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Review

Devices for In Vitro Simulation of Dental Wear: A Scoping Review

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Highlights

What are the main findings?

- This scoping review identified 19 devices or device families used for in vitro simulation of dental wear and oral aging.
- No single device reproduced all relevant intraoral conditions; most systems focused on a dominant mechanism, such as two-body wear, three-body abrasion, erosion/pH-cycling, tribocorrosion, or combined oral aging.

What are the implications of the main findings?

- Device selection should be guided by the dominant wear mechanism, material type, and research objective.
- More complete reporting of device parameters is needed to improve reproducibility, comparability, and clinical relevance in dental wear simulation studies.

Abstract

Background/Objectives: In vitro simulation of dental wear is essential for preclinical evaluation of dental materials, but available devices differ widely in operating principles and simulated oral conditions. This scoping review mapped devices used to reproduce dental wear and oral aging and classified them according to the dominant wear mechanism. Methods: Searches were conducted in PubMed/MEDLINE, Scopus, Web of Science Core Collection, Embase, and Google Scholar for records published between 1985 and 2026. Eligible sources reported an identifiable in vitro device or setup, a dental material or hard-tissue substrate, and extractable device-level data on operating principles, parameters, environment, antagonist, or outcomes. Results: Sixty-eight reports were retained and consolidated into 19 devices or device families. The systems included two-body chewing simulators, three-body wear machines, robotic or multiaxial masticatory platforms, tribometers, toothbrushing abrasion devices, erosion and pH-cycling systems, tribocorrosion setups, and multifunctional oral aging simulators. Device development showed a transition from mainly mechanical wear testing toward integrated platforms combining load, sliding, thermocycling, saliva or electrolyte exposure, pH control, chemical challenge, biofilm-related conditions, and electrochemical monitoring. Reporting remained heterogeneous, particularly for load, cycle number, frequency, sliding distance, antagonist material, medium, temperature, pH, and outcome measurement. Conclusions: Device selection should be based on the dominant wear mechanism, material type, and research

Academic Editor: Ourania Nicolatou-Galitis

Received: 23 May 2026
Revised: 23 June 2026
Accepted: 6 July 2026
Published: 8 July 2026

objective. More complete source-level reporting is needed to improve reproducibility and comparability.

Keywords: dental wear; chewing simulator; artificial mouth; oral aging; tribometer; tribocorrosion; pH-cycling; dental materials; scoping review

1. Introduction

Tooth wear and the degradation of restorative dental materials represent complex, multifactorial phenomena that may occur under the combined influence of mechanical, chemical, biological, and thermal factors [1]. In the oral environment, enamel, dentin, ceramics, resin-based composites, metallic alloys, and polymeric restorative materials are continuously exposed to occlusal loading, sliding contact, abrasion, erosion, saliva, pH fluctuations, temperature changes, and, in some cases, biofilm-mediated degradation. These interactions may lead to progressive material loss, surface roughening, antagonist wear, marginal degradation, and failure of dental restorations, including fracture, chipping, debonding, or loss of marginal integrity [2]. Consequently, understanding and reproducing oral wear mechanisms under controlled laboratory conditions remains essential for the preclinical evaluation of dental materials and for predicting their long-term clinical performance [3].

Historically, in vitro wear testing in dentistry has evolved from relatively simple mechanical systems toward increasingly complex oral simulation platforms [4]. Early approaches focused mainly on two-body or three-body wear mechanisms, using devices such as artificial mouth systems, three-body wear machines, and chewing simulators designed to approximate mastication or occlusal contact [5,6]. Among the historically influential systems, the Minnesota artificial mouth/ART method [7], ACTA wear machine [5], Alabama wear simulator [8], Zurich/CoCoM simulator [9], OHSU oral wear simulator [10], and Willytec/SD Mechatronik chewing simulator [11] have played a major role in defining experimental parameters subsequently used in validation studies and comparative wear investigations. More recent developments include programmable two-axis chewing simulators, multiaxial robotic masticators, tribometers adapted for dental applications, and multifunctional oral environment simulators capable of combining mechanical loading with saliva flow, thermal cycling, pH changes, erosion, abrasion, or biofilm-related challenges [12,13].

Despite recent technological progress, no in vitro device can fully reproduce the complexity of the oral environment. Intraoral wear results from several mechanisms that may act separately or together. Attrition is produced by direct contact between teeth or between a material and its antagonist under occlusal loading, whereas abrasion involves an external agent, such as food particles, toothpaste slurry, or other abrasive media. Erosion refers to chemical surface loss or softening caused by non-bacterial acids, while corrosion describes electrochemical degradation, mainly relevant for metallic dental materials in saliva or other electrolytes. Tribocorrosion occurs when mechanical wear and corrosion interact [14]. Repeated cyclic loading may also induce fatigue-related damage, leading to cracks, chipping, or fracture. The relative contribution of these mechanisms depends on the clinical situation, material type, antagonist, oral medium, and experimental protocol [15,16]. As a result, laboratory devices have generally been developed to isolate or emphasize specific aspects of oral degradation. Chewing simulators are commonly used to reproduce occlusal loading and sliding contact; three-body wear machines are useful for abrasive media-mediated wear; toothbrushing machines and pH-cycling systems are applied to

abrasion and erosion models; while reciprocating or pin-on-disk tribometers are frequently used to study friction, wear scars, and tribological behavior under standardized contact conditions. For tribocorrosion studies, dental research often relies on tribometers coupled with electrochemical cells and potentiostats rather than on a single standardized dental wear simulator [9,13,17–19].

The diversity of available devices has generated substantial methodological heterogeneity across in vitro dental wear studies [20,21]. Experimental protocols differ in terms of load magnitude, number of cycles, frequency, sliding distance, antagonist material, lubrication medium, temperature, pH, specimen geometry, and outcome measurement. Reported outcomes may include wear depth, volume loss, surface roughness, mass loss, friction coefficient, antagonist wear, fracture, chipping, ion release, or electrochemical parameters [11,12]. These differences complicate direct comparison between studies and make it difficult to establish universal equivalences between laboratory cycles and clinical service time. Moreover, some devices are well documented through manufacturer specifications or original methodological articles, whereas others are custom-built, regionally used, or reported only briefly in experimental studies [11].

In recent years, the scope of in vitro oral simulation has expanded beyond conventional wear testing. Newer platforms have increasingly aimed to reproduce combined chemomechanical aging, sequential abrasion–erosion–attrition processes, saliva flow, thermal control, biofilm activity, and pH-dependent hard tissue degradation [22]. Examples include multifunctional oral aging systems, sequential wear platforms, robotic six-axis chewing simulators, and oral cavity simulators designed to model clinically relevant environmental interactions. This development reflects a broader shift from isolated mechanical wear testing toward integrated oral aging models that more closely represent the multifactorial nature of the intraoral environment [1].

Given the large number of devices, the diversity of experimental principles, and the absence of a single standardized approach for simulating oral wear, a structured mapping of the available evidence is needed. A scoping review is particularly appropriate for this purpose because it allows the identification, classification, and synthesis of heterogeneous study designs, device types, experimental parameters, and reported applications. Such an overview may help clarify which devices have been used for specific wear mechanisms, how their operating principles differ, which outcomes are commonly assessed, and where methodological gaps remain.

Accordingly, the present scoping review aims to systematically map and synthesize the scientific literature concerning in vitro devices used to simulate wear and oral aging of dental materials and dental hard tissues. Particular emphasis is placed on identifying the main categories of devices, including chewing simulators, three-body wear machines, robotic masticatory systems, tribometers, toothbrushing and erosion/pH-cycling platforms, tribocorrosion setups, and multifunctional oral cavity simulators. This review also aims to summarize their operating principles, controllable experimental parameters, environmental simulation capabilities, reported applications, and major methodological limitations, in order to support more appropriate device selection and future standardization of in vitro dental wear testing.

2. Materials and Methods

2.1. Review Design and PCC Framework

This scoping review was conducted in accordance with the PRISMA Extension for Scoping Reviews (PRISMA-ScR) [23,24]. The review was designed to map, classify, and synthesize the available evidence on in vitro devices used to simulate dental wear, oral aging, and degradation of dental materials or dental hard tissues.

The eligibility framework was structured according to the Population–Concept–Context (PCC) approach. The Population included dental hard tissues, restorative dental materials, prosthetic materials, implant-related materials, and dental material–antagonist systems tested under laboratory conditions. For clarity, the population was further separated into three application groups: tooth-wear models, restoration/material-wear models, and combined tooth–material antagonist models. Tooth-wear models referred primarily to enamel and dentin substrates and included attrition, abrasion, erosion, pH-cycling, demineralization, and hard-tissue surface loss. Restoration/material-wear models referred to resin-based composites, ceramics, metallic alloys, polymers, prosthetic materials, implant-related materials, and other restorative substrates, with outcomes such as material loss, surface roughness, gloss change, fracture, chipping, ion release, corrosion, or tribocorrosion. Combined tooth–material antagonist models included studies in which both the tested specimen and the antagonist were clinically relevant substrates, such as restorative materials opposed to enamel or prosthetic components interacting with dental hard tissues.

The Concept was the use of an identifiable in vitro device, simulator, apparatus, or experimental setup designed to reproduce or investigate intraoral wear mechanisms and oral aging processes, including masticatory wear, attrition, two-body or three-body abrasion, erosive challenge, pH-cycling, fatigue-related degradation, corrosion, tribocorrosion, and combined chemo-mechanical aging. The Context was preclinical, laboratory-based dental materials research, including experimental studies, device descriptions, validation studies, comparative studies, patents, manufacturer documentation, and technical reports reporting device-level information.

A formal protocol was not registered before conducting the review. However, the review question, eligibility criteria, information sources, search strategy, data extraction items, and device-level consolidation approach were defined before final data extraction and synthesis.

2.2. Research Questions

The review was guided by the following research questions:

1. What in vitro devices or device families have been reported for simulating wear, oral aging, or degradation of dental materials and dental hard tissues?
2. What major categories can be identified according to the dominant wear mechanism or operating principle reproduced by these devices?
3. Which experimental parameters are most commonly controlled or reported, including load, number of cycles, frequency, sliding distance, antagonist type, lubrication medium, temperature, saliva flow, pH, and thermocycling?
4. What outcomes are most frequently reported, such as wear depth, volume loss, surface roughness, friction coefficient, antagonist wear, fracture, chipping, ion release, or electrochemical parameters?
5. What are the main methodological limitations and reporting gaps associated with current in vitro dental wear simulation devices?

2.3. Information Sources and Search Strategy

A comprehensive literature search was performed in PubMed/MEDLINE, Scopus, Web of Science Core Collection, Embase, and Google Scholar. These databases were selected because they cover biomedical, dental, materials science, engineering, and interdisciplinary literature relevant to in vitro oral wear simulation. Searches were designed to retrieve both named devices and broader categories of experimental systems.

The electronic searches were performed on 10 April 2026 and covered records published from 1 January 1985 to 10 April 2026. This period was selected to include historically

important artificial mouth systems and early three-body wear devices, as well as recent robotic, tribocorrosion, and multifunctional oral-aging platforms.

The search strategy combined terms related to dental wear, dental hard tissues, restorative materials, oral simulation, mastication simulation, tribology, pH-cycling, erosion, abrasion, and tribocorrosion. Search syntax was adapted to the indexing structure and search functionality of each database. No restrictions were applied regarding country of origin or device manufacturer.

