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MATERIAL EVIDENCE OF HISTORICAL DENTISTRY: A CRITICAL REVIEW OF RESTORATIONS, PROSTHESES AND THEIR CONSERVATION

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Abstract

Historical dental restorations and prostheses constitute a distinctive category of archaeological, technological, and medical heritage, documenting changes in therapeutic practice, craftsmanship, material availability, aesthetics, and access to dental care. This structured critical review examines historical dental materials through three functional systems: restorative and stabilising materials, prosthetic teeth and crowns, and denture bases and frameworks. Evidence is considered in relation to chronology, manufacturing technology, archaeological or collection context, analytical identification, degradation, and conservation requirements. Particular attention is given to metallic corrosion, interactions between dental tissues and restorative materials, fracture and detachment of ceramic components, and deterioration of vulcanite, acrylic resins, and other polymeric materials. Radiography, micro-computed tomography, X-ray fluorescence, SEM-EDS, X-ray diffraction, FTIR, and Raman spectroscopy are evaluated as complementary approaches for material identification and condition assessment. Ethical and curatorial considerations are addressed for objects containing human teeth or remaining associated with human remains. An object–material–priority classification framework is proposed to support consistent documentation, comparative assessment, storage planning, and conservation triage of historical dental objects.

***Keywords**: dental heritage; historical restorations; dental prostheses; material characterization; degradation; conservation science*

Introduction

Historical dental interventions constitute a distinctive form of material evidence, documenting not only disease and treatment but also technical skill, material availability, aesthetic expectations, and access to care. Archaeological investigations have identified restorative and stabilising procedures ranging from metallic ligatures to possible filling and extraction practices, although interpretation requires careful distinction between analytically

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supported intervention and retrospective attribution [1], [2], [3]. Historical prostheses preserved in skeletal and museum collections further demonstrate how dental appliances can retain information on individual treatment, craftsmanship, use, repair, and changing prosthetic concepts [4], [5], [6].

The material history of dentistry reflects a progressive transition from individually fabricated interventions toward increasingly standardised restorative and prosthetic systems. Metallic materials became particularly important in this development. Dental amalgam represents a major historical restorative technology whose composition, biological interactions, persistence within dental tissues, environmental implications, and safety considerations remain subjects of contemporary investigation [7]-[11]. Likewise, cobalt–chromium alloys illustrate the later expansion of corrosion-resistant metallic systems used in prosthetic rehabilitation [12].

Dental prosthetics subsequently incorporated increasingly diverse ceramic and polymeric materials. Artificial teeth, dental ceramics, crowns, denture-base polymers, and metallic frameworks exhibit material-specific patterns of wear, fracture, surface alteration, corrosion, and dimensional change [13]-[21]. Polymeric oral appliances further illustrate the functional diversification of dental materials and the importance of considering service-related deformation and surface changes when interpreting preserved objects [22]. At the same time, micro-computed tomography, SEM-EDS, and CBCT demonstrate the growing role of non-destructive and minimally invasive imaging and compositional analysis in examining dental tissues and complex structures [23], [24].

Despite this extensive literature, contemporary research predominantly evaluates clinical performance, mechanical behaviour, or material optimization. Historical dental objects are less frequently examined through an integrated framework combining chronology, manufacturing evidence, archaeological or collection context, analytical identification, degradation, and conservation. Accordingly, this review focuses on three functional systems, restorative and stabilising materials, prosthetic teeth and crowns, and denture bases and frameworks, to evaluate historical dental materials as composite heritage evidence requiring both scientific characterization and context-sensitive preservation.

Review Methodology

Search Strategy

This structured critical review was designed to synthesize recent evidence concerning historical dental interventions and prostheses from a materials-conservation perspective. Literature published between 2020 and 2026 was considered, with the search focused on historical restorations, prosthetic appliances, denture materials, manufacturing technologies, analytical characterization, degradation mechanisms, preventive conservation, and ethical or curatorial management. The search strategy combined terms related to dental function, material composition, historical context, conservation, and analytical investigation. Core concepts included historical dentistry, archaeological dental interventions, historical dental prostheses, dental heritage, amalgam, metallic restorations, dental ceramics, vulcanite, cellulose-based materials, PMMA, cobalt–chromium alloys, X-ray fluorescence, SEM-EDS, micro-computed tomography, FTIR, Raman spectroscopy, degradation, and conservation.

Particular attention was given to studies involving archaeological teeth, historical prostheses, identified skeletal collections, museum or university teaching collections, and dental objects retaining evidence of manufacture, repair, use, or material deterioration. Because direct conservation literature on historical dental objects remains comparatively limited, contemporary experimental studies were considered when their analytical methodology or material-behaviour findings were directly transferable to the characterization, interpretation, or conservation assessment of historical specimens. Such studies were not used to infer historical clinical performance, but rather to support interpretation of material structure, surface characteristics, fracture behaviour, corrosion, polymer degradation, and non-destructive analytical approaches.

The literature was organized around three functional systems defined a priori: restorative and stabilising materials; prosthetic teeth, crowns, and aesthetic components; and denture bases and frameworks. This structure was selected to integrate chronological development with material composition, manufacturing evidence, deterioration, and conservation requirements rather than treating individual materials as isolated categories.

Eligibility Criteria

Studies were considered eligible when they provided relevant information on at least one of the following domains: object or specimen type, dental function, chronological or archaeological context, material composition, manufacturing or attachment technique, analytical characterization, degradation process, conservation condition, preventive conservation, or curatorial and ethical management. Priority was given to peer-reviewed publications directly addressing historical dentistry, archaeological dental interventions, museum or skeletal collections, cultural heritage materials, and analytical methods applicable to composite dental objects.

