thus, the subsurface conditions may play a role in the wear of enamel opposing glazed dental ceramics.

Owing to its polycrystalline structure, which results in a dense, well-packed microstructure without voids [30], polished zirconia causes less antagonist enamel wear than glazed zirconia [27] and natural enamel [26,30]. This suggests that mechanical polishing of zirconia is the most effective method for reducing antagonist wear. It is recommended that zirconia restorations are repolished after any necessary adjustments to reduce antagonist enamel wear [7]. Dental chairside diamond-impregnated rotary devices, specifically intended for repolishing zirconia surfaces after adjustment, can successfully reduce surface roughness and minimize antagonist enamel wear [25].

Regarding the surface finish of lithium disilicate glass-ceramics, Fouda *et al.* [78] reported that glazing fully crystallized lithium disilicate glass-ceramic restorations does not significantly affect the wear of natural antagonist teeth [78]. This aligns with the results of Lawson *et al.* [31]. However, other studies have reported that polished lithium disilicate glass-ceramic crowns cause less antagonist wear than glazed ones [52,80]. Fine-grained diamond points can be used to adjust lithium disilicate glass-ceramic restorations [80]. The chairside polishing of dental CAD-CAM materials such as lithium disilicate glass-ceramics and ceramic composites yields equivalent surface roughness to that achieved using laboratory polishing techniques [81]. Additionally, chairside polishing is preferable to glazing for fully crystallized lithium disilicate glass-ceramic blocks owing to its lower process time and cost while maintaining the desired qualities of the final restoration [78].

Ghaffari *et al.* [82] recommend the use of polished zirconia crowns in clinical practice [82]. Nevertheless, occlusal adjustments and repolishing are necessary in clinical situations. Furthermore, the extent to which glazed zirconia contributes to natural tooth wear after polishing remains a subject of controversy [83]. One measure of tooth wear is the mean maximum vertical loss. The maximum vertical loss is defined as the depth at ten points around the maximum depth peak from the individual differential scan area of an investigated tooth. Averaging the maximum vertical loss around all regions of interest on a single tooth provides the mean maximum vertical loss [84]. The mean maximum vertical loss of enamel opposing polished and glazed zirconia after occlusal adjustment ranges between 51.9 and 77.1 μm after six months [85,86], increasing up to 172.3 μm for enamel opposing restorations requiring extensive occlusal adjustment and polishing [86]. The mean maximum vertical loss is 70.3–87.0 μm after one year [85,87] and 115–204 μm after two years [84,87,88]. Another measure of tooth wear is the mean vertical enamel wear. The occlusal surfaces of teeth are measured individually to quantify the vertical loss of enamel at each point, and the mean vertical distance for an individual tooth is considered the mean wear value [89]. The mean enamel wear against polished zirconia is 42.5–50.3 μm after six months [24,46] and 42–127 μm after one year [6,24,46,90–92]. For glazed zirconia, the mean wear of antagonist enamel is 59.4–113 μm after one year [24,90,92]. *In vivo*, antagonist wear is similar or higher than that against natural teeth when using well-polished monolithic zirconia [93].

Few clinical studies have reported the antagonist enamel wear induced by lithium disilicate glass-ceramic restorations. In one study, the mean wear of antagonist enamel caused by lithium disilicate glass-ceramics was 40.6 μm after one year [6]. In another study, the mean maximum vertical loss was 69 μm after one year and 81 μm after two years [94].

Under clinical conditions, enamel-to-enamel wear is significantly lower than enamel-to-dental ceramic wear, regardless of the surface preparation and material type. This could be mitigated by occlusal adjustment after try-in. Furthermore, polishing is recommended to reduce antagonist enamel wear, particularly in the occlusal contact area. When aesthetic considerations are high, glazing materials containing porcelain [19] should be confined to non-occlusal loading areas [31], such as the labial surfaces. Clinical studies on enamel wear against polished and glazed zirconia antagonists are summarized in Table 3.

3.4. Environmental factors

3.4.1. Motion

The degree of enamel loss differs depending on whether the enamel is exposed to an impact load or a sliding load over different wear periods under impact–slide conditions. Impact is the leading cause of antagonist enamel wear in the early stages of wear, resulting in a high wear rate and extensive enamel loss, whereas sliding contributes more in the later stages of wear, with a steady wear rate and moderate material loss [95].