Records were considered potentially eligible when the title, abstract, full text, or technical source reported: (i) an identifiable in vitro device, simulator, apparatus, or experimental setup; (ii) a dental material, dental hard tissue, or dental material–antagonist system; and (iii) device-level information on at least one relevant feature, such as operating principle, movement pattern, load, number of cycles, frequency, sliding distance, antagonist, medium, temperature, pH, environmental simulation, or wear-related outcome.

The complete database-specific search strings are presented in Table 1. The number of records retrieved from each source is reported in Section 3 and in the PRISMA-ScR flow diagram.

Table 1. Database-specific electronic search strategy used in the scoping review.

Database	Search String/Keywords	Filters Applied	Time Span
PubMed/MEDLINE	(“dental wear” OR “tooth wear” OR “restorative material wear”) AND (“chewing simulator” OR “mastication simulator” OR “wear simulator” OR “tribometer”)	English abstract; dental/materials studies	1985–2026
Scopus	TITLE-ABS-KEY (“dental material wear” OR “tooth wear”) AND (“chewing simulator” OR “tribometer” OR “artificial mouth” OR “oral aging”)	Articles and conference papers	1985–2026
Web of Science Core Collection	(“dental wear” AND “in vitro”) AND (“wear simulator” OR “mastication simulator” OR “tribocorrosion”)	Dentistry, materials science, engineering	1985–2026
Embase	(“dental material” AND “wear simulation”) OR (“chewing simulator” OR “tooth wear”)	Experimental studies; English abstract	1985–2026
Google Scholar	“dental chewing simulator”; “artificial mouth dental wear”; “dental tribometer wear”; “oral aging simulator”	First 200 relevant results screened	1985–2026
Total records identified	–	–	–

In addition to database searching, reference lists of relevant articles were manually screened. Patents, manufacturer websites, and official technical documentation were also consulted when they provided device specifications, operating parameters, or information not fully available in journal articles.

2.4. Eligibility Criteria

Studies and technical sources were considered eligible if they met all predefined inclusion criteria shown in Table 2. Because the purpose of this scoping review was to map devices rather than to estimate pooled effects, experimental studies, device descriptions, validation studies, comparative studies, patents, manufacturer documentation, and technical reports were considered eligible when they reported extractable device-level information.

Table 2. Eligibility criteria applied to selected sources.

Criterion	Inclusion	Exclusion
Study/source type	In vitro experimental studies, device descriptions, validation studies, comparative wear studies, patents, manufacturer documentation, and methodological or technical sources reporting device-level data	Clinical-only studies, editorials, opinion papers, and sources without device-level information
Material or substrate	Dental materials, enamel, dentin, restorative materials, prosthetic systems, implant-related systems, or dental material–antagonist systems	Non-dental materials without oral or dental relevance
Device or setup	Chewing simulator, artificial mouth, tribometer, robotic masticator, toothbrushing simulator, pH-cycling/erosion system, tribocorrosion setup, oral aging platform, or other identifiable in vitro wear-related setup	No identifiable in vitro device, simulator, apparatus, or experimental setup
Experimental parameters	At least one extractable device-level or protocol parameter, such as load, cycles, frequency, sliding distance, antagonist, medium, temperature, pH, saliva, thermocycling, movement pattern, or environmental condition	No extractable device-level or protocol parameter
Outcome	Wear depth, volume loss, surface roughness, friction coefficient, antagonist wear, fracture, ion release, electrochemical response, or another wear-/degradation-related indicator	Only hardness, flexural strength, or unrelated mechanical testing without wear or oral aging simulation
Accessibility	Full text, patent, manufacturer document, technical report, or related methodological source providing extractable information for classification	No accessible source from which device-level information could be extracted

2.5. Record Management and Duplicate Removal

All records retrieved from the electronic databases were exported to reference management software and screened for duplicates before title and abstract screening. Duplicate removal was performed using Mendeley v2.145.0 and was followed by manual verification of potentially duplicated records based on title, author names, year of publication, journal, DOI, and device name.

2.6. Study Selection Process

The study selection process was conducted independently by two reviewers (I.T. and I.S.). Titles and abstracts were screened first, followed by full-text assessment of potentially eligible records. Disagreements were resolved by discussion, and a third reviewer (I.N.) was consulted when consensus could not be reached. The results of the study selection process are reported in Section 3 and summarized in Figure 1.

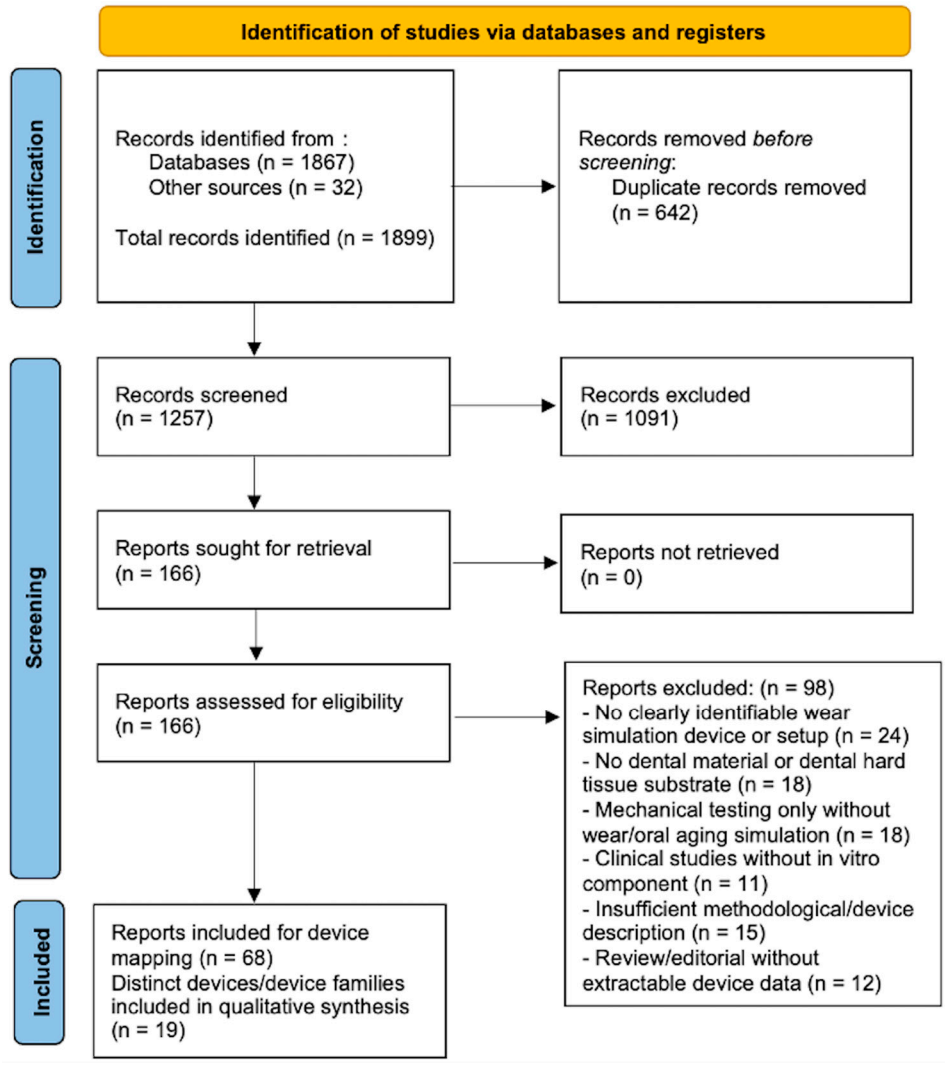

Figure 1. PRISMA-ScR Diagram.

2.7. Data Extraction and Organization Process

Data extraction was performed using a standardized data extraction form developed before the final synthesis. The form was pilot-tested on a subset of included studies and refined to improve consistency between reviewers.

The following information was extracted from each eligible source:

- Bibliographic details: first author, year of publication, journal/source, and country or research group;
- Source type: original experimental study, device description, validation study, comparative wear study, patent, manufacturer documentation, or technical report;
- Material or substrate tested: enamel, dentin, composite, ceramic, metal alloy, polymer, implant/prosthetic component, or other dental material;
- Device name or device family;
- Device status: commercial device, custom-built device, historical system, research prototype, patent-based system, or generic instrumental family;
- Dominant wear mechanism or device category: chewing simulation, artificial mouth, two-body wear, three-body abrasion, robotic mastication, tribometry, toothbrushing abrasion, erosion/pH-cycling, tribocorrosion, or multifunctional oral-aging simulation;
- Operating principle and movement pattern;
- Number of axes or degrees of freedom, when available;

- Mechanical parameters: load, frequency, number of cycles, sliding distance, mouth opening, contact pattern, and force-control strategy;
- Environmental parameters: water, artificial saliva, natural saliva, slurry, acidic challenge, pH, temperature, thermocycling, saliva flow, biofilm simulation, or electrochemical monitoring;
- Antagonist type and geometry;
- Reported outcomes: wear depth, volume loss, mass loss, surface roughness, gloss change, coefficient of friction, antagonist wear, fracture, chipping, corrosion potential, corrosion current, ion release, and other degradation indicators;
- Main methodological limitations reported by the source or identified during data extraction.

Data extraction was conducted independently by two reviewers (I.T. and I.S.). Extracted data were compared after completion, and discrepancies were resolved through discussion and consensus. When information was unclear or incomplete, Supplementary Materials, related publications from the same research group, manufacturer documentation, patents, or official technical sources were consulted when available. The complete source-level data extraction table is provided as Supplementary Table S1. References cited in Supplementary Table S1 are included in the reference list.

2.8. Device-Level Consolidation and Classification

Because several eligible reports described the same device, commercial version, historical variant, or closely related experimental setup, the final synthesis was performed at the device or device-family level rather than at the individual-study level. This approach was chosen to avoid overcounting devices that appeared repeatedly in the literature and to provide a practical taxonomy of in vitro oral wear simulation systems.

Reports were consolidated into the same device or device-family entry when they met at least one of the following criteria:

1. They referred to the same named device or simulator;
2. They described different studies using the same commercial device or model series;
3. They described historical variants or modified versions of the same device with an unchanged core mechanical principle;
4. They described closely related custom-built setups from the same research group with comparable movement pattern, operating principle, and simulation objective;
5. They represented a generic instrumental family commonly used in dental wear research, such as pin-on-disk tribometers, reciprocating tribometers, toothbrushing abrasion machines, pH-cycling systems, or tribocorrosion rigs.

Devices were classified as separate entries when they differed substantially in at least one of the following aspects:

1. Dominant simulated wear mechanism;
2. Movement complexity or number of controlled axes;
3. Presence of robotic or force/position-controlled kinematics;
4. Type of environmental control, such as saliva flow, pH regulation, thermocycling, biofilm simulation, or electrochemical monitoring;
5. Intended experimental purpose, such as chewing simulation, three-body abrasion, tribological friction testing, erosion/pH-cycling, tribocorrosion, or multifunctional oral aging.

2.9. Descriptive Methodological Appraisal

Although formal risk-of-bias assessment is not mandatory for scoping reviews, a descriptive methodological appraisal was performed to contextualize the quality and inter-

pretability of the included sources. This appraisal was not used as a criterion for study exclusion or for weighting the included studies. Instead, it was intended to identify reporting gaps and limitations related to device description and experimental reproducibility.