Publications focused exclusively on contemporary clinical effectiveness, treatment outcomes, patient-reported outcomes, or optimization of modern dental procedures were excluded from the core evidence base when their findings had no clear relevance to historical-material interpretation or conservation. Experimental studies of modern dental materials were retained selectively when they provided transferable evidence concerning fracture morphology, surface characterization, microstructure, corrosion behaviour, material interfaces, micro-computed tomography, SEM-EDS, or other analytical approaches useful for assessing historical dental objects [13]- [25].

Ethical and curatorial literature was included when it addressed human remains, identified skeletal collections, extracted human teeth, provenance, acquisition practices, or institutional stewardship. This evidence was considered essential because historical restorations and prostheses may remain physically associated with human biological material or may derive from teaching and research collections whose acquisition histories require specific ethical consideration [26]-[33].

No material identification was accepted as definitive solely on the basis of visual resemblance when the cited source itself reported uncertainty. Historical descriptions, morphological interpretations, documentary attributions, and analytically confirmed identifications were therefore treated as distinct levels of evidence.

Data Extraction and Evidence Classification

For each included publication, information was extracted according to a predefined comparative framework comprising: publication year; chronological period of the object or intervention; geographical, archaeological, museum, skeletal, or institutional context; object type; dental function; constituent material or material system; manufacturing or attachment features; analytical method; reported deterioration phenomena; conservation implications; ethical or curatorial considerations; and basis of material identification.

Evidence was classified into four categories according to the strength of identification: analytically confirmed, when supported by instrumental or laboratory characterization; historically documented, when supported by reliable archival, collection, or manufacturing records; morphologically inferred, when attribution was primarily based on macroscopic or structural features; and uncertain, when the available evidence did not permit a definitive identification. This distinction was used to avoid conflating historical attribution with direct material characterization and to preserve the evidential limitations of individual studies.

The extracted evidence was subsequently compared across the three functional systems with particular attention to five conservation-relevant dimensions: material composition and technological development; manufacturing and repair evidence; degradation mechanisms and material interactions; suitability and limitations of analytical methods; and implications for conservation, storage, handling, and ethical management. Particular emphasis was placed on composite objects, because interactions between biological tissues, metals, ceramics, natural organic materials, and polymers may determine both deterioration behaviour and conservation priority.

Rather than providing a purely chronological or descriptive synthesis, the review integrated material, analytical, historical, and curatorial evidence to identify recurrent conservation risks and transferable assessment strategies. This comparative synthesis also formed the basis for the proposed Object–Material–Priority classification framework, which separates object context, constituent material system, and conservation urgency in order to support documentation, collection surveys, storage planning, analytical prioritization, and conservation triage.

Chronological Overview of Historical Dental Materials

Early Dental Interventions

The earliest evidence of dental intervention must be interpreted cautiously because post-mortem alteration, disease-related defects, and intentional treatment may produce superficially similar findings. Recent archaeological studies have nevertheless documented interventions consistent with restorative or stabilising procedures, including metallic ligatures and possible filling or extraction practices [1], [2], [3]. Such findings are particularly important because they demonstrate that dental treatment was not limited to pain relief or extraction, but could also involve attempts to stabilize teeth, restore damaged structures, or replace lost dental function. For conservation purposes, the distinction between analytically confirmed intervention and morphology-based interpretation remains essential.

Pre-Industrial Prosthetic Practice

Before industrial standardisation, dental prostheses were individually fabricated and frequently combined biological and metallic materials. Human or animal teeth, ivory, bone, gold, and silver could be incorporated into removable or fixed appliances, with attachment achieved through wires, ligatures, plates, or mechanically adapted components. Historical and identified skeletal collections demonstrate the value of such prostheses as evidence of treatment history, craftsmanship, and individual access to dental care [4], [5]. Their composite character also creates conservation challenges because biological tissues, metals, and organic materials may deteriorate through different mechanisms.

Nineteenth-Century Transformation

The nineteenth century marked a major technological transition toward more standardized restorative and prosthetic systems. Dental amalgam became increasingly established as a restorative material, while porcelain teeth and vulcanised rubber expanded the possibilities for more affordable and reproducible prosthetic rehabilitation [6], [7]. Vulcanite was particularly influential because it provided a mouldable denture-base material that could support artificial teeth while facilitating larger-scale production [5], [6]. At the same time, metallic restorations and frameworks continued to evolve, establishing combinations of materials that remain characteristic of surviving historical dental objects.

Twentieth-Century Dental Heritage

During the twentieth century, acrylic resins, especially polymethyl methacrylate, became central to denture fabrication, while cobalt–chromium and other base-metal alloys became increasingly important for frameworks and fixed prosthetic systems [12], [13], [18]-[21]. Ceramic materials also diversified through improved manufacturing and bonding technologies, producing crowns and prosthetic teeth with increasingly standardized structural and aesthetic properties [14]-[17]. These developments transformed dentistry from predominantly handcrafted fabrication toward laboratory-controlled and industrially produced material systems. From a heritage perspective, twentieth-century prostheses are therefore valuable not simply as obsolete clinical devices, but as material records of changing manufacturing methods, material science, aesthetics, affordability, and expectations of durability.

The principal chronological transitions in historical dental materials, together with their functional applications, preserved object forms, documentary contexts, and principal evidence basis, are summarized in Table 1.