The wear behavior of human enamel under impact–sliding wear is strongly influenced by its structure and mechanical properties. Enamel rods made up of hydroxyapatite crystals serve as the fundamental framework of dental enamel, with protein-rich prism sheaths forming boundaries between the enamel rods. The hardness and elastic modulus of the protein-rich prism sheaths are lower than those of the enamel rods. The impact wear of enamel from chewing in the early stages of wear occurs by plastic deformation, quasi-plastic deformation, and brittle fracture. This causes the enamel to break into large fragments with relatively low material loss. By contrast, the sliding wear of enamel in the later stages of wear mainly involves three-body wear with plowing and wear debris formation, leading to rapid volume loss [95]. The greater the number of impact cycles, the more compact the hydroxyapatite crystals become, leading to increased hardness of the worn enamel surface. Under impact loading, the size of the wear particles gradually decreases until the worn surface is completely covered by a layer of particles. This wear particle layer increases the real contact area, thereby reducing contact stress. Furthermore, the particle layer undergoes frequent compression and delamination under impact loading, resulting in absorption of a portion of the impact energy. Consequently, the size of the wear region gradually increases with subsequent impact cycles, while the wear rate decreases slightly [96].

3.4.2. Wear cycling and applied force

The wear of zirconia increases as the number of wear cycles increases [34,97]. The extent of wear gradually increases over time, whereas the wear rate of the opposing enamel decreases. This is because running-in wear is predominant following the initial placement of restorations, whereas stable wear is predominant after approximately two years [93].

Wear cycling has different effects on the surface roughness of lithium disilicate glass-ceramic and zirconia restorations. Rough-finished lithium disilicate glass-ceramic specimens exhibit lower surface roughness following wear cycling [42,98], whereas smooth lithium disilicate glass-ceramic specimens (e.g., with glazed [35] or polished surfaces [42]) exhibit increased surface roughness after wear cycling. By contrast, zirconia surfaces maintain their surface state after wear cycling. The crystalline structure of zirconia, with many fine grains and strong grain boundaries [56], along with its excellent hardness, fracture toughness [42], and surface features [23], is likely to hinder microcrack propagation. This inhibition of microfractures means that zirconia exhibits surface integrity during abrasive wear [36]. This surface integrity means that smooth zirconia can maintain its smoothness during wear; however, it also means that rough zirconia is less likely to become smooth over time [39,42,99] and more likely to cause more abrasive wear on the opposing enamel [25,31,39,42]. Overall, lithium disilicate glass-ceramics exhibit different degrees of surface roughness after wear cycling, whereas polished or ground zirconia ceramics maintain their surface state regardless of the initial surface roughness.

In addition to wear cycling, antagonist wear is also influenced by masticatory forces. The wear behavior of lithium disilicate and zirconia might change under higher chewing loads [100]. Greater forces generate greater stresses per unit contact area; therefore, patients with parafunctional habits are likely to exhibit different wear behaviors when ceramic restorations are used. Furthermore, whereas ground zirconia restorations retain their surface state over time, lithium disilicate restorations can become smoother after wear cycling, thereby increasing the contact area. This may reduce the stress on the antagonist enamel as wear cycling continues, which could affect the wear pattern of the antagonist enamel over time. Nevertheless, more studies are required to confirm this hypothesis.

3.4.3. Geometry

The wear results differ depending on the specimen geometry [12]. For example, the geometry of the crown influences the two-body wear between the crown and antagonist enamel. An increase in cusp inclination results in increased wear. Antagonist teeth can move laterally on dental restorations with level occlusal surfaces (known as flat cusp inclinations) with minimal interference. Flat cusp inclinations allow for a wider contact area during chewing, thereby reducing the strain on the tooth. By contrast, dental restorations with irregular anatomical surfaces (known as medium cusp inclinations) result in more material loss owing to an increase in resistance and friction, which promotes chipping [101]. In addition to the restoration geometry, differences in the preparation, morphology, and structure of the enamel specimen can lead to discrepancies in the wear results [102]. Hence, the geometry of both the restoration and natural enamel can influence the tribological behavior.

Over time, the cusps flatten and shorten, while the contact area increases. As the contact area and number of wear facets increase, there is a corresponding reduction in the occlusal force per unit surface area, resulting in a decrease in vertical height loss. In this sense, high wear rates may exhibit self-limiting behavior owing to a decrease in occlusal stress [93]. Hence, clinicians should prioritize increasing the contact area during occlusal adjustments, as this may mitigate the contact stress on tooth enamel and minimize the risk of accelerated wear and brittle fracture [95]. Different patients exhibit varying degrees of occlusion. Clinicians must consider crown shape, particularly when treating individuals with parafunctional habits.