The appraisal focused on domains considered relevant for in vitro dental wear simulation:

- Clarity of device identification and technical description;
- Reporting of mechanical parameters, including load, frequency, number of cycles, and sliding distance;
- Reporting of environmental simulation parameters, including medium, temperature, pH, saliva, thermocycling, or biofilm conditions;
- Clarity of specimen and antagonist description;
- Reproducibility of outcome measurement, including measurement method and units;
- Transparency of statistical analysis.

Each domain was categorized as low concern, unclear concern, or high concern. A low concern rating was assigned when the source clearly described the device, protocol, specimen preparation, antagonist, environmental conditions, and outcome measurement. An unclear concern rating was assigned when one or more relevant methodological details were incomplete but interpretation remained possible. A high concern rating was assigned when critical device or protocol parameters were missing or when the experimental design substantially limited interpretation of the reported results.

The methodological appraisal domains used in the present review are presented in Table 3. The results of this descriptive appraisal are presented in Section 3.

Table 3. Methodological appraisal domains used in the present review.

Domain	Low Concern	Unclear Concern	High Concern
Device description	Device clearly named and technically described	Device partly described	Device not clearly identifiable
Mechanical parameters	Load, cycles, frequency, and movement reported	Some parameters missing	Major mechanical parameters absent
Environmental parameters	Medium, temperature, pH/saliva/thermocycling reported when relevant	Partially reported	Not reported
Specimen and antagonist	Both clearly described	Incomplete description	Missing or ambiguous
Outcome measurement	Method and units clearly reported	Method partly described	Outcome measurement unclear
Statistical analysis	Appropriate analysis reported	Limited reporting	No statistical analysis or unclear analysis

3. Results

3.1. Study Selection

The literature search identified 1867 records across the selected electronic databases: 426 from PubMed/MEDLINE, 567 from Scopus, 393 from Web of Science Core Collection, 281 from Embase, and 200 from Google Scholar. An additional 32 records were identified through manual searching of reference lists, patents, manufacturer websites, and technical documentation, resulting in 1899 records before duplicate removal.

After removal of 642 duplicate records, 1257 records remained for title and abstract screening. During this stage, 1091 records were excluded because they did not meet the predefined eligibility criteria. The most common reasons for exclusion were absence of

an in vitro dental wear component, lack of a device-based testing approach, clinical-only design, or focus on mechanical properties unrelated to wear or oral aging simulation.

A total of 166 full-text reports were assessed for eligibility. Of these, 98 reports were excluded for predefined reasons: no clearly identifiable wear simulation device or setup, no dental material or dental hard tissue substrate, mechanical testing without wear or oral aging simulation, insufficient methodological or device description, duplicate technical descriptions without additional device-level data, or review/editorial format without extractable device-level information.

The remaining 68 reports were retained for source-level data extraction and device mapping. Because several reports described the same device, commercial version, historical variant, or closely related experimental configuration, these reports were consolidated at device level. This process resulted in 19 distinct devices or device families included in the qualitative synthesis. The study selection process is summarized in Figure 1.

3.2. General Characteristics of the Included Devices and Device Families

The 19 devices or device families included in this scoping review covered a broad methodological spectrum of in vitro oral wear simulation. The identified systems ranged from historically important artificial mouth and three-body wear machines to commercially available chewing simulators, custom-built robotic platforms, tribometers adapted for dental research, toothbrushing abrasion systems, erosion/pH-cycling platforms, and tribocorrosion setups [25].

The included devices were not homogeneous in design, purpose, or level of oral simulation. Some systems were developed primarily to reproduce occlusal contact and mastication-like movement, while others were designed to isolate specific degradation mechanisms such as three-body abrasion, brushing abrasion, erosive wear, frictional sliding, or electrochemical degradation. More recent systems combined mechanical loading with saliva flow, temperature control, pH variation, biofilm-related conditions, or chemical aging, reflecting a shift from isolated wear testing toward multifactorial oral aging models. This evolution is consistent with the preliminary device catalog, which identified a progression from servo-hydraulic artificial mouth systems to two-axis chewing simulators, multiaxial robotic masticators, and multifunctional oral cavity simulation platforms.

The final synthesis included both named devices and broader instrumental families. Named or historically recognizable devices included systems such as Minnesota ART/artificial mouth [7], ACTA [5], Alabama [8], Zurich/CoCoM [9], OHSU [10], Willytec/SD Mechatronik [11], Regensburg/eGo [12], Dento-Munch [18], Rub&Roll [26,27], Biocycle V2 [28], Esetron MOD/MOY-101 [29], DUT-2 [30], NIOM sequential wear platform [22], and MOCS [31]. Broader device families included generic reciprocating or pin-on-disk tribometers, toothbrushing abrasion simulators, pH-cycling or erosion systems, and tribocorrosion rigs. This distinction was necessary because some devices are repeatedly reported under specific names, whereas other experimental approaches are widely used as instrumental families rather than as single standardized commercial systems.

3.3. Separation Between Tooth-Wear and Restoration/Material-Wear Applications

Although the included devices were classified primarily according to their dominant operating principle, the reviewed evidence also showed an important distinction between devices used to simulate tooth wear and those used to evaluate restoration or material wear. Tooth-wear applications generally involved enamel or dentin substrates and focused on hard-tissue loss, erosive softening, abrasive loss, attrition, demineralization/remineralization cycling, or pH-dependent surface changes. These applications were

particularly relevant for erosion/pH-cycling systems, toothbrushing abrasion simulators, oral cavity simulation systems, and sequential abrasion–erosion–attrition platforms.

In contrast, restoration/material-wear applications involved resin-based composites, ceramics, metallic alloys, polymers, prosthetic materials, implant-related materials, or material–antagonist systems. These studies most commonly assessed volume loss, wear depth, mass loss, surface roughness, gloss changes, fracture, chipping, antagonist wear, ion release, corrosion parameters, or tribocorrosion. Chewing simulators, three-body wear machines, tribometers, robotic masticatory platforms, and tribocorrosion rigs were most frequently used in this context.

A third group consisted of combined tooth–material models, in which the tested specimen and antagonist represented different clinically relevant substrates, such as restorative material opposed to enamel, ceramic antagonist opposed to enamel, or prosthetic components interacting with hard tissues or restorative materials. In these cases, the distinction between specimen wear and antagonist wear is essential, because the same experimental device may provide different information depending on whether the primary outcome is tooth wear, restoration/material wear, or mutual wear at the tooth–material interface.

3.4. Classification of Devices According to Operating Principle

The included devices were classified according to their dominant operating principle and primary wear mechanism. Seven main categories were identified: two-body chewing simulators, three-body wear simulators, multiaxial robotic masticators, generic dental tribometers, toothbrushing abrasion simulators, erosion and pH-cycling systems, and tribocorrosion rigs.

Two-body chewing simulators were among the most frequently represented systems. These devices are designed to reproduce direct contact between a dental material or hard tissue substrate and an antagonist under controlled loading and sliding conditions. Examples include Willytec/SD Mechatronik CS-4/CS-4.8, Regensburg/eGo, Zurich/CoCoM, Biocycle V2, Esetron MOD/MOY-101, and several custom mastication devices. They are primarily used to evaluate wear of restorative materials, enamel antagonist wear, fracture behavior, and thermomechanical fatigue.

Three-body wear simulators represented another historically important group. These devices reproduce wear in the presence of an intermediate abrasive medium, such as slurry, food-like particles, PMMA beads, or other abrasive materials. ACTA and Alabama were the main examples in this category. These systems are particularly relevant for ranking restorative materials under abrasive conditions, although their anatomical and kinematic realism is more limited than that of chewing simulators.

Multiaxial robotic masticators included more advanced custom-built systems designed to reproduce mandibular movement using multiple degrees of freedom, force feedback, or hybrid force/position control. Examples include Dento-Munch, masticatory robot systems, force/position-controlled robotic dental wear simulators, and DUT-2. These platforms generally provide higher biomechanical fidelity than conventional two-axis chewing simulators, but they are also more complex, less accessible, and often limited to specialized research laboratories.

Generic dental tribometers included pin-on-disk, ball-on-flat, pin-on-plate, and reciprocating tribometer configurations adapted to dental materials. These devices are frequently used to study friction coefficient, wear scar morphology, wear volume, and material–antagonist interactions under standardized contact conditions. Although they do not reproduce mastication in a fully anatomical manner, they offer precise control over load, sliding distance, speed, lubrication, and contact geometry. Pin-on-disk and reciprocating tribometers are also central to dental tribology and tribocorrosion studies.

Toothbrushing abrasion simulators were used to reproduce abrasive wear induced by brushing under controlled load, brushing stroke, toothpaste slurry, and number of cycles. These systems are particularly relevant for evaluating surface roughness, material loss, gloss changes, and abrasion resistance of restorative materials and dental hard tissues.

Erosion and pH-cycling systems were identified as devices or protocols designed to reproduce chemical degradation, acid challenge, remineralization/demineralization cycling, and erosive tooth wear. In some studies, these systems were combined with mechanical abrasion or attrition to reproduce sequential or multifactorial degradation.

Tribocorrosion rigs represented the electrochemical end of the device spectrum. These setups typically combine a tribometer, an electrochemical cell, and a potentiostat to evaluate the interaction between mechanical wear and corrosion. They are particularly relevant for metallic dental materials, implant components, and situations where friction, saliva, pH, and electrochemical behavior interact. A classification of in vitro devices used for dental wear and oral aging simulation is presented in Figure 2.

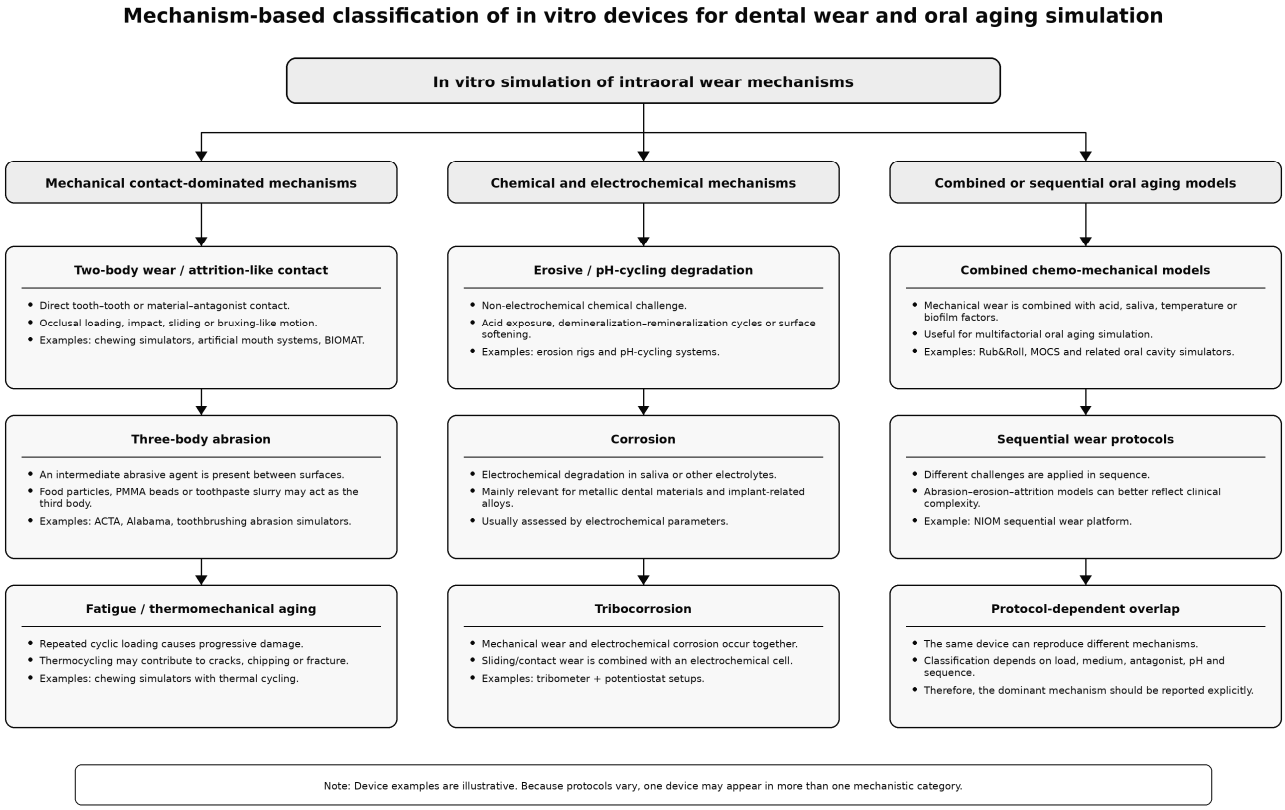

Figure 2. Mechanism-based classification of in vitro devices used for dental wear and oral aging simulation.