Table 1. Chronological overview of historical dental materials, dental applications, and evidence basis

Period	Material / material group	Principal dental use	Representative object form	Documented context	Evidence basis
Ancient to medieval	Gold and other metallic ligatures	Stabilisation, connection, or tooth replacement	Wire, ligature, band, bridge-like intervention	Archaeological human remains and curated skeletal collections	In situ examination, radiography, contextual assessment, elemental analysis [1], [2], [3]
Pre-industrial to 19th century	Human/animal teeth, ivory, bone, noble metals	Replacement teeth and individually fabricated prostheses	Artificial tooth, carved base, partial or complete prosthesis	Historical dentures, skeletal collections, museum and university collections	Morphology, provenance, documentary evidence, imaging and material analysis [4], [5]
18th–20th century	Gold, silver, dental amalgam and related metallic restorative systems	Restoration, cavity filling, stabilisation	Foil, metallic filling, ligature, inlay	Archaeological remains, extracted teeth, teaching specimens and dental collections	Historical documentation, radiography, elemental/material analysis [1], [7]-[11]
19th–20th century	Porcelain and dental ceramics	Artificial teeth, crowns and aesthetic components	Denture tooth, crown, ceramic facing	Historical dentures, museums and university teaching collections	Microscopy, SEM-EDS, radiographic or three-dimensional imaging, compositional analysis [5], [13]-[17]
Mid-19th–early 20th century	Vulcanite / hard rubber and transitional early polymers	Denture bases	Complete or partial denture	Museum, university and historical dental collections	Manufacturing evidence, historical documentation and material characterization [5], [6]
20th century	PMMA and cobalt–chromium alloys	Denture bases and metallic frameworks	Acrylic denture, removable partial denture framework	Clinical heritage, teaching specimens, museum and institutional collections	Imaging, SEM-EDS, surface/material characterization and documentary evidence [5], [12], [18]-[21]

The historical dental materials considered in this review were organized into three functional systems: restorative and stabilising materials, prosthetic teeth and crowns, and denture bases and frameworks, as summarized in Figure 1.

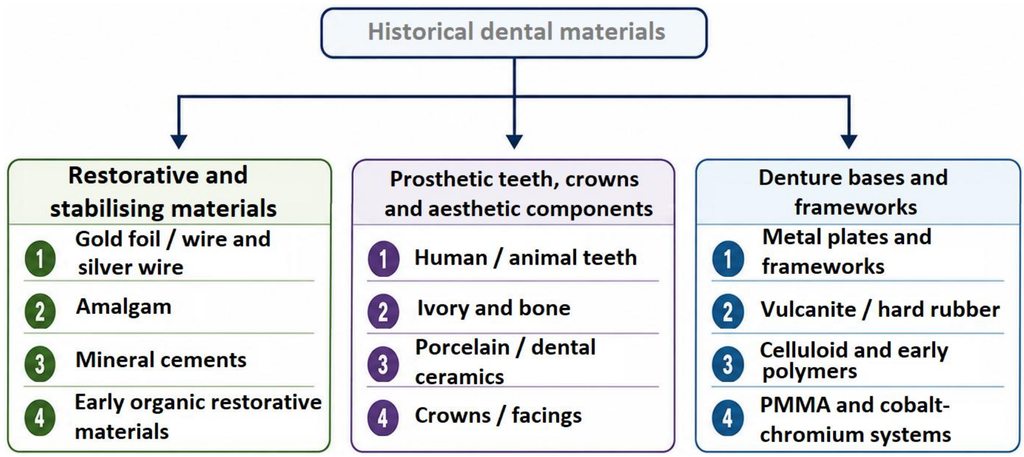

Fig. 1. Functional classification of historical dental materials according to the three principal systems used in the present review.

Restorative and Stabilising Materials

Materials and Dental Functions

Historical restorative and stabilising interventions include metallic ligatures, metallic fillings, amalgams, and other materials used to retain, reconnect, or replace lost dental structure. Archaeological evidence of gold ligatures demonstrates that metallic elements could serve a stabilising or connecting role and that their interpretation depends on the relationship between the material, tooth position, and surviving attachment features [1]. Evidence from ancient Egyptian remains suggests that some defects may represent intentional intervention, although attribution must remain cautious when analytical confirmation is absent [2], [3].

Dental amalgam subsequently became one of the most influential metallic restorative systems. Its long clinical history reflects the combination of relatively simple placement, adaptability to prepared cavities, and durable service performance [7]. Recent studies remain relevant to historical specimens because they document the persistence of metallic constituents within dental tissues, biological interactions, and mercury-related considerations that may also affect the handling and interpretation of older restored teeth [8]-[11]. Other metallic systems, including cobalt–chromium alloys, became important mainly in later prosthetic applications and illustrate the broader transition toward corrosion-resistant dental alloys [12].

Mineral cements and early organic filling substances should be considered only where composition or historical documentation can be demonstrated. Within the present evidence set, these materials are less directly represented than metallic restorations; consequently, they should not be assigned specific compositions or functions without analytical or documentary support.

Context, Evidence and Manufacturing Techniques

The interpretation of a historical restoration requires more than recognition of the material itself. In situ interventions on archaeological teeth, extracted teaching specimens, detached restorations, and objects preserved within museum or skeletal collections represent different evidential contexts and must be documented accordingly [1]- [5]. Cavity preparation, wire bending, ligature placement, condensation of metallic restorative material, marginal finishing, and repair traces may provide technological information even when the original clinical record is unavailable.

The evidential strength of material identification should therefore be explicitly stated. Radiographic and three-dimensional imaging can reveal internal morphology, retained restorative material, marginal relationships, or hidden structural features, while micro-computed tomography and SEM-EDS can provide complementary structural and compositional information [23], [24]. Where destructive sampling is inappropriate, the combination of imaging, surface examination, and documentary evidence offers a more defensible basis for interpretation than visual identification alone.