3.4.4. Saliva and acidity

Saliva can exert lubricating and cooling effects during wear, thereby protecting the enamel. In laboratory tests, artificial saliva effectively mitigates risks associated with tooth wear. Wear scars are significantly deeper and more severe in its absence. In clinical practice, rapid enamel wear can occur in the absence of saliva, such as in patients with xerostomia or tumors of the salivary gland or those undergoing radiation

Table 3
Clinical studies of antagonist enamel wear of zirconia and lithium disilicate and their surface condition.

Year	Author	Surface condition	Restoration material	Crown region	Enamel control	Measurement	Vertical wear of antagonistic enamel	Volumetric wear of antagonist enamel	Vertical wear of enamel-to-enamel control
2020	Nazirkar *et al.* [6]	Polished	Zirconia, lithium disilicate	Molar	Contralateral molar	Baseline: at time of cementation; follow up: 12 months	Mean wear: 42 μm (polished zirconia); 40.06 μm (polished lithium disilicate)	N/A	Control group: 34.68 μm (polished zirconia); 35.09 μm (polished lithium disilicate)
2015	Mundhe *et al.* [91]	Polished (polished after occlusal adjustment)	Zirconia	Molar and premolar	Molar and premolar	Baseline: just before treatment; follow up: 12 months	Mean wear of premolar and molar: 42.10 and 127 μm	N/A	Premolar: 17.3 μm; molar: 35.1 μm
2023	Dondani *et al.* [24]	Polished and glazed	Zirconia	Molar	Same arch, premolar	Baseline: after 24 h; follow-up: 6 and 12 months	Mean wear (6 and 12 months): 42.5 and 71.43 μm (polished); 42.8 and 81 μm (glazed)	N/A	Premolar (after 6 and 12 months): 14.7 and 15.9 μm
2021	Ç ömlekoğlu *et al.* [51]	Glazed lithium disilicate (polished and then reglazed after occlusal adjustment)	Zirconia: lithium disilicate layered zirconia	Molar	N/A	Baseline: after 1 week; follow up: 24 months	Mean vertical loss of buccal cusp and palatal cusp: −0.33 and 0.3 μm (lithium disilicate layered zirconia); 0.13 and 0.14 μm (translucent monolithic zirconia)	N/A	N/A
2019	Yang *et al.* [70]	Polished (polished after occlusal adjustment)	Zirconia	Molar	N/A	Baseline: after 1 week; follow-up: 6 months	Presented in figure	N/A	N/A
2022	Rouchdy *et al.* [80]	Polished (polished after occlusal adjustment); glazed (reglazed after occlusal adjustment)	Lithium disilicate	Molar or premolar	N/A	Baseline: immediately after crown placement; follow up: 2, 4, 6, 8, 10, and 12 months	N/A	Mean volume loss (6 and 12 months): 0.0554 and 0.098 mm^3 (polished); 0.2169 and 0.2544 mm^3 (glazed)	N/A
2016	Stober *et al.* [88]	Glazed (polished after clinical adjustment)	Zirconia	Molar	Contralateral molar	Baseline: immediately after crown placement; follow up: 6, 12, and 24 months	Mean wear and mean maximum vertical loss (24 months): 46 and 151 μm	N/A	Mean wear (24 months): between 19 and 26 μm
2018	Esquivel-Upshaw *et al.* [85]	Polished (polished after clinical adjustment)	Zirconia	Molar	Contralateral enamel	Baseline: after 1 week; follow up: 6 and 12 months	Mean maximum vertical loss (6 and 12 months): 51.9 and 70.3 μm	N/A	Mean maximum vertical loss (6 and 12 months): 61.8 and 61.1 μm
2021	Selvaraj *et al.* [92]	Polished (after occlusal adjustment of milled crown); glazed (after occlusal adjustment of milled crown)	Zirconia	Molar	Contralateral molar and premolar	Baseline: just before cementation; follow up: 1 year	Mean wear of premolar and molar: 44 and 63 μm (polished); 69 and 113 μm (glazed)	N/A	Mean wear of premolar and molar: 13 and 34 μm
2017	Lohbauer and Reich [84]	Polished (polished after occlusal adjustment)	Zirconia	Molar or premolar	N/A	Baseline and follow-up: 24 months	Mean maximum vertical loss of enamel: 0.204 mm	Mean volume loss: 0.361 mm^3	N/A
2017	Hartkamp *et al.* [87]	Polished (staining on lateral part of crown)	Zirconia	Molar or premolar	N/A	Baseline and follow-up: 12–24 months	Mean maximum vertical loss (12 and 24 months): 87 and 115 μm	N/A	N/A
2021	Solá-Ruiz *et al.* [106]	Polished (polished after	Zirconia	Molar or premolar	N/A	Baseline: after cementation;	Maximum and mean wear (5	N/A	N/A