3.5. Distribution of Devices by Category

The 19 included devices or device families were distributed across the main categories of in vitro oral wear simulation. Chewing and mastication simulators formed the largest category, reflecting their central role in the evaluation of restorative material wear, antagonist wear, thermomechanical aging, and fatigue. These devices included both historical systems and modern commercial platforms.

Three-body wear machines accounted for a smaller but historically important group, mainly represented by ACTA and Alabama. Robotic and multiaxial systems formed a distinct category characterized by increased movement complexity and improved reproduction of mandibular trajectories. Generic tribometers and tribocorrosion rigs were classified separately because they are primarily tribological and electrochemical tools rather

than mastication simulators. Toothbrushing abrasion and pH-cycling/erosion devices were included as additional categories because they simulate specific non-occlusal or chemo-mechanical wear mechanisms.

A practical distribution of the included devices is presented in Table 4.

Table 4. Classification of the 19 included devices/device families according to operating principle.

No.	Device or Device Family	Main Category	Dominant Simulation Mechanism	Primary Substrate/Application
1	Minnesota ART/artificial mouth [7]	Artificial mouth/chewing simulation	Occlusal loading, sliding, saliva/temperature control	Tooth wear, restoration/material wear, and combined sequential protocols
2	ACTA wear machine [5]	Three-body wear simulator	Abrasion with intermediate medium	Mainly restoration/material wear; three-body abrasive ranking
3	Alabama wear simulator [8]	Three-body wear simulator	Impact/abrasion with intermediate medium	Mainly restoration/material wear; impact/abrasion
4	Zurich/CoCoM [9]	Computer-controlled chewing simulator	Occlusal loading and sliding with thermocycling	Tooth wear, restoration/material wear, and combined sequential protocols
5	OHSU oral wear simulator [10]	Multi-mode oral wear simulator	Abrasion and attrition	Tooth wear, restoration/material wear, and combined sequential protocols
6	BIOMAT wear simulator [17]	Two-body wear simulator	Simulated jaw movement/contact wear	Tooth wear, restoration/material wear, and combined sequential protocols
7	Willytec/SD Mechatronik CS-4/CS-4.8 [11]	Commercial chewing simulator	Two-axis mastication, sliding, bruxism simulation	Restoration/material wear and antagonist tooth wear
8	Regensburg/eGo chewing simulator [12]	Thermomechanical chewing simulator	Vertical/lateral loading with thermocycling	Restoration/material wear, thermomechanical aging, antagonist wear
9	Dento-Munch [18]	Multiaxial chewing simulator	Six-degree-of-freedom mastication	Tooth wear, restoration/material wear, and combined sequential protocols
10	Masticatory robot/robotic chewing simulator [32]	Robotic mastication simulator	3D mandibular movement and implant/prosthetic loading	Tooth wear, restoration/material wear, and combined sequential protocols
11	Force/position-controlled robotic dental wear simulator [33]	Robotic wear simulator	Hybrid force/position control, multi-contact wear	Tooth wear, restoration/material wear, and combined sequential protocols
12	Dual-direction masticatory simulator [20]	Custom mastication simulator	Uni- and bidirectional loading trajectories	Tooth wear, restoration/material wear, and combined sequential protocols
13	Rub&Roll [26,27]	Multifunctional oral aging device	Combined mechanical and chemical aging	Tooth wear, restoration/material wear, and combined sequential protocols
14	MARIO chewing bench [21]	Oral aging/compound-release simulator	Chemo-mechanical aging and eluate analysis	Tooth wear, restoration/material wear, and combined sequential protocols

Table 4. *Cont.*

No.	Device or Device Family	Main Category	Dominant Simulation Mechanism	Primary Substrate/Application
15	Biocycle V2 [28]	Commercial mechanical cycling simulator	Compression/impact cycling and optional sliding	Tooth wear, restoration/material wear, and combined sequential protocols
16	Esetron MOD/MOY-101 [29]	Dynamic mastication simulator	Mono- or biaxial wear simulation	Tooth wear, restoration/material wear, and combined sequential protocols
17	DUT-2 [30]	Six-axis robotic chewing simulator	Mandibular motion, high occlusal force, saliva environment	Tooth wear, restoration/material wear, and combined sequential protocols
18	NIOM sequential wear platform [22]	Sequential abrasion–erosion–attrition platform	Combined abrasion, erosion, and attrition	Tooth wear, restoration/material wear, and combined sequential protocols
19	MOCS [31]	Multifunctional/tribological device family	pH-cycling, biofilm, tribometry, tribocorrosion	Tooth-wear models, biofilm/pH-cycling, and material tribology

3.6. Chronological Development of In Vitro Dental Wear Simulation Devices

The chronological distribution of the included devices showed a progressive but non-linear development of in vitro dental wear simulation. Early devices from the 1980s and early 1990s focused mainly on artificial mouth systems, three-body wear machines, and computer-controlled mastication. Minnesota ART/artificial mouth, ACTA, Alabama, and Zurich/CoCoM represented this early phase and contributed substantially to the establishment of experimental parameters for dental wear testing.

During the mid- and late 1990s, devices such as the OHSU oral wear simulator, BIOMAT, Willytec, and Regensburg chewing simulator expanded the field toward multimodal wear testing and thermomechanical aging. These systems introduced more standardized chewing cycles, sliding movement, antagonist control, and thermal cycling protocols.

From approximately 2007 onward, the field moved toward multiaxial and robotic platforms. Dento-Munch, masticatory robot systems, force/position-controlled robotic wear simulators, and later DUT-2 reflected the increasing interest in reproducing mandibular kinematics, force feedback, and multi-contact occlusal loading. These systems provided improved biomechanical realism, although often at the expense of cost, complexity, and throughput.

Since 2014, a further shift was observed toward multifunctional oral aging systems. Devices such as Rub&Roll, MARIO, NIOM sequential wear platform, and MOCS expanded the simulation target from mechanical wear alone to combined chemical, thermal, biological, and mechanical degradation. This development reflects a broader conceptual transition from “wear testing” to “oral environment simulation”. The chronological development of the main in vitro devices used for dental wear and oral aging simulation is represented in Figure 3.

3.7. Controllable Experimental Parameters

Across the included devices, the most commonly controlled mechanical parameters were vertical load, number of cycles, loading frequency, sliding distance, movement trajectory, mouth opening, antagonist geometry, and contact pattern. Chewing simulators generally controlled load, frequency, vertical movement, and lateral sliding. Robotic simulators provided additional control over multidirectional movement, force feedback, and sometimes hybrid force/position regulation.

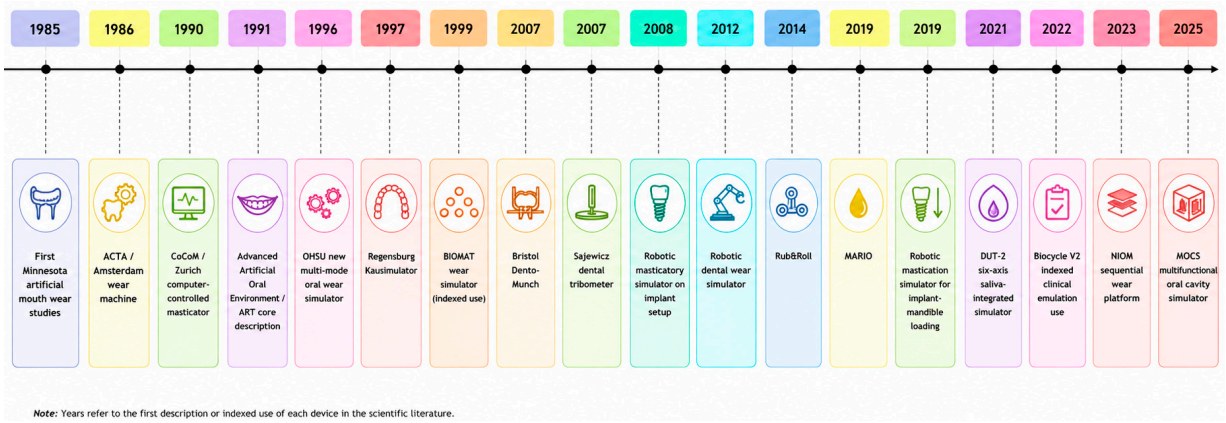

Figure 3. Chronological development of the main in vitro devices used for dental wear and oral aging simulation.

Environmental parameters varied considerably between devices. Some systems operated only in water or artificial saliva, whereas others incorporated temperature control, thermocycling, saliva flow, pH variation, acidic solutions, abrasive slurry, or biofilm-related conditions. Minnesota ART, Rub&Roll, DUT-2, NIOM sequential platform, and MOCS were among the devices with broader environmental simulation capabilities.

The type of antagonist was another important variable. Reported antagonists included human enamel, steatite, ceramic spheres, metal balls, tungsten carbide styluses, stainless steel balls, PMMA beads, polyethylene tape, toothbrush bristles, and custom prosthetic or implant-related components. The choice of antagonist strongly influenced the clinical relevance and comparability of wear results.

Overall, the extracted data showed that load, cycles, frequency, sliding, antagonist type, medium, temperature, and pH were the most relevant parameters for protocol standardization. However, these variables were not consistently reported across all studies, contributing to methodological heterogeneity. The preliminary catalog similarly identified force, cycle number, frequency, sliding path, lubrication medium, temperature, thermocycling, pH, saliva flow, antagonist type, and force/position feedback as the principal controllable variables in dental wear simulation devices.

3.8. Outcomes Reported in Wear Simulation Studies

The outcomes reported across the included devices reflected the diversity of wear mechanisms and simulation objectives. The most frequently reported outcomes were wear depth, volume loss, surface roughness, mass loss, two-dimensional or three-dimensional contour change, and antagonist wear. Chewing simulators and three-body wear machines most commonly reported material wear, antagonist wear, and surface degradation.

Tribological systems, including pin-on-disk and reciprocating tribometers, frequently reported coefficient of friction, wear scar morphology, wear volume, and contact surface changes. Toothbrushing abrasion systems usually reported surface roughness, mass loss, gloss loss, and profilometric changes. Erosion and pH-cycling platforms often evaluated mineral loss, surface softening, roughness, and lesion development. Tribocorrosion setups reported electrochemical parameters such as corrosion potential, corrosion current, ion release, and mechanically induced surface degradation.