Degradation and Conservation Issues

Historical restorative materials may deteriorate through corrosion, tarnishing, marginal fracture, loss of material, cracking of adjacent dental tissues, or chemical interaction between restoration and substrate. Metallic ions may persist within tooth structure after amalgam removal, demonstrating that the tooth–restoration interface can retain evidence of previous treatment even when the restoration itself is incomplete [9]. Mercury-containing specimens require additional handling precautions because preservation decisions must consider both heritage value and material safety [8], [10], [11].

Conservation should prioritize documentation before cleaning or mechanical intervention. Surface deposits, marginal staining, wear, repair marks, and corrosion products may retain evidence of fabrication, use, or long-term ageing and should not automatically be classified as undesirable alteration. The primary objective is therefore stabilization of the object and preservation of diagnostically or historically meaningful features rather than reconstruction of an ideal clinical appearance.

Prosthetic Teeth, Crowns and Aesthetic Components

Natural and Biological Materials

Before the widespread availability of standardized artificial teeth, prosthetic rehabilitation relied on materials that could approximate dental form while permitting mechanical adaptation to individually fabricated appliances. Historical prostheses therefore incorporated human or animal teeth and, in some instances, carved ivory or bone components. Their significance extends beyond their original clinical function because the morphology, attachment features, wear patterns, repairs, and association with other materials can preserve evidence of manufacturing practice and previous use [4], [5].

Natural dental tissues present particular interpretive and conservation challenges. Human or animal teeth may be difficult to distinguish solely on visual criteria when they have been extensively modified, incorporated into composite prostheses, or subjected to prolonged ageing. Their identification should consequently consider morphology, attachment method, associated materials, provenance, and, where justified, analytical investigation. The ethical status of objects containing human teeth must also be considered separately from that of purely manufactured prosthetic components, particularly when they remain associated with identifiable human remains or documented individuals [26]-[29]. Ivory and bone require similar caution in attribution because visual resemblance alone does not provide sufficient evidence for definitive material identification. Accordingly, historical descriptions should be distinguished from analytically confirmed identifications.

Dental Ceramics

The introduction and progressive refinement of porcelain and other dental ceramics represented a major development in prosthetic dentistry because these materials permitted more standardized reproduction of tooth morphology and appearance. Historical ceramic components may occur as denture teeth, crowns, facings, or elements mechanically or chemically associated with metallic and polymeric structures [5]. Their interpretation requires consideration of both the ceramic material and the interface through which it was attached to the supporting prosthesis.

Contemporary material-characterization studies provide useful methodological analogues for examining historical ceramic objects. Artificial and ceramic dental materials display differences in microstructure, surface morphology, wear resistance, fracture behaviour, and marginal adaptation that can be assessed using microscopy, SEM-based analysis, and three-dimensional imaging [13]-[17]. SEM examination of fractured ceramic and polymer surfaces can help distinguish characteristic failure patterns [15], while micro-computed tomography permits non-destructive evaluation of internal and marginal relationships in crown structures [16]. Surface characterization combined with SEM-EDS further contributes information on compositional heterogeneity and manufacturing-related features [17].

For historical specimens, such methods should be used primarily to establish material identity, internal construction, attachment systems, and deterioration rather than to retrospectively assess clinical performance. Fracture, glaze abrasion, staining, chipping, detachment, corrosion of metallic pins or supports, and deterioration of joining materials may all constitute relevant condition indicators.

Interpretation and Conservation

A central conservation problem is distinguishing original prosthetic components from later replacements, repairs, or modifications. Differences in tooth morphology, shade, wear, surface texture, attachment systems, and composition may indicate multiple phases in the working history of an appliance [4,5]. Mechanical and fracture studies also demonstrate that interfaces between ceramics, polymers, and metallic components represent structurally important regions where deterioration or previous repair may become concentrated [15], [17], [25].

Non-destructive imaging should precede disassembly or invasive investigation whenever hidden pins, roots, screws, voids, or joining structures are suspected. Micro-CT and related three-dimensional approaches can reveal internal relationships that are inaccessible by surface inspection alone [16], [23], [24]. These data should be interpreted together with visible manufacturing traces and documentary evidence.

Conservation should prioritize preservation of the existing material history rather than restoration to an idealized clinical appearance. Staining within cracks, attachment interfaces, wear facets, replacement teeth, repair materials, and altered supporting components may retain evidence of manufacture, prolonged use, or later intervention. Cleaning, consolidation, or reconstruction should therefore follow comprehensive documentation and material assessment, with particular ethical consideration when human dental tissues form part of the object [26]-[29].

Denture Bases and Frameworks

Principal Materials

Denture bases and frameworks represent one of the clearest examples of technological transition in historical dentistry because they combine changes in material availability, fabrication methods, cost, aesthetics, and industrial production. Nineteenth-century prostheses frequently incorporated vulcanised rubber as a denture-base material, while surviving collections also document transitional use of celluloid and related early polymers [5], [6]. These materials were gradually supplemented and later largely replaced by polymethyl methacrylate (PMMA), which became a dominant denture-base polymer during the twentieth century. Contemporary studies of PMMA-based systems remain useful for understanding polymer structure, surface behaviour, mechanical performance, and degradation mechanisms relevant to historical acrylic dentures [13], [18], [21].

Metallic components remained equally important. Gold, silver, aluminium, and later cobalt–chromium alloys were used for plates, clasps, wires, frameworks, and joining elements. Cobalt–chromium became particularly significant in twentieth-century removable prosthodontics because of its combination of rigidity, reduced bulk, and corrosion resistance

[12], [19], [20]. Historical dentures are therefore often composite objects in which metals, polymers, artificial teeth, solders, and repair materials interact over prolonged periods [5].