(continued on next page)

Table 3 (*continued*)

Year	Author	Surface condition	Restoration material	Crown region	Enamel control	Measurement	Vertical wear of antagonistic enamel	Volumetric wear of antagonist enamel	Vertical wear of enamel-to-enamel control
		occlusal adjustment)				follow-up: 5 years	years): 170.1 and 131 μm		
2018	Shi *et al.* [86]	Self-glazed (polished after occlusal adjustment)	Zirconia	Molar or premolar	Contralateral teeth	Baseline and follow-up: 6 months	Mean maximum vertical loss: 77.11 μm (small adjustment and polish); 172.34 μm (large adjustment and polish)	N/A	Mean maximum vertical loss: 63.01 μm (small adjustment and polish); 98.75 μm (large adjustment and polish)
2022	Von der Stück *et al.* [94]	Glazed (polished after occlusal adjustment)	Lithium disilicate	Molar or premolar	Adjacent mesial tooth	Baseline and follow-up: 12–24 months	Mean maximum vertical loss (12 and 24 months): 69 and 81 μm	N/A	Mean maximum vertical loss (12 and 24 months): 66 and 71 μm
2021	Deval *et al.* [90]	Glaze	Zirconia	Molar	Mandibular right and left premolars	Baseline: at time of cementation; follow up: 12 months	Mean wear (12 months): 59.4 μm	N/A	Mean wear (12 months): 14.8 μm
2021	Tang *et al.* [46]	Polished (polished after occlusal adjustment)	Zirconia	Molar or premolar	Contralateral teeth	Baseline: immediately after crown placement; follow up: 6 and 12 months	Mean wear (6 and 12 months): 50.3 and 81.57 μm	Mean volume loss (6 and 12 months): 0.49 and 0.61 mm^3	Mean wear (6 and 12 months): 20.13 and 33.69 μm
2016	Cardelli *et al.* [89]	Glazed on buccal side	Zirconia	Implant-supported full arch restoration	Full arch	Baseline: after 2 weeks; follow-up: 12 months	Mean wear (12 months): 76 μm	N/A	N/A

Abbreviation: N/A = not applicable.

therapy [103].

Exposure to acidic conditions can make the surfaces of zirconia restorations smoother with a reduced friction coefficient owing to tribocorrosion [104], whereas glass-ceramic restorations become more abrasive owing to etching, crystal deposition, and glass corrosion that exposes the underlying rough surface [18]. Consequently, in acidic environments, zirconia surfaces offer greater advantages in terms of antagonist wear.

As many populations around the world age, with increased tendency to retain teeth owing to better dental service availability, further studies are needed to explore the relationship between aging-related conditions, such as salivary conditions, and novel dental ceramics to better understand their tribological properties.

4. Conclusion

We used a realistic approach to discuss the multiple factors that influence antagonist enamel wear caused by two commonly used dental ceramics. Extensive clinical and *in vitro* research has been conducted on antagonist enamel wear by zirconia. However, studies on the antagonist enamel wear of lithium disilicate glass-ceramics are still limited despite their frequent use in restorative dentistry. This study has some limitations. For example, we did not perform a quality assessment of the reviewed manuscripts. In addition, the meta-analysis design limits our ability to draw conclusions. However, the following conclusions can be drawn within the limitations of this study:

1. Wear should not be estimated using a single mechanical parameter, and a conclusion should not be drawn or generalized broadly to all dental ceramics by testing a single type of material.
2. The glassy matrix of lithium disilicate glass-ceramics has low fracture toughness and poor microstructural characteristics, resulting in its loss during wear cycling and thus the dislodgement of the crystalline particles. This can increase the surface roughness, leading to heightened friction and increased antagonist wear.
3. Polished zirconia may be a more suitable option in terms of wear.
4. Well-controlled studies are needed to assess the influence of material degradation on the wear behavior of dental restorations.
5. It is important to explore how restorative materials behave in different oral environments, with consideration to the needs of aging populations.

This review advances our understanding of tribology in dentistry and will stimulate further research in this area in the future.

Conflict of interests

The authors 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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Data availability

Data will be made available upon request.

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