Some advanced or multifunctional systems reported additional outcomes beyond wear volume or surface loss. These included fracture, chipping, fatigue failure, marginal degradation, compound release, eluate analysis, and biofilm-related changes. MARIO, Rub&Roll, NIOM sequential wear platform, DUT-2, and MOCS were particularly relevant

in this respect because they were designed to evaluate more complex oral aging processes rather than simple mechanical wear alone.

3.9. Device Suitability According to Research Objective

The suitability of each device category depended strongly on the dominant degradation mechanism being investigated. For studies focused on occlusal contact, sliding wear, antagonist wear, or thermomechanical aging of restorations, two-axis chewing simulators such as Willytec/SD Mechatronik, Regensburg/eGo, Zurich/CoCoM, Biocycle V2, and Esetron MOD/MOY-101 were the most relevant systems. For three-body abrasion and comparative material ranking, ACTA and Alabama remained historically important.

For studies requiring more realistic mandibular motion or implant/prosthetic loading, multiaxial robotic systems such as Dento-Munch, masticatory robot platforms, force/position-controlled robotic wear simulators, and DUT-2 were more appropriate. However, these systems were generally associated with higher complexity and lower accessibility.

For chemo-mechanical oral aging, Rub&Roll and NIOM sequential wear platform were particularly suitable because they allowed the combination or sequencing of mechanical contact, abrasion, erosion, acidic exposure, saliva, and immersion conditions. For pH-cycling, biofilm-related degradation, and hard tissue lesion development, MOCS and related oral cavity simulation systems were more appropriate. For tribocorrosion, the most relevant setup was not a single named dental device, but rather a combination of reciprocating or ball-on-flat tribometry with an electrochemical cell and potentiostat.

This device-specific suitability supports the principle that device selection should be based on the dominant phenomenon to be isolated—occlusal contact, sliding, three-body abrasion, erosive wear, tribocorrosion, biofilm/pH-cycling, or thermomechanical aging—rather than on the general popularity of a given simulator.

3.10. Descriptive Methodological Appraisal

The descriptive methodological appraisal showed substantial variability in the completeness of device and protocol reporting. Commercial systems such as SD Mechatronik CS-4/CS-4.8 and Biocycle V2 generally provided clearer information regarding load range, number of chambers, operating frequency, and optional modules. In contrast, some custom-built or regionally used systems were less consistently described, particularly regarding exact movement trajectory, calibration, force control, and environmental parameters.

Studies using chewing simulators usually reported basic mechanical parameters such as load, number of cycles, frequency, and antagonist type. However, details regarding system compliance, exact sliding path, antagonist wear calibration, and conversion of cycles to clinical time were often incomplete. Tribometer-based studies tended to report load, sliding speed, distance, and lubrication conditions more precisely, but their anatomical relevance was more limited. Erosion, pH-cycling, and oral cavity simulation studies frequently reported chemical conditions in detail but varied in their reporting of mechanical or flow-related parameters.

Overall, the most common methodological limitations were incomplete reporting of environmental conditions, insufficient description of custom-built devices, lack of standardized outcome units, variability in antagonist selection, and limited justification of cycle numbers or clinical equivalence. These findings indicate that future studies should report device parameters more consistently, including load, frequency, sliding distance, contact geometry, antagonist material, medium composition, temperature, pH, number of cycles, and outcome measurement method.

Because several devices can be used under different experimental protocols, the descriptive appraisal was organized by methodological reporting domain rather than by mutually exclusive device category. Descriptive appraisal of reporting quality and methodological limitations across the included sources are presented in Table 5.

Table 5. Descriptive appraisal of methodological reporting across included sources.

Reporting Domain	Generally Well-Reported Items	Common Reporting Gaps	Relevance for Interpretation and Reproducibility
Device identification and technical description	Named commercial systems, historical devices, and some original device descriptions were usually clearly identifiable.	Custom-built or modified devices were sometimes described only briefly, with limited technical detail regarding movement pattern, calibration, or control strategy.	Incomplete device description limits reproducibility and makes it difficult to compare results across laboratories.
Mechanical testing parameters	Load, number of cycles, frequency, and basic movement type were commonly reported in chewing simulator, tribometer, and toothbrushing studies.	Sliding distance, contact sequence, load profile, force control, antagonist path, and clinical justification of cycle number were inconsistently reported.	Mechanical parameters strongly influence wear magnitude, fatigue behavior, and material ranking.
Environmental simulation parameters	Medium type, temperature, thermocycling, pH, slurry composition, or electrolyte were often reported when central to the protocol.	Saliva composition, flow rate, pH variation over time, temperature control, biofilm conditions, and chemical challenge sequence were frequently incomplete or device-dependent.	Environmental conditions determine whether the protocol mainly reproduces attrition, abrasion, erosion, corrosion, tribocorrosion, or combined oral aging.
Specimen and antagonist description	Material type, specimen geometry, and antagonist material were usually stated in comparative wear studies.	Antagonist shape, surface preparation, wear of the antagonist itself, specimen mounting, and pre-test conditioning were not always fully described.	Differences in antagonist material and contact geometry can substantially change wear behavior and reduce comparability.
Outcome measurement	Wear depth, volume loss, surface roughness, mass loss, friction coefficient, antagonist wear, fracture, ion release, or electrochemical parameters were commonly reported.	Measurement technique, scanning resolution, wear-facet definition, data-processing method, and units were not consistently standardized.	Outcome variability may lead to different material rankings even when similar devices are used.
Protocol rationale and clinical relevance	Some studies justified selected loads, cycles, temperatures, or media using previous literature or clinical assumptions.	Direct equivalence between laboratory cycles and clinical service time was often uncertain or insufficiently justified.	Lack of protocol rationale limits the clinical interpretation of in vitro wear data.
Statistical and comparative analysis	Many comparative studies reported statistical testing between materials or protocols.	Sample size justification, handling of repeated measurements, inter-device comparisons, and uncertainty reporting were variable.	Transparent statistical reporting is needed to support reliable comparison between devices, materials, and wear mechanisms.

3.11. Summary of Main Findings

The results of this scoping review indicate that in vitro dental wear simulation has developed from isolated mechanical wear testing toward increasingly complex oral environment simulation. Historical systems established the foundation for device-based dental wear testing, while modern platforms increasingly incorporate multidirectional movement, saliva, temperature, pH, chemical challenge, biofilm, and electrochemical monitoring.

The 19 included devices or device families can be grouped according to the dominant mechanism simulated: mastication and occlusal wear, three-body abrasion, robotic mandibular motion, tribological sliding, brushing abrasion, erosion/pH-cycling, tribocorrosion, and multifunctional oral aging. No single device was capable of reproducing all intraoral conditions. Therefore, device selection should be guided by the specific wear mechanism, material type, and research question under investigation.

The main methodological gap identified across the literature was the lack of standardized reporting and protocol harmonization. Differences in load, cycles, frequency, sliding distance, antagonist material, medium, pH, temperature, and outcome measurement limit direct comparison between studies and restrict the ability to translate laboratory cycles into clinical service time.

To address the overlap between device designs and experimental protocols, the device mapping was reorganized according to the dominant wear mechanism reproduced by each testing approach. This mechanism-based structure distinguishes two-body wear, three-body abrasion, erosive or pH-cycling degradation, corrosion/tribocorrosion, and combined or sequential oral aging models. The mechanism-based mapping of in vitro devices and device families used for dental wear and oral aging simulation.

4. Discussion

The present scoping review provides a structured map of a field that has often appeared more fragmented than it actually is. Although the initial database yield was broad, device-level consolidation showed that much of the literature repeatedly relies on a relatively limited set of recurring simulator logics, including artificial-mouth systems, chewing simulators, three-body wear devices, tribometers, toothbrushing/erosion platforms, robotic masticatory systems, and multifunctional oral-aging assemblies. This synthesis is important because it reframes the literature from a study-by-study perspective into a platform-by-platform perspective, which is more useful for methodology selection, critical comparison, and future standardization. In practical terms, the present review indicates that the central problem in this field is no longer the absence of devices, but the absence of a shared framework for matching devices to specific wear mechanisms and for reporting their parameters with sufficient consistency.

These findings are broadly consistent with earlier reviews, but they also extend them in a useful way [1]. Previous methodological overviews emphasized that oral wear is inherently multifactorial and that no single laboratory method can reproduce all clinically relevant parameters simultaneously [34]. The present review confirms that conclusion, while also showing that the contemporary literature has moved beyond the older idea of a generic “chewing simulator” and now includes a wider set of tools designed to isolate or integrate different mechanisms, such as tribological friction, erosive softening, abrasion–attrition coupling, saliva-mediated ageing, and biofilm-associated degradation. In that sense, the present mapping complements earlier reviews of wear simulation and chewing simulators by offering a broader taxonomy that better reflects how current laboratories actually structure in vitro testing [35,36].

A key interpretive point is that the included systems are best understood as mechanistic families rather than interchangeable brands or isolated instruments. Two-body chewing simulators remain most informative when the research objective is controlled impact-plus-sliding contact between a restoration and an antagonist [13,25,35]. By contrast, three-body wear systems are more appropriate when the presence of an interposed abrasive medium is central to the phenomenon of interest [5,25]. Tribometers offer greater precision when the main outcomes are coefficient of friction, wear-track morphology, or surface-mechanism analysis, but they necessarily simplify occlusal kinematics. Robotic

and multiaxial platforms improve kinematic realism and therefore offer particular value for full-contour prosthetic testing, yet their complexity may reduce accessibility and inter-laboratory reproducibility [2,37,38]. Multifunctional oral-aging systems represent a further conceptual step because they attempt to model oral wear as a coupled chemo-mechanical or bio-chemo-mechanical process rather than as a purely mechanical event [26,39].

The chronology of the mapped devices is also analytically informative. Early systems such as the Minnesota artificial-mouth lineage, Zurich/CoCoM, ACTA, and later OHSU were developed primarily to create wear patterns and failure modes with plausible clinical relevance, and in some cases to claim explicit links between in vitro cycling and clinical service [40]. Over time, the field moved toward improved programmability and more standardized commercial thermomechanical platforms. More recently, however, the dominant ambition has changed again: devices such as Rub&Roll [26,27], MARIO [21], DUT-2 [30], sequential abrasion–erosion–attrition platforms, and MOCS [31] are not simply wear testers, but attempts to reconstruct broader aspects of the oral environment, including fluid flow, acidity, abrasive challenge, temperature regulation, released-compound analysis, or biofilm growth [1]. This temporal sequence strongly suggests that the field has evolved from comparative wear ranking toward mechanistic oral-environment emulation.

The major obstacle to cumulative interpretation across this literature remains methodological heterogeneity. Studies differ not only in force magnitude, cycle number, frequency, and antagonist selection, but also in the shape of the load profile, the sequence of sliding and impact events, the presence or absence of third-body media, thermal cycling regimens, pH control, specimen geometry, and the definition of the measured endpoint [1,20,41]. This lack of harmonization is not merely inconvenient; it affects scientific conclusions. Round-robin studies have shown that different wear methods may produce different rankings for the same materials, and large methodological reviews have concluded that methods based on different wear concepts are not directly comparable. More recent analyses have added that even the measurement stage itself may be a meaningful source of variation, whether because of profilometric strategy, wear-facet definition, or data-processing assumptions. The descriptive methodological appraisal in the present review should therefore be read as one of its principal findings, rather than as a secondary methodological aside [42,43].