Manufacturing Evidence

Manufacturing traces are essential for distinguishing original construction from subsequent modification. Carving, swaging, casting, soldering, wire forming, moulding, vulcanisation, polymerisation, finishing, and chairside or laboratory repair may all leave diagnostically useful evidence on historical prostheses [5], [6]. Vulcanite bases may retain moulding and finishing traces associated with nineteenth-century processing, whereas acrylic dentures can preserve flask-processing marks, repair lines, additions, or changes in tooth arrangement. Metallic frameworks may show casting defects, polishing patterns, soldered joints, clasp adjustments, and areas of localized deformation.

Modern investigations of cobalt–chromium frameworks demonstrate that manufacturing and finishing procedures can measurably affect surface morphology, microstructure, corrosion behaviour, and fit [19], [20]. Although these studies concern contemporary production, the same analytical principles are transferable to historical objects when assessing casting traces, surface finishing, repair joints, or manufacturing-related heterogeneity. Manufacturer marks, laboratory inscriptions, serial numbers, mould seams, and replaced components should therefore be documented before cleaning or treatment because they may contribute to chronological attribution and provenance.

Degradation and Conservation

The conservation of dentures is complicated by mixed-material ageing. Metallic frameworks may undergo corrosion, tarnishing, or localized degradation at joints and stressed areas, while adjacent polymers or artificial teeth may display staining, fracture, or loss of attachment [5], [12], [19]. Early polymeric denture bases can undergo discoloration, embrittlement, dimensional change, and surface alteration, whereas PMMA-based materials may develop crazing, fracture lines, surface roughening, or changes associated with ageing and environmental exposure [18], [21]. Vulcanised rubber is particularly significant from a heritage perspective because oxidation and sulphur-related chemical change may alter both its mechanical properties and surface appearance [5], [6].

Conservation should therefore begin with material mapping and assessment of the interaction between all components. Composite dentures should not be stored or supported according to the requirements of only the visually dominant material. Custom inert mounts are preferable when fragile bases, clasps, teeth, or repaired regions are mechanically vulnerable. Cleaning should remain conservative, especially where surface discoloration, repair lines, deposits, or corrosion may provide evidence of manufacture or long-term use. For unstable composite appliances, stabilization, controlled storage, and periodic monitoring are generally more appropriate than extensive reconstruction of an idealized clinical appearance.

Analytical Strategy, Conservation and Ethical Management

Analytical Strategy

The investigation of historical dental objects should follow a staged analytical workflow in which increasingly complex techniques are introduced only when they are necessary to resolve a specific material, structural, or conservation question. The first stage should consist of contextual and visual documentation, including provenance review, photography under normal and raking light, macrophotography, dimensional recording, inscriptions, manufacturing marks, condition mapping, and visible evidence of repair or use. This documentation establishes the interpretive framework within which subsequent analytical results can be evaluated.

Radiography and three-dimensional imaging are particularly valuable for identifying internal structures without disassembly. Conventional radiography, CBCT, and micro-computed tomography can reveal retained roots, pins, voids, hidden joins, marginal relationships, framework geometry, and previous repairs [16], [23], [24]. Micro-CT is especially useful when internal construction or material interfaces cannot be assessed visually, while CBCT provides a transferable model for volumetric assessment of complex dental structures [24].

Elemental and mineralogical characterization should then be selected according to material type. XRF can support non-destructive identification of metallic components, while SEM-EDX provides localized elemental information on alloys, corrosion products, ceramics, and material interfaces [17], [23]. XRD may be indicated where crystalline phase identification is required, particularly for mineral-based materials, corrosion products, or ceramic constituents. For organic and polymeric components, FTIR and Raman spectroscopy are appropriate for identifying acrylics, vulcanite, celluloid, resins, adhesives, and related materials, and are particularly relevant to nineteenth- and twentieth-century dentures [5], [6], [13], [18], [21].

Targeted sampling should remain a secondary option and be justified by a clearly defined research question. Metallography, chromatographic analysis, proteomics, or DNA-based methods may provide decisive evidence in selected cases, but their use must be proportionate to the expected information gain and to the ethical and curatorial status of the object. Analytical interpretation should ultimately integrate material composition with chronology, manufacturing traces, object context, degradation state, and documentary evidence rather than treating laboratory results in isolation.The principal analytical methods applicable to historical dental objects, together with the information they provide and their main limitations, are summarized in Table 2.

Table 2. Analytical methods applicable to historical dental materials

Method	Information obtained	Suitable materials/objects	Main limitation
Radiography / CBCT / micro-CT	Internal structure, joins, pins, voids, repairs [16], [23], [24]	Teeth, crowns, dentures, composite prostheses	Limited chemical identification
XRF / SEM-EDX	Elemental composition, alloys, interfaces, corrosion products [17], [23]	Metals, ceramics, dental tissues	Surface/accessibility limitations
XRD	Crystalline phase identification	Cements, ceramics, corrosion products	Limited for amorphous materials
FTIR / Raman	Molecular identification of polymers, resins and pigments [5], [6], [13], [18], [21]	PMMA, vulcanite, celluloid, adhesives, ceramics	Spectral overlap or fluorescence
Targeted sampling	Detailed microstructural or biomolecular confirmation [26]-[29]	Selected metals and biological materials	Destructive; requires justification

Conservation and Ethical Management

Conservation planning must begin by establishing whether a dental object remains associated with human remains, incorporates human teeth, or can be linked to an identifiable individual or collection context. Such objects require ethical and curatorial evaluation in addition to conventional materials-based conservation. Current recommendations for the stewardship of human remains emphasize transparent governance, provenance, respectful handling, and consideration of community or institutional responsibilities [26], [27]. Comparable ethical concerns apply to extracted human teeth used in teaching or research collections, particularly where acquisition histories or consent records are incomplete [28]. Broader bioethical discussions of anatomical collections further underline the need to treat human-derived material as more than a conventional museum substrate [29].

Before cleaning, disassembly, or consolidation, all constituent materials, joins, restorations, repair lines, deposits, and previous interventions should be mapped. Clinically derived deposits, burial residues, corrosion products, adhesives, polishing traces, and later conservation additions may have different origins and historical meanings and should therefore not be removed solely because they alter appearance. Composite dentures and restorations are especially vulnerable because metals, ceramics, polymers, and biological tissues may respond differently to humidity, temperature, mechanical stress, and chemical ageing [5], [12], [18]-[21].

Environmental and storage conditions should be determined by the most vulnerable component of the object. Fragile dentures or prostheses benefit from inert custom supports that distribute load across stable regions rather than individual teeth, clasps, or weakened repair zones. Objects containing unstable polymers or active metallic corrosion should be isolated when deterioration products could affect neighbouring materials. In such cases, stabilization, controlled storage, and periodic reassessment are generally preferable to extensive reconstruction.

Conservation should therefore preserve the evidential integrity of the object rather than recreate an idealized clinical state. Wear, fracture, replacement components, repair materials, discoloration, and previous intervention may document the working life of the prosthesis and should be retained when they contribute to interpretation. Ethical stewardship, analytical evidence, and material-specific risk must consequently be considered together when deciding whether intervention is necessary and how far it should proceed.

Object–Material–Priority Classification Framework

Object Category

The first axis classifies each object according to its archaeological, historical, educational, or collection context. Category A designates an archaeological dental intervention, including a restoration, ligature, appliance, or modification retained in association with human remains. Category B refers to a detached historical prosthesis, such as a complete or partial denture, bridge, crown, plate, obturator, or other prosthetic appliance preserved independently of the individual. Category C includes isolated restorative or prosthetic components, for example detached fillings, artificial teeth, crowns, clasps, framework fragments, or repair elements. Category D is assigned to educational or manufacturing specimens, including extracted teeth, teaching models, moulds, impressions, trial dentures, fabrication stages, or demonstration objects. Finally, category E encompasses historical material references, such as commercial samples, alloys, cements, porcelain tooth sets, polymer specimens, packaging, or manufacturer-related reference materials. This distinction is necessary because archaeological remains, detached prostheses, teaching specimens, and curated museum objects differ substantially in provenance, evidential value, permissible sampling, and conservation requirements [1], [4], [5], [27], [28].

Material-System Code

The second axis identifies the dominant material system. The code B denotes biological dental tissue or a human or animal tooth, whereas M indicates a metal or alloy. The code C is used for ceramic materials or mineral cements, and O designates natural organic materials, including ivory or bone. Polymeric materials and rubber are classified as P, while X identifies composite objects containing two or more significant material systems.

The **X** category is particularly important for historical prostheses because many dentures and prosthetic appliances combine metals, artificial teeth, polymers, biological tissues, and joining materials within a single object [4], [5]. The interfaces between these materials may influence corrosion, fracture, dimensional stability, staining, and mechanical integrity, making composite construction directly relevant to conservation planning [12], [18]-[21].

Conservation-Priority Code

The third axis defines the required level of conservation attention. Priority 1 indicates a stable object with no evidence of active deterioration, for which routine monitoring and appropriate storage are sufficient. Priority 2 identifies a vulnerable object that is environmentally sensitive or mechanically fragile and therefore requires controlled conditions and scheduled reassessment. Priority 3 denotes a high-priority object showing active degradation, unstable components, weak joins, insufficient mechanical support, or interacting materials with potential for progressive damage. Priority 4 is reserved for urgent cases involving imminent material loss, active corrosion, hazardous degradation, severe structural instability, or risk to associated human remains or neighbouring collection objects.

Priority assignment should be based on documented condition, material behaviour, object complexity, and ethical status rather than visual appearance alone. This is particularly relevant for prostheses containing unstable polymers, corroding metallic components, or human-derived materials, where deterioration may affect both the object itself and its broader collection environment [5], [18], [19], [26]-[29].

The three axes are combined into a single classification code. For example, A-X-3 identifies an archaeological dental intervention composed of multiple significant material systems and requiring high-priority conservation attention. This coding system allows rapid comparison between objects while preserving the distinction between provenance, material complexity, and conservation risk. It may therefore support cataloguing, collection surveys, storage planning, research prioritization, and conservation decision-making across archaeological, museum, university, and clinical heritage collections [4], [5], [27]- [29]. The proposed three-axis classification system, integrating object category, material system, and conservation priority, is illustrated in Figure 2 using the example code A-X-3.