The mapped devices also show complementary strengths and limitations that help explain why no single system has become universally dominant [33]. Historically validated artificial-mouth and oral wear simulators are valuable because they are among the few platforms linked to published clinical-correlation claims, yet they may be expensive, technically demanding, or only partially accessible outside specialized centers [2,44]. Modern commercial thermomechanical simulators provide robust workflow advantages, including multiple chambers, programmable motion, and options for thermocycling or bruxism-style sliding, but in many studies they are used primarily for fatigue or fracture ageing rather than for deep mechanistic wear analysis. Pneumatic mechanical cycling systems improve throughput and permit higher forces or frequencies, but they may simplify the environmental dimension. Tribometers and tribocorrosion assemblies are particularly strong when frictional behavior, electrochemical interaction, or surface-wear mechanisms are the main target outcomes [44], whereas multifunctional platforms such as Rub&Roll, DUT-2, and MOCS are more suitable for explicitly coupled chemo-mechanical or saliva-regulated experiments. However, those newer platforms still require broader cross-center validation before they can serve as benchmark methods [45,46].

The present scoping review itself has several notable strengths. Most importantly, it adopts the device or device-family as the unit of synthesis, which is methodologically appropriate for a field in which the same platform may be described in an original device paper, used in multiple material studies, modified in later methodological reports, and

supplemented by manufacturer documentation. This approach reduces artificial inflation of diversity that would arise from counting papers rather than platforms. The review is also strengthened by its inclusion of historical sources and technical documentation, which is necessary because some devices are better documented through foundational methodology articles or official specifications than through later application studies [1]. Nevertheless, important limitations should be acknowledged. The review maps the evidence but does not estimate pooled predictive validity; device-family consolidation may obscure meaningful within-family technical variation; English-language accessible sources may underrepresent regionally used systems; and some in-house or commercial devices remain only partially documented in the public domain. These limitations are compatible with scoping-review methodology, which is designed to map breadth and identify gaps rather than to produce an effect estimate, but they should temper overly strong claims about comparative superiority [23].

From a practical standpoint, device selection should be driven by the primary research objective rather than by historical familiarity or the visibility of a particular platform in the literature [47]. If the objective is comparative ranking of restorative materials under controlled occlusal contact, two-body chewing simulators or established oral wear simulators remain reasonable options [48]. If the study seeks to reproduce food-mediated generalized wear, three-body systems are better aligned with that mechanism. If the key question concerns friction, wear tracks, or tribocorrosive interaction, a reciprocating or ball-on-flat tribometer, optionally coupled with electrochemical monitoring, is usually more informative than a chewing simulator [1,45]. If the target phenomenon is erosive tooth wear, sequential abrasion–erosion–attrition, or saliva- and biofilm-mediated lesion development, multifunctional platforms should be preferred because they more explicitly reproduce the environmental context [49,50]. Finally, if the question concerns complex prosthetic contact, mandibular-path replication, or combined force/position control, robotic and six-axis systems offer capabilities that simpler devices cannot provide. In other words, the correct question is not "Which simulator is best?", but "Which simulator best isolates or integrates the mechanism under investigation?".

Tooth wear and restoration/material wear should be distinguished because, although they may be simulated with similar devices, they represent different experimental targets. Tooth-wear models focus mainly on enamel or dentin loss caused by attrition, abrasion, erosion, pH-cycling, or biofilm-related degradation, whereas restoration/material-wear models assess degradation of composites, ceramics, metals, polymers, prosthetic, or implant-related materials. Therefore, future studies should clearly report the worn substrate, antagonist, and whether the main endpoint concerns tooth wear, restoration/material wear, or combined tooth–material interface wear.

Because incomplete reporting is one of the most remediable sources of irreproducibility in this field, future primary studies should include a minimum dataset covering device identity, calibration, kinematics, environment, antagonists, specimen configuration, and metrology. Existing standards and reviews already imply many of these requirements, but they are inconsistently operationalized in published studies [51–53]. The consequence is that nominally similar protocols cannot be compared with confidence, and new devices cannot be evaluated fairly against established ones [54]. Table 6 therefore proposes a pragmatic set of minimal reporting items for in vitro device studies. The purpose of the table is not to constrain innovation, but to make innovation interpretable, reproducible, and usable for meta-research, standards work, and future interlaboratory validation studies.

Table 6. Mechanism-based mapping of in vitro devices and device families used for dental wear and oral aging simulation.

Dominant Wear Mechanism/Tester Class	Device or Device Family	Contact Configuration/Mechanism Reproduced	Typical/Reported Load	Protocol Modifiers	Main Limitations
Two-body wear/attrition-like contact	Minnesota ART/artificial mouth [7]	Direct antagonist–specimen contact with occlusal loading and sliding movement	Programmable; protocol-dependent	Saliva or artificial saliva; temperature control around 37 °C	Historically important, but limited throughput and complex setup
Two-body wear/attrition-like contact	Zurich/CoCoM [9]	Vertical impact combined with short lateral sliding	~49 N	Water; thermocycling commonly reported at 5–55 °C	Good for thermomechanical wear, but limited biological complexity
Two-body wear/attrition-like contact	Willytec/SD Mechatronik CS-4/CS-4.8 [11]	Two-axis chewing simulation with vertical loading and lateral sliding	Protocol-dependent, commonly within masticatory-load ranges	Water or artificial saliva; optional thermocycling	Widely used, but protocols vary considerably between studies
Two-body wear/attrition-like contact	Regensburg/eGo chewing simulator [12]	Vertical and lateral loading under thermomechanical conditions	Protocol-dependent	Thermocycling; antagonist-controlled testing	Mainly reproduces simplified occlusal contact
Two-body wear/attrition-like contact	BIOMAT wear simulator [17]	Direct two-body contact simulating jaw movement and occlusal stresses	225 N impact force and 28 MPa impact stress reported in the original study	Limited environmental control reported	Historical device; protocol details not always extensively reproduced in later sources
Two-body wear/attrition-like contact	Biocycle V2 [28]	Mechanical cycling with compression, impact, and optional sliding	Protocol-dependent	Optional water/thermal cycling depending on configuration	Useful for mechanical cycling, but oral environmental factors are limited
Two-body wear/attrition-like contact	Esetron MOD/MOY-101 [29]	Mono- or biaxial dynamic mastication simulation	Protocol-dependent	Optional medium depending on protocol	Commercially available, but published dental protocols remain heterogeneous
Two-body/multi-contact robotic wear	Dento-Munch [18]	Multiaxial chewing simulation with six degrees of freedom	Protocol-dependent	Force and motion control; prosthetic or restorative setups	High biomechanical fidelity but greater cost and complexity
Two-body/multi-contact robotic wear	Masticatory robot/robotic chewing simulator [32]	Three-dimensional mandibular movement and prosthetic or implant loading	Protocol-dependent	Force/path control; device-specific environmental conditions	Limited accessibility and lower interlaboratory comparability

Table 6. *Cont.*

Dominant Wear Mechanism/Tester Class	Device or Device Family	Contact Configuration/Mechanism Reproduced	Typical/Reported Load	Protocol Modifiers	Main Limitations
Two-body/multi-contact robotic wear	Force/position-controlled robotic dental wear simulator [33]	Hybrid force/position-controlled contact and sliding wear	Protocol-dependent	Multi-contact loading; robotic control	Technically complex and usually limited to specialized laboratories
Two-body/multi-contact robotic wear	Dual-direction masticatory simulator [20]	Uni- and bidirectional loading trajectories	Protocol-dependent	Directional sliding control	Custom design; comparability with standard chewing simulators may be limited
Two-body/multi-contact robotic wear	DUT-2 six-axis robotic chewing simulator [30]	Six-axis mandibular motion with high occlusal-force simulation	Protocol-dependent; high-force capability reported	Saliva environment; complex mandibular movement	High complexity and limited independent validation
Three-body abrasion	ACTA wear machine [5]	Abrasive medium placed between specimen and antagonist	~0–50 N	Abrasive slurry or intermediate medium	Useful for comparative ranking, but limited anatomical realism
Three-body abrasion	Alabama wear simulator [8]	Impact and abrasion with an intermediate abrasive medium	~55–75 N	Polyethylene tape or PMMA slurry, depending on version	Historical system; protocol variations affect comparability
Three-body abrasion/mixed abrasion–attrition	OHSU oral wear simulator [10]	Combined abrasion and attrition, often with sliding and particulate medium	~20/80 N reported in common protocols	Particulate medium; limited environmental complexity	Multi-mode testing, but mechanisms may overlap within the same protocol
Three-body abrasion	Toothbrushing abrasion simulators	Abrasion by toothbrush bristles and toothpaste slurry	Protocol-dependent	Brushing load, stroke number, slurry composition	Simulates brushing abrasion rather than occlusal wear
Erosive/pH-cycling degradation	pH-cycling and erosion systems	Chemical challenge, demineralization–remineralization, or acid-induced softening	Not applicable unless combined with mechanical loading	Acid type, pH, exposure time, remineralizing solution	Does not reproduce mechanical contact unless combined with abrasion or attrition
Corrosion/tribocorrosion	Tribometer coupled with electrochemical cell and potentiostat	Mechanical sliding combined with electrochemical degradation	Protocol-dependent	Electrolyte, pH, applied potential, sliding distance	Not a single standardized dental device; high protocol dependence

Table 6. *Cont.*

Dominant Wear Mechanism/Tester Class	Device or Device Family	Contact Configuration/Mechanism Reproduced	Typical/Reported Load	Protocol Modifiers	Main Limitations
Combined chemo-mechanical oral aging	Rub&Roll [26,27]	Combined mechanical and chemical aging	Protocol-dependent	Saliva or immersion media; chemical challenge; rolling/sliding contact	Multifactorial simulation, but device-specific validation is needed
Combined chemo-mechanical oral aging	MARIO chewing bench [21]	Chemo-mechanical aging with compound-release assessment	Protocol-dependent	Medium collection; eluate analysis; mechanical cycling	Mainly suited for compound release and aging protocols
Combined sequential wear	NIOM sequential wear platform [22]	Sequential abrasion–erosion–attrition simulation	Protocol-dependent	Abrasion, acid challenge, and attrition applied sequentially	More clinically representative, but complex and less standardized
Combined oral cavity simulation	MOCS [31]	Multifunctional oral cavity simulation including pH-cycling, biofilm, tribometry, and tribocorrosion	Protocol-dependent	pH control, biofilm simulation, tribological and electrochemical modules	Broad simulation capacity, but high complexity and protocol dependence

Several priorities for future research emerge from this review. First, more head-to-head studies should test identical materials across different device families using harmonized endpoints, so that convergence or divergence of rankings can be documented explicitly. Second, the field would benefit from shared reference materials and reference antagonists that could be reused across laboratories to establish benchmarking datasets and uncertainty ranges. Third, newer multifunctional platforms should be subjected to multicenter reproducibility studies rather than remaining single-center proofs of concept. Fourth, translational studies should move beyond simple cycle-count equivalence claims and instead compare laboratory outcomes with longitudinal clinical metrics such as volumetric wear, maximum depth, antagonist damage, marginal breakdown, and observed failure modes. Fifth, environmental complexity should be introduced stepwise in validation research so that the incremental effect of pH, thermal cycling, saliva flow, abrasive media, and microbial challenge can be quantified rather than merely bundled into a single complex protocol.