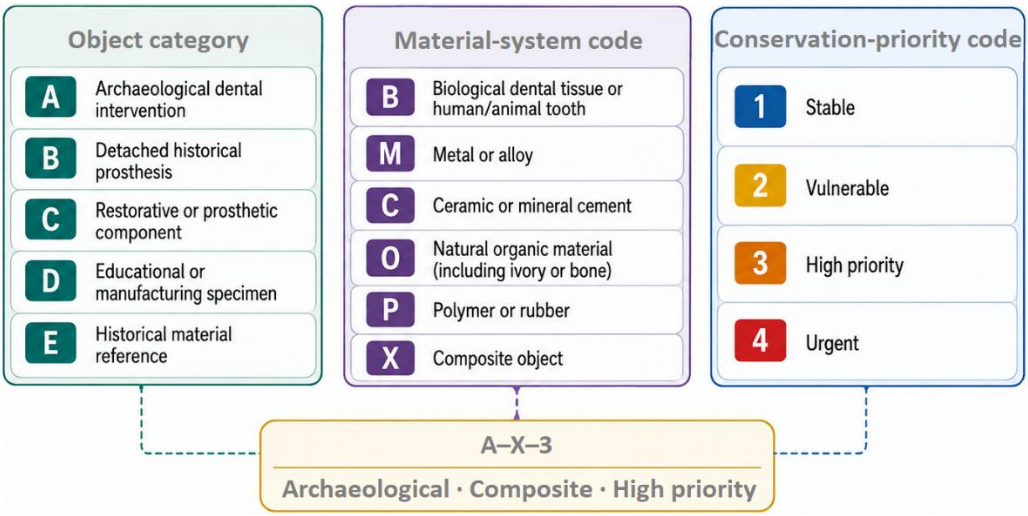

Fig. 2. Object–Material–Priority classification framework for historical dental objects, illustrated using the example code A-X-3.

The principal deterioration patterns and corresponding conservation priorities for historical dental objects are summarized in Table 3, illustrating the practical application of the proposed classification framework.

Table 3. Degradation patterns and conservation priorities for historical dental objects

Object / material system	Principal deterioration	Recommended conservation approach	Priority
Metallic restorations and	Corrosion, tarnishing, weak joints, staining of adjacent materials [8], [9],	Material characterization, corrosion monitoring, controlled storage,	2–4

frameworks	[12], [19]	selective stabilization	
Ceramic teeth and crowns	Fracture, chipping, glaze abrasion, detachment, interface failure [15]-[17], [25]	Mechanical support, documentation of fractures and joins, minimal intervention	1–3
Vulcanite and early polymers	Oxidation, embrittlement, discoloration, dimensional change [5], [6]	Isolation when unstable, environmental control, inert supports	2–4
PMMA denture bases	Crazing, fracture, surface alteration, deformation [18], [21]	Controlled handling, mechanical support, periodic reassessment	1–3
Human teeth / biological components	Cracking, structural loss, deposits, deterioration of associated materials [4], [26]-[29]	Ethical assessment, minimal handling, documentation, context-specific storage	1–4
Composite prostheses (X)	Mixed-material corrosion, weak interfaces, differential ageing [5], [12], [18]-[21]	Material mapping, support according to most vulnerable component, targeted stabilization	2–4

Discussion

The present review indicates that historical dental objects should be interpreted as complex material records rather than as obsolete clinical devices. Restorative interventions, prosthetic teeth and crowns, and denture bases and frameworks differ in function and chronology, yet all preserve information about material availability, craftsmanship, technological standardization, clinical adaptation, and patterns of use. This distinction is particularly important for conservation because the significance of a historical dental object cannot be reduced to its present appearance or to the nominal identity of its principal material. Archaeological context, manufacturing evidence, repair history, biological association, and interactions between constituent materials must be considered together when assessing condition and deciding whether intervention is justified [1]-[7].

A central finding of this review is that analytical confirmation is essential when historical attribution is uncertain. Visual examination alone may suggest that a component is gold, silver, porcelain, ivory, vulcanite, or acrylic resin, but appearance can be modified substantially by corrosion, staining, ageing, polishing, burial, or previous repair. The X-ray fluorescence investigation of a historical fixed dental prosthesis from an identified skeletal collection provides a particularly relevant example, demonstrating how elemental analysis can correct assumptions based on visual appearance and strengthen interpretation of manufacturing technology and material choice [30]. This principle extends beyond material identification itself. The curatorial context of extracted human teeth and prosthetic appliances also requires documented acquisition history, because collection practices may not always meet contemporary ethical expectations [31]. Recent discussions on human remains in museums further emphasize that conservation and research decisions must integrate stewardship, provenance, institutional responsibility, and the status of associated individuals or communities [32], [33]. Historical dental collections therefore occupy a distinctive position in which conservation science and bioethical management intersect.

Metallic components present another major conservation challenge. Gold, silver, amalgam, cobalt–chromium alloys, clasps, wires, soldered joints, and metallic frameworks may appear mechanically robust but remain susceptible to corrosion, environmental contamination, surface alteration, and long-term microstructural change [7]- [12], [19], [20]. Studies of metal-based objects in scientific and technical museums demonstrate that corrosion risk is influenced not only by alloy composition but also by relative humidity, pollutants, enclosure materials, and interactions with adjacent organic components [34]. This is directly relevant to historical dentures and restorations, which frequently combine metals with acrylics, rubber, ceramic teeth, biological tissues, adhesives, or storage materials. Cleaning must therefore be selective. Research on corroded lacquered brass shows that the effectiveness and aggressiveness of complexing agents depend strongly on the condition and composition of the treated surface [35], while long-term studies of copper- and silver-based heritage alloys demonstrate that embrittlement and microstructural alteration may develop independently of obvious surface corrosion [36]. Investigations of laser cleaning further illustrate that technically effective removal of corrosion products must still be evaluated in relation to preservation of the underlying surface and historical evidence [37]. These findings support the conservative approach proposed in this review: material characterization should precede aggressive polishing, chemical cleaning, or disassembly.

The analytical strategy used for historical dental objects should likewise be problem-oriented rather than technique-driven. XRF is particularly valuable because it permits rapid elemental characterization with minimal or no sampling, but interpretation must account for surface geometry, coating thickness, corrosion, and measurement angle [38], [39]. Raman spectroscopy offers complementary molecular information and is especially useful for identifying pigments, corrosion products, mineral phases, and selected organic materials without extensive sampling [40]. Three-dimensional X-ray methods add an important structural dimension. X-CT can reveal internal joins, voids, framework geometry, fracture propagation, concealed supports, and previous repairs without dismantling the object [41]. More advanced diffraction-based approaches can provide crystalline phase information when conventional imaging or elemental analysis is insufficient [42]. For historical dental prostheses, where a single object may contain teeth, ceramics, metals, polymers, screws, pins, repair materials, and voids, such complementary methods are more informative than isolated measurements.