Clinical translation nevertheless remains the central challenge for the entire field. Even the best-known artificial-mouth systems and oral wear simulators provide only partial models of intraoral function, and historical in vitro-to-clinical cycle equivalences should be interpreted as device- and context-specific approximations rather than universal conversion factors. Clinical wear is strongly influenced by patient-level variability, restorative design, antagonist characteristics, parafunction, lubrication, diet, and biological adaptation, all of which exceed what any bench model can fully reproduce. Accordingly, in vitro findings should be interpreted primarily as mechanism-informed comparative evidence, not as direct predictions of service life. The implications for standards development and regulator-facing preclinical testing are substantial. Existing ISO guidance remains highly valuable for toothbrushing and two-/three-body contact methods, but the present review suggests that future standards should adopt a more modular logic, with expandable domains for multiaxial kinematics, force-profile verification, thermo-chemo-mechanical coupling, tribocorrosion, and measurement uncertainty. Because restorative materials are

regulated as medical devices, more explicit and standardized preclinical wear reporting would likely strengthen the interpretability of evidence for both standards bodies and regulatory assessment.

In conclusion, this scoping review indicates that the literature on in vitro dental wear simulation is sufficiently mature to support a coherent taxonomy of devices, but not yet sufficiently standardized to support effortless comparison across studies or laboratories. The most defensible interpretation is that no device should be considered universally superior; rather, device suitability depends on the dominant wear mechanism, environmental challenge, and translational endpoint under investigation. Future progress will depend less on the proliferation of ever more elaborate machines and more on rigorous validation, complete reporting, and stronger linkage between laboratory outputs and clinical outcomes.

5. Conclusions

The findings show that no single device can reproduce all oral conditions. Each system is suited to specific mechanisms: chewing simulators for occlusal loading and antagonist wear, three-body wear machines for abrasive wear, tribometers for friction and wear-track analysis, and tribocorrosion rigs for combined mechanical and electrochemical degradation.

The development of these devices reflects a shift from simple mechanical wear testing toward more complex oral simulation platforms that integrate saliva, temperature, pH, erosion, biofilm, chemical aging, or multiaxial mandibular motion.

The main limitation identified across the literature is methodological heterogeneity. Differences in load, cycles, frequency, sliding distance, antagonist material, medium, pH, temperature, and outcome measurement reduce comparability between studies.

Therefore, device selection should be guided by the dominant wear mechanism, material type, and research question. Future studies should improve reporting and standardization of device parameters, protocols, and outcome measurements.

Overall, this review provides a device-centered taxonomy that may support better selection of experimental platforms and contribute to more standardized and clinically relevant in vitro testing of dental materials and hard dental tissues.

In addition, future device-based studies should explicitly distinguish between tooth-wear models, restoration/material-wear models, and combined tooth–material antagonist models, because the same simulator may answer different research questions depending on the substrate, antagonist, and selected outcome.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/oral6040086/s1. Supplementary Table S1. Source-level data extraction table for the reports included in the scoping review [55–76].

Author Contributions: Conceptualization, I.T., I.-G.Ș., I.L., C.I.L. and I.N.; methodology, N.C., F.C.B., A.C.T.-G., B.C.V. and M.C.B.; validation, I.T., I.-G.Ș. and I.N.; investigation, I.T., I.-G.Ș. and A.C.T.-G.; writing—original draft preparation, I.T., F.C.B., A.C.T.-G., C.I.L., B.C.V. and M.C.B.; writing—review and editing, I.-G.Ș., I.L., N.C. and I.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Soriano-Valero, S.; Román-Rodríguez, J.L.; Agustín-Panadero, R.; Bellot-Arcís, C.; Fons-Font, A.; Fernández-Estevan, L. Systematic review of chewing simulators: Reality and reproducibility of in vitro studies. *J. Clin. Exp. Dent.* **2020**, *12*, e1189–e1196. [CrossRef] [PubMed]
2. Wang, R.; Zhu, Y.; Chen, C.; Han, Y.; Zhou, H. Tooth wear and tribological investigations in dentistry. *Appl. Bionics Biomech.* **2022**, *2022*, 2861197. [CrossRef] [PubMed]
3. Ferracane, J.L. Is the wear of dental composites still a clinical concern? Is there still a need for in vitro wear simulating devices? *Dent. Mater.* **2006**, *22*, 689–692. [PubMed]
4. Lambrechts, P.; Debels, E.; Van Landuyt, K.; Peumans, M.; Van Meerbeek, B. How to simulate wear? Overview of existing methods. *Dent. Mater.* **2006**, *22*, 693–701. [CrossRef] [PubMed]
5. De Gee, A.J.; Pallav, P. Occlusal wear simulation with the ACTA wear machine. *J. Dent.* **1994**, *22*, S21–S27. [CrossRef] [PubMed]
6. Suzuki, S.; Leinfelder, K.F.; Kawai, K.; Tsuchitani, Y. Effect of particle variation on wear rates of posterior composites. *Am. J. Dent.* **1995**, *8*, 173–178. [PubMed]
7. DeLong, R.; Douglas, W.H. An artificial oral environment for testing dental materials. *IEEE Trans. Biomed. Eng.* **1991**, *38*, 339–345. [CrossRef] [PubMed]
8. Leinfelder, K.F.; Beaudreau, R.W.; Mazer, R.B. An in vitro device for predicting clinical wear. *Quintessence Int.* **1989**, *20*, 755–761. [PubMed]
9. Krejci, I.; Lutz, F.; Reimer, M. Wear of CAD/CAM ceramic inlays: Restorations, opposing cusps, and luting cements. *Quintessence Int.* **1994**, *25*, 199–207. [PubMed]
10. Condon, J.R.; Ferracane, J.L. Evaluation of composite wear with a new multi-mode oral wear simulator. *Dent. Mater.* **1996**, *12*, 218–226. [CrossRef] [PubMed]
11. Heintze, S.D. How to qualify and validate wear simulation devices and methods. *Dent. Mater.* **2006**, *22*, 712–734. [CrossRef] [PubMed]
12. Rosentritt, M.; Behr, M.; van der Zel, J.M.; Feilzer, A.J. Approach for valuating the influence of laboratory simulation. *Dent. Mater.* **2009**, *25*, 348–352. [CrossRef] [PubMed]
13. Rosentritt, M.; Preis, V.; Behr, M.; Hahnel, S.; Handel, G.; Kolbeck, C. Two-body wear of dental porcelain and substructure oxide ceramics. *Clin. Oral Investig.* **2012**, *16*, 935–943. [PubMed]
14. Mair, L.H. Wear in dentistry—Current terminology. *J. Dent.* **1992**, *20*, 140–144. [CrossRef] [PubMed]
15. Mair, L.H.; Stolarski, T.A.; Vowles, R.W.; Lloyd, C.H. Wear: Mechanisms, manifestations and measurement. Report of a workshop. *J. Dent.* **1996**, *24*, 141–148. [CrossRef] [PubMed]
16. Sajewicz, E. On evaluation of wear resistance of tooth enamel and dental materials. *Wear* **2006**, *260*, 1256–1261. [CrossRef]
17. Yap, A.U.J.; Ong, L.F.; Teoh, S.H.; Hastings, G.W. Comparative wear ranking of dental restoratives with the BIOMAT wear simulator. *J. Oral Rehabil.* **1999**, *26*, 228–235. [CrossRef] [PubMed]
18. Alemzadeh, K.; Raabe, D. Prototyping Artificial Jaws for the Bristol Dento-Munch Robo-Simulator. 'A parallel robot to test dental components and materials'. In *2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society 22 August 2007*; IEEE: NewYork, NY, USA, 2007; pp. 1453–1456.
19. Rosentritt, M.; Steiger, D.; Behr, M.; Handel, G.; Kolbeck, C. Influence of substructure design and spacer settings on the in vitro performance of molar zirconia crowns. *J. Dent.* **2009**, *37*, 978–983. [CrossRef] [PubMed]
20. Singhatanadgit, W.; Junkaew, P.; Singhatanadgid, P. Effect of bidirectional loading on contact and force characteristics under a newly developed masticatory simulator with a dual-direction loading system. *Dent. Mater. J.* **2016**, *35*, 952–961. [CrossRef] [PubMed]
21. Abouelleil, H.; Jeannin, C.; Sadat, A.; Grosgogeat, B. Development of a Chewing Simulator for Testing Dental Materials: A Pilot Study. *Curr. J. Appl. Sci. Technol.* **2014**, *5*, 1–8.
22. Mulic, A.; Ruud, A.; Stenhagen, I.R.; Bruzell, E.; Tulek, A. Deterioration of direct restorative materials under erosive conditions with impact of abrasion and attrition in vitro. *Biomater. Investig. Dent.* **2023**, *10*, 2202211. [CrossRef] [PubMed]
23. Tricco, A.C.; Lillie, E.; Zarin, W.; O'Brien, K.K.; Colquhoun, H.; Levac, D.; Moher, D.; Peters, M.D.; Horsley, T.; Weeks, L.; et al. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and explanation. *Ann. Intern. Med.* **2018**, *169*, 467–473. [CrossRef] [PubMed]
24. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef] [PubMed]
25. *ISO/TS 14569-2*; Dental Materials—Guidance on Testing of Wear—Part 2: Wear by Two- and/or Three-Body Contact. ISO: Geneva, Switzerland, 2001.
26. Ruben, J.L.; Roeters, F.J.M.; Montagner, A.F.; Huysmans, M.C.D.N.J.M. A multifunctional device to simulate oral ageing: The "Rub&Roll". *J. Mech. Behav. Biomed. Mater.* **2014**, *30*, 75–82. [CrossRef] [PubMed]