Polymeric components require particular attention because their degradation may remain chemically active long after the object has left clinical use. Celluloid, cellulose nitrate, cellulose acetate, vulcanite, PMMA, and related materials may undergo yellowing, embrittlement, loss of plasticizer, shrinkage, surface exudation, chain degradation, and volatile emission [5], [6], [18], [21]. Infrared spectroscopy has been shown to provide useful indicators of degradation in cellulose nitrate and acetate and can help distinguish visually similar polymers with markedly different conservation requirements [43]. Historical plastics may also undergo colour change as a result of degradation of pigments or interactions between polymer matrices and additives [44]. Broader studies of industrial heritage polymers demonstrate that visual ageing phenomena can be correlated with underlying material changes and therefore used as part of systematic condition assessment [45]. Long-term research on historical PMMA further shows that additive composition and manufacturing processes influence ageing behaviour, reinforcing the need to consider production history rather than treating all acrylic materials as equivalent [46].

Non-contact and minimally invasive methods are particularly important for fragile polymeric components. Reflection and transflection FTIR can improve material characterization where direct contact or sampling is undesirable [47]. Chemometric assessment of cellulose nitrate demonstrates that spectral changes can provide measurable information on degradation state [48], while image-based approaches can detect and map yellowing at pixel level and potentially support longitudinal monitoring [49]. These techniques are relevant to denture bases and other polymeric components because deterioration is often spatially heterogeneous, with localized cracking, staining, shrinkage, or exudation occurring around repaired regions, tooth attachments, metal interfaces, or stressed areas.

The storage environment must also be considered as an active component of deterioration rather than as a neutral background condition. Investigations of museum storage rooms have shown that degrading plastics can contribute to indoor pollutants while simultaneously being affected by volatile compounds emitted by surrounding materials [50]. This reciprocal relationship is especially important for composite dental objects because one unstable polymeric component may influence adjacent metal, paper, textile, adhesive, or biological material. Preventive conservation should therefore be tailored to actual material behaviour, rather than applying a single environmental target uniformly across all objects [51]. Collection-level risk analysis provides a practical way to prioritize limited resources by distinguishing stable objects from those requiring isolation, improved environmental control, analytical clarification, or urgent stabilization [52].

These findings support the object–material–priority framework proposed in the present review. Its principal value lies in separating three questions that are often conflated in museum practice: what the object is, what it is made of, and how urgently it requires conservation attention. An archaeological dental intervention associated with human remains cannot be managed in the same way as an isolated museum denture, even if both contain similar metallic or polymeric materials. Likewise, two acrylic dentures may require different priorities if one is mechanically stable and the other exhibits active cracking, unstable repairs, or interaction with corroding metallic components. The framework therefore provides a rapid comparative tool while preserving the need for detailed documentation, material characterization, and case-specific ethical evaluation.

A further implication concerns the interpretation of damage. Wear facets, corrosion products, marginal staining, fracture lines, replaced teeth, clasp adjustments, soldered repairs, relining materials, and surface deposits may represent evidence of the working life of a dental appliance rather than simply deterioration. Their removal may erase information about clinical adaptation, laboratory repair, reuse, economic constraints, or changing prosthetic practice [4]- [7]. Conservation should therefore aim to preserve evidential integrity rather than recreate an idealized clinical appearance. Intervention is justified primarily when deterioration is active, structural stability is threatened, hazardous materials are present, or adjacent collection objects are at risk.

Overall, the evidence reviewed here supports a conservation model based on characterization, minimal intervention, preventive management, and explicit recognition of composite-object behaviour. Historical dental objects are particularly challenging because they combine materials with very different chemical and mechanical properties and may also retain direct association with human biological tissues. Their preservation therefore requires collaboration between conservators, materials scientists, dental historians, archaeologists, curators, and specialists in the ethical management of human remains. Within this interdisciplinary framework, the proposed classification system can support cataloguing, comparison, storage planning, treatment prioritization, and future research without replacing detailed analytical and curatorial assessment.

Conclusions

Historical dental interventions and prostheses constitute a distinct category of medical, technological, archaeological, and cultural heritage. Organizing the evidence into three functional systems—restorative and stabilising materials, prosthetic teeth and crowns, and denture bases and frameworks—provides a clearer analytical structure than an exhaustive catalogue of individual materials. This approach also highlights the importance of composite construction, where biological tissues, metals, ceramics, natural organic materials, and polymers may coexist within a single object and deteriorate through different but interacting mechanisms.

Reliable interpretation requires more than visual attribution. Provenance, manufacturing traces, radiographic and three-dimensional imaging, elemental analysis, mineralogical characterization, and molecular spectroscopy should be integrated whenever necessary to distinguish original materials, later repairs, degradation products, and uncertain identifications. Wear, staining, replacement components, marginal alterations, and previous repairs should be documented before cleaning or reconstruction because they may retain evidence of clinical use, craftsmanship, material ageing, and subsequent intervention.

Conservation decisions must also account for ethical and curatorial responsibilities when human teeth or associated human remains are present. Within this context, the proposed object–material–priority classification offers a practical framework for cataloguing, comparative assessment, storage planning, and conservation triage. Its value lies in structuring complex information without replacing detailed documentation, analytical confirmation, or case-specific ethical evaluation.

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