27. Maier, E.; Ruben, J.; Palin, W.M.; Bronkhorst, E.; Olmos, M.; Matta, R.E.; Loomans, B. Developing an optimised method for accurate wear testing of dental materials using the 'Rub&Roll'device. *Sci. Rep.* **2024**, *14*, 17885. [PubMed]
28. Biopdi. *Biocycle V2: Mechanical Cycling Simulator*; Biopdi: São Carlos, Brazil. Available online: https://biopdi.com.br/ciclagem/ciclagem-mecanica/biocycle-v2/ (accessed on 10 April 2026).
29. Esetron Smart Robotechnologies. *MOD/MOY-101 Dynamic Mastication Simulator: Technical and Application Information*; Esetron Smart Robotechnologies: Ankara, Turkey.
30. Qin, W.; Cong, M.; Liu, D.; Ren, X. A robotic chewing simulator supplying six-axis mandibular motion, high occlusal force, and a saliva environment for denture tests. *Proc. Inst. Mech. Eng. Part H* **2021**, *235*, 751–761. [CrossRef]
31. Maske, T.T.; Cenci, M.S.; Patzlaff, R.T.; Initiative MOCS; Hashizume, L.N.; Maltz, M.; Arthur, R.A. Presentation of a new multifunctional oral cavity simulator: The MOCS. *Braz. Oral Res.* **2025**, *39*, e022. [CrossRef] [PubMed]
32. Conserva, E.; Menini, M.; Tealdo, T.; Bevilacqua, M.; Pera, F.; Ravera, G.; Pera, P. Robotic chewing simulator for dental materials testing on a sensor-equipped implant setup. *Int. J. Prosthodont.* **2008**, *21*, 501–508. [PubMed]
33. Raabe, D.; Harrison, A.; Ireland, A.; Alemzadeh, K.; Sandy, J.; Dogramadzi, S.; Melhuish, C.; Burgess, S. Improved single-and multi-contact life-time testing of dental restorative materials using key characteristics of the human masticatory system and a force/position-controlled robotic dental wear simulator. *Bioinspir. Biomim.* **2011**, *7*, 016002.
34. Krejci, I.; Albert, P.; Lutz, F. The influence of antagonist standardization on wear. *J. Dent. Res.* **1999**, *78*, 713–719. [CrossRef] [PubMed]
35. Stawarczyk, B.; Özcan, M.; Schmutz, F.; Trottmann, A.; Roos, M.; Hämmerle, C.H.F. Two-body wear of monolithic, veneered and glazed zirconia and their corresponding enamel antagonists. *Acta Odontol. Scand.* **2013**, *71*, 102–112. [PubMed]
36. Conserva, E.; Menini, M.; Tealdo, T.; Bevilacqua, M.; Ravera, G.; Pera, F.; Pera, P. The use of a masticatory robot to analyze the shock absorption capacity of different restorative materials for prosthetic implants: A preliminary report. *Int. J. Prosthodont.* **2009**, *22*, 53–55. [PubMed]
37. Sajewicz, E. Effect of saliva viscosity on tribological behaviour of tooth enamel. *Tribol. Int.* **2009**, *42*, 327–332. [CrossRef]
38. Zheng, J.; Zhou, Z.R. Study of in vitro wear of human tooth enamel. *Tribol. Lett.* **2007**, *26*, 181–189. [CrossRef]
39. Jeannin, C.; Gritsch, K.; Liodénot, J.J.; Grosgogeat, B. MARIO: The first chewing bench used for ageing and analysis the released compounds of dental materials. *Comput. Methods Biomech. Biomed. Eng.* **2020**, *22*, S62–S64.
40. Preis, V.; Behr, M.; Handel, H.; Schneider-Feyrer, S.; Hahnel, S.; Rosentritt, M. Wear performance of dental ceramics after grinding and polishing treatments. *J. Mech. Behav. Biomed. Mater.* **2012**, *10*, 13–22. [CrossRef] [PubMed]
41. Tahir, A.M.; Jilich, M.; Trinh, D.C.; Cannata, G.; Barberis, F.; Zoppi, M. Architecture and design of a robotic mastication simulator for interactive load testing of dental implants and the mandible. *J. Prosthet. Dent.* **2019**, *122*, 389.e1–389.e8. [CrossRef]
42. Zheng, J.; Zhou, Z.R. Friction and wear behavior of human teeth under various wear conditions. *Tribol. Int.* **2007**, *40*, 278–284. [CrossRef]
43. Wang, L.; Liu, Y.; Si, W.; Feng, H.; Tao, Y.; Ma, Z. Friction and wear behaviors of dental ceramics against natural tooth enamel. *J. Eur. Ceram. Soc.* **2012**, *32*, 2599–2606. [CrossRef]
44. Mathew, M.T.; Cheng, K.Y.; Sun, Y.; Barao, V.A. The progress in tribocorrosion research (2010–21): Focused on the orthopedics and dental implants. *J. Bio-Tribo-Corros.* **2023**, *9*, 48. [CrossRef] [PubMed]
45. Johnsen, G.F.; Taxt-Lamolle, S.F.; Haugen, H.J. Wear model simulating clinical abrasion on composite filling materials. *Dent. Mater. J.* **2011**, *30*, 739–748. [CrossRef] [PubMed]
46. Faverani, L.P.; Barão, V.A.; Ramalho-Ferreira, G.; Delben, J.A.; Ferreira, M.B.; Júnior, I.R.; Assunção, W.G. The influence of bone quality on the biomechanical behavior of full-arch implant-supported fixed prostheses. *Mater. Sci. Eng. C* **2014**, *37*, 164–170.
47. Wiegand, A.; Attin, T. Design of erosion/abrasion studies—Insights and rational concepts. *Caries Res.* **2011**, *45*, 53–59. [PubMed]
48. Hahnel, S.; Behr, M.; Handel, G.; Rosentritt, M. Two-body wear of artificial acrylic and composite resin teeth in relation to antagonist material. *J. Prosthet. Dent.* **2009**, *101*, 269–278. [CrossRef] [PubMed]
49. Attin, T.; Wegehaupt, F.J. Impact of erosive conditions on tooth-colored restorative materials. *Dent. Mater.* **2014**, *30*, 43–49. [CrossRef] [PubMed]
50. Shellis, R.P.; Addy, M. The interactions between attrition, abrasion and erosion in tooth wear. *Monogr. Oral Sci.* **2014**, *25*, 32–45. [CrossRef] [PubMed]
51. Yilmaz, E.C. Investigation of two-body wear resistance of composite materials for biomaterial application in oral environment: The influence of antagonist material. *Mater. Technol.* **2020**, *35*, 159–167.
52. Koottathape, N.; Takahashi, H.; Iwasaki, N.; Kanehira, M.; Finger, W.J. Quantitative wear and wear damage analysis of composite resins in vitro. *J. Mech. Behav. Biomed. Mater.* **2014**, *29*, 508–516. [CrossRef] [PubMed]
53. Koottathape, N.; Takahashi, H.; Iwasaki, N.; Kanehira, M.; Finger, W.J. Two- and three-body wear of composite resins. *Dent. Mater.* **2012**, *28*, 1261–1270. [CrossRef] [PubMed]
54. Lanza, A.; Ruggiero, A.; Sbordone, L. Tribology and dentistry: A commentary. *Lubricants* **2019**, *7*, 52. [CrossRef]

55. Heintze, S.D.; Zappini, G.; Rousson, V. Wear of ten dental restorative materials in five wear simulators—Results of a round robin test. *Dent. Mater.* **2005**, *21*, 304–317. [CrossRef] [PubMed]
56. Heintze, S.D.; Barkmeier, W.W.; Latta, M.A.; Rousson, V. Round robin test: Wear of nine dental restorative materials in six different wear simulators—Supplement to the round robin test of 2005. *Dent. Mater.* **2011**, *27*, e1–e9. [CrossRef] [PubMed]
57. Heintze, S.D.; Zellweger, G.; Cavalleri, A.; Ferracane, J. Influence of the antagonist material on the wear of different composites using two different wear simulation methods. *Dent. Mater.* **2006**, *22*, 166–175. [CrossRef] [PubMed]
58. Heintze, S.D.; Cavalleri, A.; Forjanic, M.; Zellweger, G.; Rousson, V. A comparison of three different methods for the quantification of the in vitro wear of dental materials. *Dent. Mater.* **2006**, *22*, 1051–1062. [CrossRef] [PubMed]
59. Heintze, S.D.; Zellweger, G.; Zappini, G. The relationship between physical parameters and wear of dental composites. *Wear* **2007**, *263*, 1138–1146. [CrossRef]
60. Hu, X.; Shortall, A.C.; Marquis, P.M. Wear of three dental composites under different testing conditions. *J. Oral Rehabil.* **2002**, *29*, 756–764. [CrossRef] [PubMed]
61. Matsumura, H.; Leinfelder, K.F.; Kawai, K. Three-body wear of light-activated composite veneering materials. *J. Prosthet. Dent.* **1995**, *73*, 233–239. [CrossRef] [PubMed]
62. Suzuki, S.; Nagai, E.; Taira, Y.; Minesaki, Y. In vitro wear of indirect composite restoratives. *J. Prosthet. Dent.* **2002**, *88*, 431–436. [CrossRef] [PubMed]
63. Turssi, C.P.; Ferracane, J.L.; Serra, M.C. Abrasive wear of resin composites as related to finishing and polishing procedures. *Dent. Mater.* **2005**, *21*, 641–648. [CrossRef] [PubMed]
64. Shabanian, M.; Richards, L.C. In vitro wear rates of materials under different loads and varying pH. *J. Prosthet. Dent.* **2002**, *87*, 650–656. [CrossRef] [PubMed]
65. Kyoizumi, H.; Yamada, J.; Suzuki, T.; Kanehira, M.; Finger, W.J.; Sasaki, K. Effects of toothbrush hardness on in vitro wear and roughness of composite resins. *J. Contemp. Dent. Pract.* **2013**, *14*, 1137–1144. [CrossRef] [PubMed]
66. Wiegand, A.; Schwerzmann, M.; Sener, B.; Magalhães, A.C.; Roos, M.; Ziebolz, D.; Imfeld, T.; Attin, T. Impact of toothpaste slurry abrasivity and toothbrush filament stiffness on abrasion of eroded enamel—An in vitro study. *Acta Odontol. Scand.* **2008**, *66*, 231–235. [CrossRef] [PubMed]
67. Al Khuraif, A.A.A. An in vitro evaluation of wear and surface roughness of particulate filler composite resin after tooth brushing. *Acta Odontol. Scand.* **2014**, *72*, 977–983. [CrossRef] [PubMed]
68. Asadian, F.; Shahidi, Z.; Moradi, Z. Evaluation of wear properties of four bulk-fill composites: Attrition, erosion, and abrasion. *BioMed Res. Int.* **2021**, *2021*, 8649616. [CrossRef] [PubMed]
69. AlAli, M.; Silikas, N.; Satterthwaite, J. The effects of toothbrush wear on the surface roughness and gloss of resin composites with various types of matrices. *Dent. J.* **2021**, *9*, 8. [CrossRef] [PubMed]
70. Honório, H.M.; Rios, D.; Francisconi, L.F.; Magalhães, A.C.; Machado, M.A.A.M.; Buzalaf, M.A.R. Effect of prolonged erosive pH cycling on different restorative materials. *J. Oral Rehabil.* **2008**, *35*, 947–953. [CrossRef] [PubMed]
71. Francisconi, L.F.; Honório, H.M.; Rios, D.; Magalhães, A.C.; Machado, M.A.A.M.; Buzalaf, M.A.R. Effect of erosive pH cycling on different restorative materials and on enamel restored with these materials. *Oper. Dent.* **2008**, *33*, 203–208. [CrossRef] [PubMed]
72. Eisenburger, M.; Addy, M. Erosion and attrition of human enamel in vitro. Part I: Interaction effects. *J. Dent.* **2002**, *30*, 341–347. [CrossRef] [PubMed]
73. Janyavula, S.; Lawson, N.; Cakir, D.; Beck, P.; Ramp, L.C.; Burgess, J.O. The wear of polished and glazed zirconia against enamel. *J. Prosthet. Dent.* **2013**, *109*, 22–29. [CrossRef] [PubMed]
74. Lawson, N.C.; Janyavula, S.; Syklawer, S.; McLaren, E.A.; Burgess, J.O. Wear of enamel opposing zirconia and lithium disilicate after adjustment, polishing and glazing. *J. Dent.* **2014**, *42*, 1586–1591. [CrossRef] [PubMed]
75. Sripetchdanond, J.; Leevailoj, C. Wear of human enamel opposing monolithic zirconia, glass ceramic, and composite resin: An in vitro study. *J. Prosthet. Dent.* **2014**, *112*, 1141–1150. [CrossRef] [PubMed]
76. Turker, I.; Kursoglu, P. Wear evaluation of CAD-CAM dental ceramic materials by chewing simulation. *J. Adv. Prosthodont.* **2021**, *13*, 281–291. [CrossRef] [PubMed]